

José R. Lerma Valero

Plastics Injection Molding

Scientific Molding, Recommendations, and Best Practices



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Lerma Valero

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José R. Lerma Valero

September 2019

Preface

This manual has been created thinking of plastics injection molding technicians as well as processing engineers and quality and design engineers.

The book was initially born as a small procedure guide for the company where I was working, for fine-tuning injection machines with the aim of creating a logical, safe, and optimized start-up method. Gradually, it grew and accumulated interesting information for the technicians, in my opinion, and it took shape until the final editing.

It was created for those who have ever needed a book to help and support them to understand the technology, materials, and thermoplastics injection process.

It is a book that helps identify the key points of the process and show, explore, and teach new tools to define more stable, robust, and consistent processes; a book with information, for example, such as the following:

- Clear explanations about the main key points of the thermoplastics injection molding process
- Glossaries with detailed explanations and easy-to-handle data tables
- Explanations about thermoplastics and their properties and behavior
- Support information to select material according to its further application
- Support information to determine the most suitable machine to use
- Real case examples, problems, analysis, and solutions
- Scientific injection molding explanations of tools, calculations, and portability
- Examples of defects and failures, their causes and possible solutions
- Easy and clear explanations for injection process optimization
- General processing recommendations

I hope that this book can be a tool for consulting and support during the professional life of the reader.

I also aim to encourage technicians toward a cultural change in both the analysis of problems and the parameterization and definition of robust plastics injection molding processes, where the transition from the empirical method toward the scientific method can be made using appropriate methodologies.

José R. Lerma Valero

September 2019

About the Author

José R. Lerma Valero was born in Barcelona, Catalonia, in 1962; he is married and has a son. He obtained a superior degree in mechanics, with specialty in molds, and studied business management. He started his professional life as a trainee in a small injection molding factory.

José R. Lerma has dedicated close to 40 years of his professional life to the world of thermoplastics. Most of this professional life in plastics injection factories has been dedicated to producing parts for the automotive sector, producing both technical and aesthetic parts, painted, with chrome plating, etc. The functions and responsibilities he carried out in these injection plants have been of all kinds; for example, Processing Engineer, Technical Department Manager, Maintenance Manager, Production Manager, and Plant Manager.

Currently, and for almost 12 years, he is the Technical Manager for Spain and Portugal in Biesterfeld Ibérica SLU, leader in polymer distribution in Europe, with a portfolio of materials from the world's leading manufacturers.

José R. Lerma has been collaborating for more than 15 years with different technical centers in Spain as a leader of different seminars all related to plastics and the transformation of plastics, having trained hundreds of technicians in this technology.

In 2013 he published the book “Advanced Manual of Thermoplastics Transformation” in the Spanish language, with great success among plastics injection technicians.

It should also be noted that for six years he has developed and taught a specific seminar about scientific injection molding methodology in Spain, Portugal, and some Latin-American countries quite successfully.

All this accumulated background of experience in real day-to-day cases in factories as well as the training received and the experience of providing training in seminars to technicians is reflected and shared in this book.



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Part 1

Plastics

Polymers

Polymers are molecules very common in our environment. They may be natural or synthetic. We can find them in our food (starches, proteins), our clothing (cotton, polyester, silk, nylon, etc.), our homes (wood, paint), and even in our body (proteins, DNA). A polymer is a macromolecule with a high molecular weight. Its name comes from the Greek and we can roughly translate it as “many parts”.

Since polymers are substances with high molecular weight, they have a large size. This size is achieved by the repeated binding of small molecules called monomers. The binding is done in sequence: one unit after the other, like a chain where each unit is a link. The number of links (or monomers) indicates the degree of polymerization.

A common molecule (such as water) has a molecular weight of 18 grams/mol. This means that 6.06×10^{23} water molecules weigh 18 grams (1 mol). In the case of hexane, a solvent, it has a molecular weight of 86 g/mol. In comparison, for example, the molecular weight of UHMW PE (ultra high molecular weight polyethylene) can be 4,000,000 g/mol, or that of rubber can reach 1,000,000 g/mol. That is, 6.06×10^{23} rubber molecules weigh 1 ton. These data can give us an idea of the difference between small molecules and polymers.

Polymers have a heterogeneous molecular weight. When we speak of the molecular weight of polymers, we are talking about average amounts (see Section 1.5).

1.1 Plastics

All plastics are composed of large molecules bound together by strong link forces. All plastics are characterized by high molecular weights.

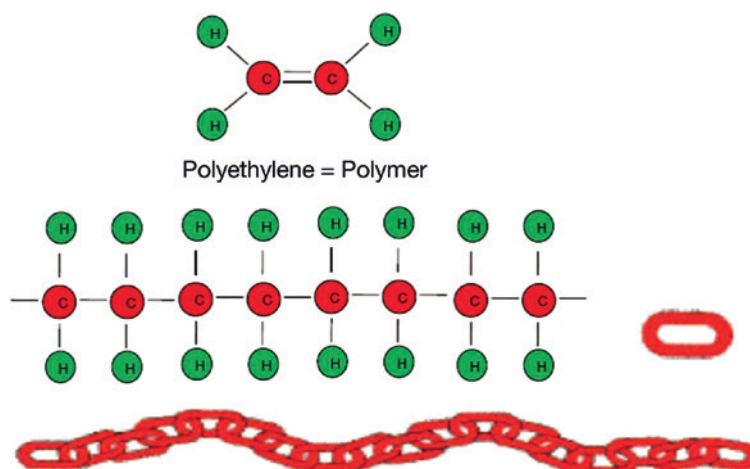
Plastics are obtained by polymerization. Through this process, a number of molecules or monomers are linked by reactions to produce a large molecule or polymer (macromolecule).

We can imagine a plastic like a ball of wool made up of many individual threads.

Monomers are chemical compounds in which the carbon atoms are linked by a double bond.



Figure 1.1 Example: ethylene monomer (molecule)



The carbon double bond ($C =$) allows the linking of molecules and the creation of polymers. The carbon atom is one of the few that can link itself through its double bonds.

When polymerized, these double bonds are broken and form bonds in two directions, forming the macromolecule. In the simplest cases they are joined one after the other like the links of a chain or a necklace.

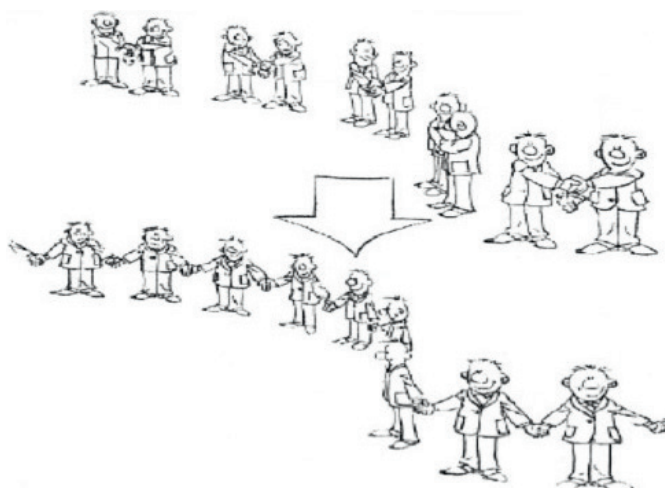
1.2 Molecular Bonds

Atoms of monomer molecules are linked by atomic bonds called covalent bonds. These bonds are forces holding two atoms together. Two atoms may be linked by single, double, or triple bonds.

Besides the bonding forces between atoms, there are bonding forces between molecules. These forces are called intermolecular forces. They attract the adjacent molecule with a certain intensity.

These forces provide and determine properties such as strength. To consider strength, we can use an analogous image: we can imagine a zipper, which provides strength to a fabric. The zipper hooks would be the intermolecular forces. Only if we pull very strongly do hooks come loose. However, these intermolecular forces are weaker than covalent bonding forces or atomic bonds.

Intermolecular forces are sensitive to the energy applied by heat. The higher the temperature, the more the molecules move; molecules begin to vibrate and intermolecular forces decrease. Above a certain temperature, those forces disappear and the molecules can move freely and easily slide against each other. However, the covalent bonds between atoms are much more resistant and their destruction requires much higher temperatures.

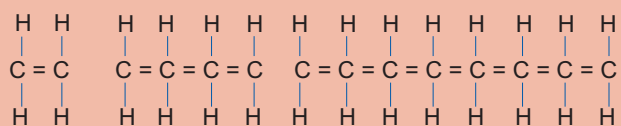


Unlike intermolecular bonds, if the heat energy is high enough, covalent bonds or bonds between atoms do not form again when the temperature decreases: the molecule remains destroyed.



Hydrocarbons

Hydrocarbons are **organic compounds** consisting only of **carbon** and **hydrogen** atoms. Their molecular structure consists of a framework of carbon atoms to which hydrogen atoms are attached.



■ C_2H_4 ethylene

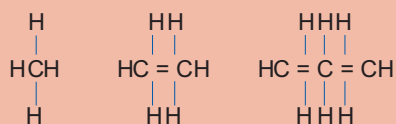
■ C_4H_8 butene

■ C_6H_{12} hexene

■ C_8H_{16} octene

Properties change depending on the molecular structure:

GAS $\longrightarrow$ SEMI-SOLID



CH_4 C_2H_6 C_3H_8 ... C_4H_{10} ... C_5H_{12} ... $\text{C}_{16}\text{H}_{34}$
 METHANE ETHANE PROPANE ... BUTANE ... PENTANE ... PARAFFIN

1.3 Functionality

Polymer formation can be explained by the notion of functionality. Functionality expresses the number of usable functional groups in a molecule for the synthesis of macromolecules. A functional group is a group of atoms that, in an organic molecule, is responsible for a characteristic reaction.

Amine groups, hydroxyl groups, and double bonds are examples of functional groups.

The starting compounds of plastic must be at least bifunctional. To understand this concept, consider the example of train cars. These cars are bifunctional: they are linked from the front and the rear with the other cars, thus forming the train. In the case of plastics, the compounds bind in the same way to form a macromolecule.

The shape and size of the molecules which react and the number and position of the functional groups determine the properties of the resulting polymers. In the case of bifunctional monomers, linear plastics are obtained. However, if they are trifunctional or polyfunctional, insoluble and infusible plastics are obtained.

The plastic material obtained does not have quite the desired properties to use these materials. It is necessary to add different additives such as plasticizers, heat stabilizers, lubricants, etc. These additives allow the processing of the material and the product obtained will thus have the desired properties and performance.

Polymers themselves do not meet the technical requirements for which they are needed and cannot be used in their original state. Polymers generally constitute only one part of plastics. But there is another part, the additives, which complements and converts polymer in plastic. These additives are dispersed in the polymeric matrix or dissolved in the polymer. The mixture of polymer and additives is plastic. These additives can be plasticizers, lubricants, flame retardants, UV blockers and protectants, nucleating, reinforcing, and antistatic agents, heat and hydrolysis stabilizers, etc.

1.4 Polymerization

1.4.1 Polycondensation

During this polymerization reaction a loss of small molecules takes place. Often it is water molecules. This process is known as condensation. Polycarbonates and polyamides, among other compounds, are obtained by polycondensation.

1.4.2 Polyaddition

This is similar to the polycondensation reaction but, rather than a loss of atoms, a migration of atoms occurs from one functional group to another. Polyurethane and epoxy resins are obtained by polyaddition.

1.5 Determination of the Molecular Weight of Polymers

Molecular Weight

Molecular weight is the weight of all the atoms in a substance. A molecule is a stable group of two or more atoms. Atoms are contained in any substance in an ordered distribution. This distribution cannot be altered without altering the properties of the substance. The molecular weight of a substance is the sum of the molecular weights of the constituent atoms.

Consider, for example, a water molecule (H_2O). It consists of two atoms of hydrogen and one of oxygen. To determine the molecular weight of water, just multiply the atomic weight of hydrogen by two (since there are two hydrogen atoms) and add the weight of oxygen. Hydrogen weighs about 1 atomic mass unit (u) and oxygen weighs about 16 u. Thus, the molecular weight of water is $(1 \times 2) + 16 = 18 \text{ g/mol}$.

The molecular weight M_n is the number average molecular weight. It corresponds to the total weight of all the molecules divided by the total number of molecules.

The molecular weight M_w is the weight average molecular weight and is obtained by multiplying the molecular weight of each of the fractions present by their respective ratio to the total weight of the specimen. Thus, this value shows us the molecular weight dominant value—either by its content (w_i/W) or by its size (M_i)—in the specimen.

Polydispersity indicates the degree of variation or amplitude of the Gaussian distribution of the molecular weight distribution of a polymer. It is represented by the quotient of the weight average molecular weight by the number average molecular weight (M_w/M_n). When the value of the polydispersity factor is 1, the sample is considered homodisperse. The further away from that value, the sample will be considered more heterodisperse.

The molecular weight is a characteristic of the plastic, because the length of the chain determines the material properties. The molecular weight is an index of the degree of polymerization of a substance.

Normally, the higher the molecular weight, the higher the mechanical properties (hardness and toughness), but also the higher the processing problems and the lower the fluidity (i.e., the material will have a higher viscosity).

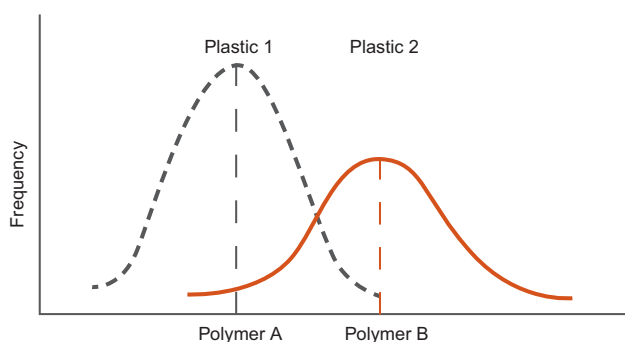


Figure 1.2 Molecular weight distribution

Table 1.1 Properties According to Level of Polymerization

High Polymerization Level	Low Polymerization Level
Viscosity increases	Crystallizing decreases
Tensile strength increases	Swelling decreases
Tear resistance increases	Stress-cracking resistance decreases
Elongation at break increases	Hardness decreases
Impact resistance increases	

1.6 Thermoplastics

Thermoplastics are substances that can be softened by applying heat and that may harden on cooling. This softening and solidification process (carried out over a range of temperatures typical of each material) may be repeated a number of times.

Polymeric thermoplastics consist of interlaced polymer chains. In solid form, these chains have no possibility of movement. By applying heat, this energy causes vibration into the system, breaking the bonds between macromolecules, sliding against each other and producing the softening and plastic flow. At room temperature, these thermoplastics may be soft or hard and brittle or tough.

1.6.1 Classification of Thermoplastics

1.6.1.1 According to Their Molecular Structure: Morphology

Amorphous

Amorphous thermoplastics have a shapeless and disorganized molecular structure, like a plate of spaghetti.

The amorphous polymer chains are not grouped in a predetermined order but randomly, interpenetrating each other. Amorphous polymers are plastics with highly branched molecular chains. Their side chains are very long. Because of their size and shape, these chains cannot be packaged compactly; they resemble a ball of string and they lack a structural order. Therefore, they are called amorphous.

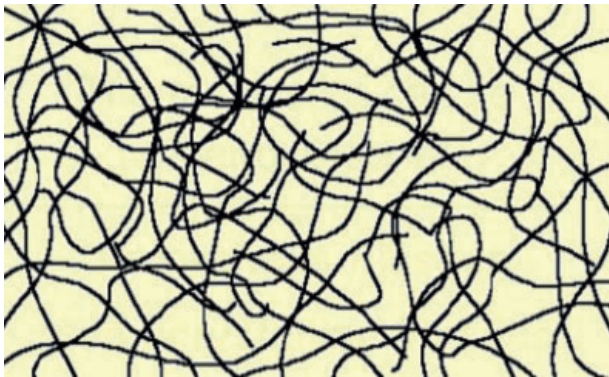


Figure 1.3 Amorphous thermoplastics melt over a fairly wide range of temperatures

PS: polystyrene

PVC-U: rigid polyvinyl chloride

PVC-P: flexible polyvinyl chloride

ABS: acrylonitrile butadiene styrene

SAN: styrene acrylonitrile

SB: styrene butadiene

PMMA: polymethyl methacrylate

PC: polycarbonate

Semi-crystalline

Semi-crystalline thermoplastics have an ordered molecular structure. Some molecules are rearranged against each other, forming crystallites. In the semi-crystalline plastics there is always an amorphous region and a crystalline region.

Macromolecules have few and short side branches. As a result, it is possible that some regions of the molecule chains be sorted and packaged against each other. These regions with molecular chains packed are called crystalline regions. A perfect crystallization from all regions of the polymer does not occur: there are always disordered or amorphous regions. Therefore, they are called semi-crystalline polymers.

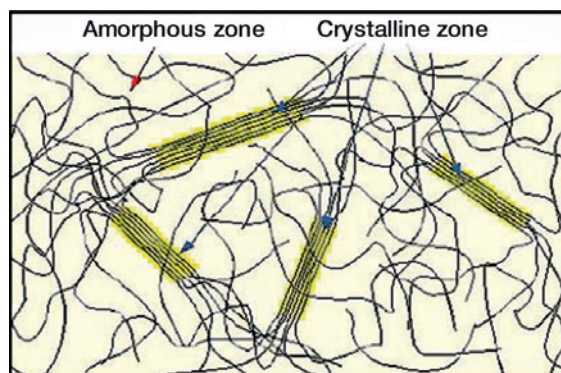


Figure 1.4 Semi-crystalline thermoplastics melt at melting temperature

LDPE: low density polyethylene

HDPE: high density polyethylene

PP: polypropylene

PA: polyamide

POM: polyoxymethylene (acetal resins)

PET: polyethylene terephthalate

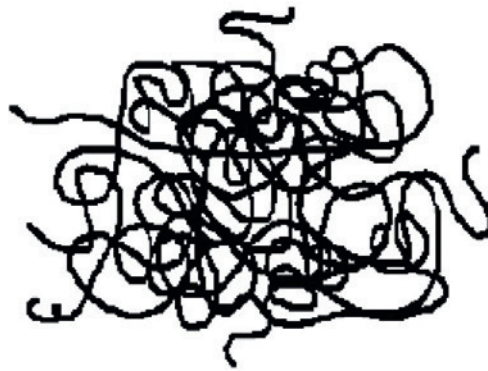
PBT: polybutylene terephthalate

PPS: polyphenylene sulfide

PEK: polyetherketone

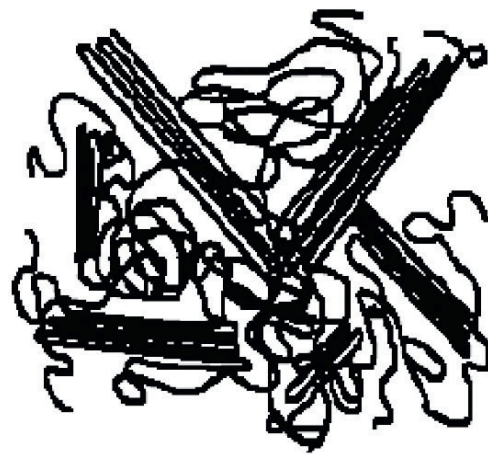
PTFE: polytetrafluoroethylene

Amorphous plastics:

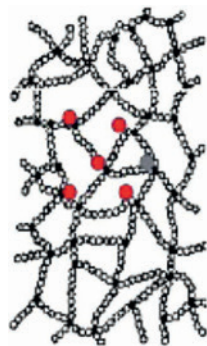


- Dimensional stability
- Isotropy
- Possibility of transparency
- Viscous
- A more uniform shrinkage
- Tendency to internal stress
- Low post-shrinkage
- Low chemical resistance
(*stress cracking*)

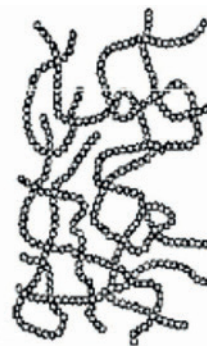
Semi-crystalline plastics:



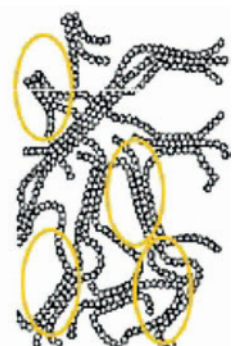
- Chemical resistance
- Fatigue resistance
- Lower presence of internal stress
- Anisotropy: molding differentiated shrinkage
- Greater fluidity



thermostable
cross-linked
molecular network



amorphous
entangled, linear
formless molecules



semi-crystalline
linear molecules
crystals

Table 1.2 Generic Differences between Amorphous and Semi-crystalline Thermoplastics

Amorphous	Semi-crystalline
Transparent (not always)	Translucent or opaque
Low molding shrinkage	High molding shrinkage
Less defined fusion temperature	Very definite and narrow melting range (3–5 °C)
Middle mechanical resistance, low fatigue resistance	High mechanical resistance (especially to fatigue)

Table 1.3 Generic Properties Comparison between Amorphous and Semi-crystalline Thermoplastics

Characteristics	Crystalline	Amorphous
Specific weight	+	–
Tensile strength	+	–
Tensile modulus	+	–
Ductility, elongation	–	+
Continuous operating temperature	+	–
Fluidity	+	–
Chemical resistance	+	–
Shrinkage	+	–

Elastomers

Elastomers are linked molecular structures in three dimensions. These links allow the molecular movement in all directions.

The molecules are linked together by bridges forming a reticule. Thus, these plastics are called cross-linked plastics.

The molecules of these materials are not only joined by intermolecular bonds, but also by covalent bonds. At room temperature, these plastics behave like rubber. Cross-links cause molecular chains to have limited mobility.

1.6.1.2 According to Their Molecular Chain Form

Linear

A-A-A-A-A-A-A-A-A-A-A-A



Homopolymer

A single monomer is involved. Molecules are composed of identical chemical units. The repeating unit is the same throughout the molecule.

Linear homopolymer

A-A-A-A-A-A-A-

Branched homopolymer

A-A-A-A-A-A-A-A
|
A-A-A-A-

Copolymer

Two or more monomers are involved (i.e., there are two or more repeating units in its structure).

A-A-A-A-B-B-A-A-A-B-B-A-A-A-A-B-B-B-A-A-A-B-B-A-A-



Block Copolymer

The monomer sequence is repeated in blocks.

AAAAA-BBBBBB-AAAAA-BBBBBB-AAAAA-BBBBBB-AAAAA-

Random Copolymer

A-B-B-A-A-A-B-B-A-A-B-B-B-B-A-A-B-B-A-A-B-B-A-A-B-B-B-A-A-B-B-A-

Alternating Copolymer

A-B-A-B-A-B-A-B-A-B-A-B-A-B-A-B-A-B-A-B-A-B

A polymer with the same number of A and B units will have very different properties depending on the type of chain ordering.

1.6.1.3 According to the Position of Atoms in the Chain

Atactic

Isotactic

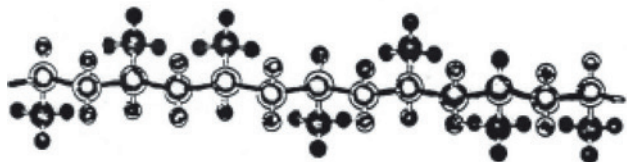
Syndiotactic



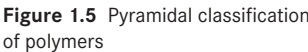
ISOTACTIC
(the same order)



SYNDIOTACTIC
(alternating order)



ATACTIC
(without order)



1.7 Properties and Characteristics of Plastics

1.7.1 Thermal and Physical Behavior

1.7.1.1 Rheology

Plastics have characteristics of both an elastic solid and a viscous liquid. They have a viscoelastic behavior.

By applying stress on them, they are deformed. This deformation can be instantaneous or continuous over time.

The stress applied to a plastic can produce three types of response:

1. Elastic deformation
2. Viscous flow
3. Break

1.7.1.2 Elastic Deformation

If a material is deformed instantly by applying stress and strain is recovered after the cessation of stress, the material is behaving elastically.

Hooke's law: the stress applied is proportional to the deformation caused.

1.7.1.3 Viscosity

Viscosity is the relationship between stress and strain rate.

When a movement is applied to a fluid, this one presents a resistance to the movement. Newtonian fluids exhibit a linear relationship between the force or pressure exerted and the fluid speed. Plastics are non-Newtonian fluids, which have no linear relationship between stress and speed or deformation.

Newtonian Viscosity



Newton’s law:

If a force is applied to a fluid, the fluid moves at a speed proportional to the force applied.

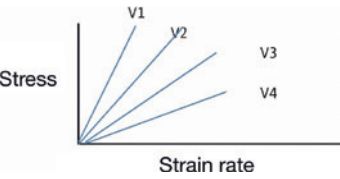


Figure 1.6 Stress vs. strain rate

In Figure 1.6, V1, V2, V3, and V4 are different viscosities. For a greater stress (pressure), the fluid deformation is proportionally faster. This ratio of proportionality is the viscosity.

In the case of a Newtonian fluid, increasing the pressure increases the rate proportionally to the pressure.

Plastics are materials with non-Newtonian behavior:

- They are viscoelastic fluids
- The viscous behavior does not obey Newton’s law
- The viscosity is not constant

Table 1.4 Generic Shear Rate for Different Processes

Compression molding	1–10 s ⁻¹
Calendering	10–100 s ⁻¹
Extrusion	100–1000 s ⁻¹
Injection	1000–10,000 s ⁻¹

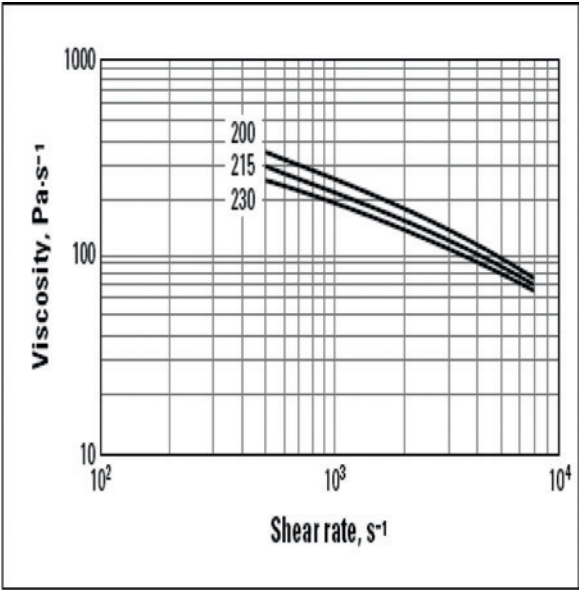


Figure 1.7 Viscosity versus shear rate, example (POM h); source: DuPont

In the case of plastic melts in the range of the conditions of injection molding, an increase in stress can quadruple the deformation or the shear rate.

In the graph (Figure 1.7) it can be seen the decrease in viscosity as the shear rate increases. Increasing the temperature at low shear rates is more effective in

reducing the viscosity. At high shear rates, the lines of viscosity behavior at different temperatures almost converge.

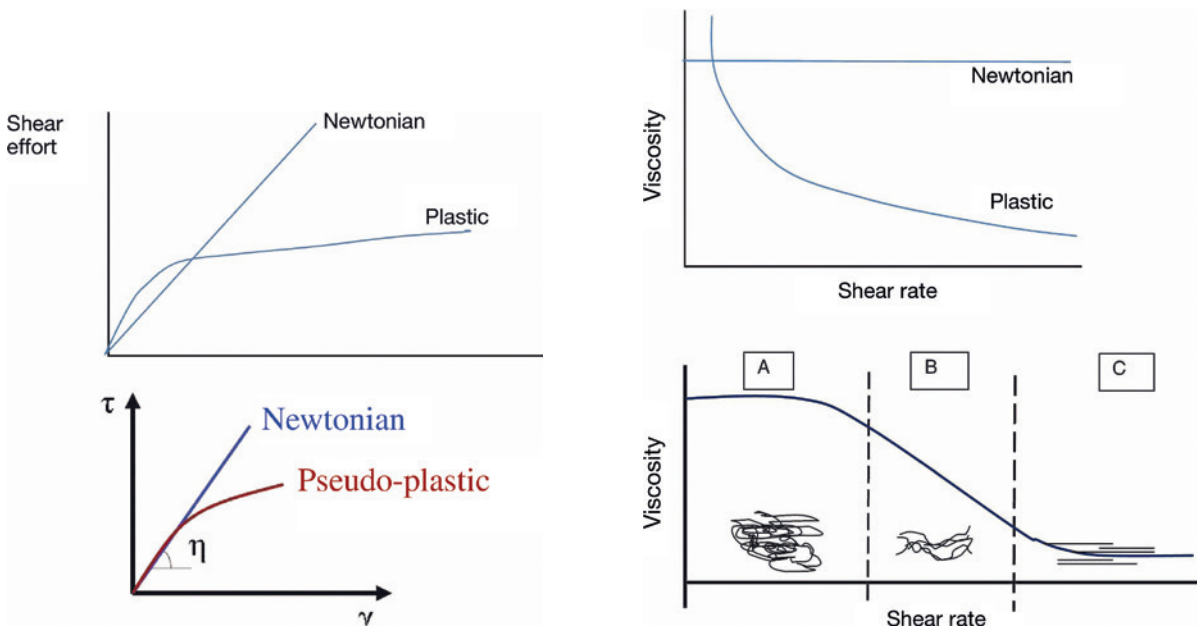


Figure 1.8 Effect of shear on the viscosity of the polymer; A: initial area, with flat viscosity at low shear rates; B: intermediate zone, with intermediate shear rate and viscosity drop depending on shear rate; C: end zone, with high shear rate and flat viscosity

Key point:

From the above information it follows that, if a polymer is processed with a constant flow ratio and constant pressure loss rates, the viscosity will be constant, this polymer will flow with the same characteristics, and will produce parts with identical dimensions and properties.

1.7.1.4 Glass Transition Temperature (T_g)

Glass transition temperature T_g is the temperature below which the molecular movement is highly restricted and limited. The material is glassy, brittle, and fragile. The movement is restricted and limited to the vibrations of the links and in some cases to the rotation of small carbon atoms (no more than 4 or 5).

Above the T_g , the molecular motions are allowed, going into a rubbery state. Large segments of chain (more than 100 atoms) are movable and one can slide on another (creep).

Table 1.5 T_g of Some Polymers

PA	from 20 to 30 °C	PC	150 °C	PMMA	105 °C
PA 66	57 °C	PE	-125 °C	POM	-80 °C
PP	from 0 to -20 °C	PS	100 °C	PET	70 °C

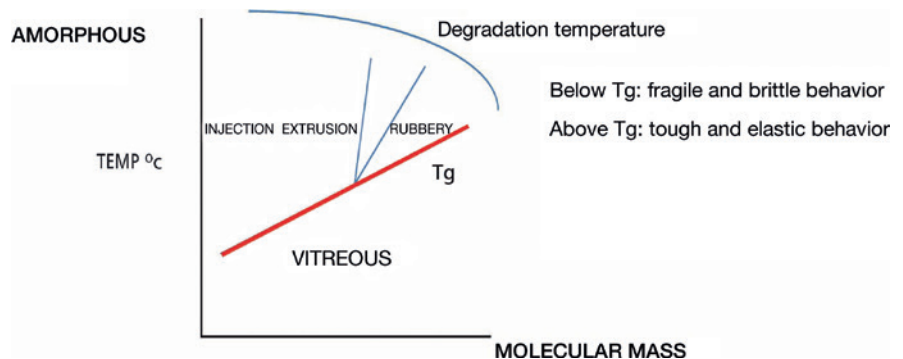
1.7.1.5 Melting Temperature (T_m)

Temperature at which the fusion or melting of the crystals formed in the semi-crystalline plastics is produced.

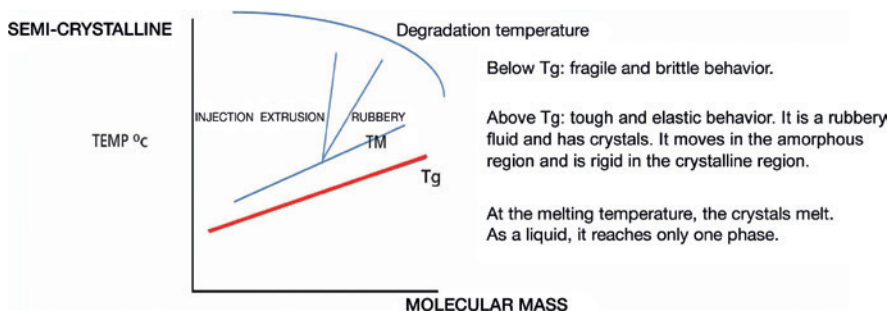
**CRYSTALLINITY DEGREE AND MELTING TEMPERATURES
OF SOME SEMI-CRYSTALLINE THERMOPLASTICS**

MATERIAL	% CRYSTALLINITY	MELTING RANGE (°C)
PELD	40 - 55	105 - 115
PEHD	60 - 80	125 - 140
PP	60 - 70	158 - 168
PIB	50	120 - 130
PA's	< 60	
PA6		215 - 225
PA66		250 - 265
PA610		210 - 225
PA11		180 - 190
PA12		175 - 185
PA46		295
POM (h)	75	175
POM ©	70	165 - 168
PET	30 - 40	255 - 258
PBT	40 - 50	220 - 225
PPS	40	280 - 288
PEEK	40	334
PTFE	53 - 70	327

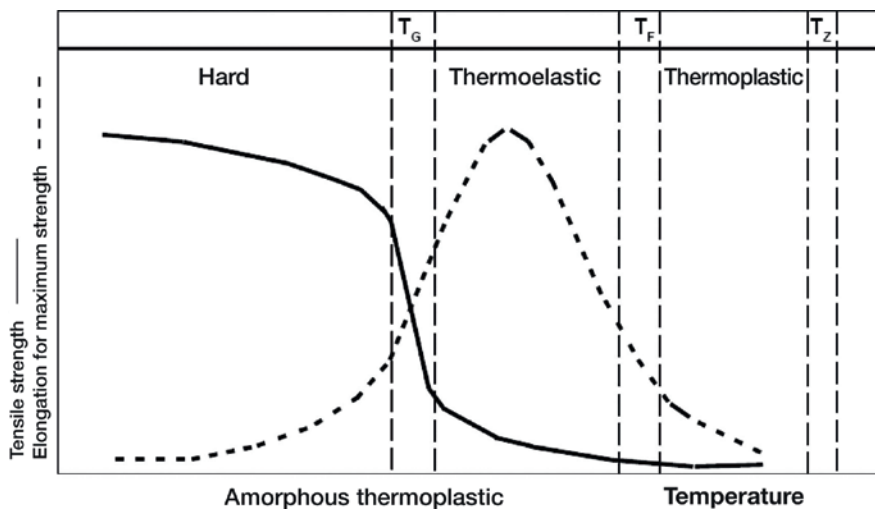
Figure 1.9 Source: Ascamm



If an amorphous polymer is subjected to a temperature increase, its chain segments will gain mobility. According to its molecular weight, the polymer will undergo one or two states. Upon reaching the glass transition temperature, the polymer will go from the glassy state to the viscous liquid state (depending on its molecular weight, it could happen before a rubbery state). The higher the molecular weight, the higher the glass transition temperature. The behavior may vary when changing phase.



1.7.1.6 Thermoplastics Behavior



1.7.1.7 Changes of State in Amorphous Materials

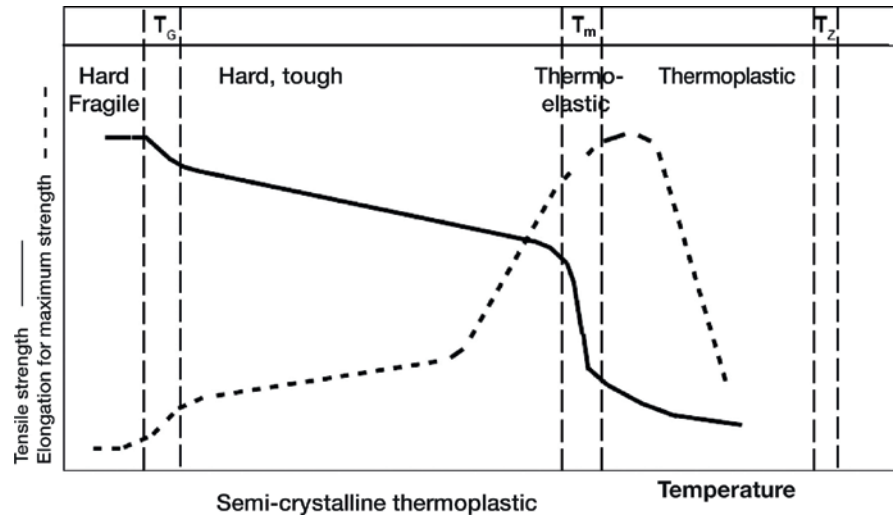
At room temperature (T_R), amorphous plastics are tough. The molecular bonds are holding the structure and molecules can hardly move.

If we increase the temperature gradually, macromolecules begin to move and the mechanical tensile strength decreases, making the material more elastic and tough.

After reaching the glass transition temperature (T_g), the intermolecular forces that held the structure become weak and macromolecules can slide against each other with relatively little external force. Mechanical properties fall down; therefore, elasticity increases abruptly. The material goes from a rigid glassy state to a rubbery state, being elastic like rubber.

If we increase the temperature, intermolecular forces disappear and the rubbery material goes into a molten state (T_f).

If the temperature continues to increase, the atomic bonds will break. Covalent bonds are destroyed, resulting in decomposition and degradation of the material. Molecular weight and material properties will disappear (T_z).



1.7.1.8 Changes of State in Semi-crystalline Materials

Semi-crystalline thermoplastics, unlike amorphous materials, have two types of structural areas or zones: an amorphous area, where molecules are located some distance from each other, and a crystalline region, where molecules are packed in the form of crystallites. In these crystalline areas intermolecular forces are considerably stronger than in the amorphous areas. These crystalline regions reach the thermoelastic area when they are melted by reaching the melting temperature (T_m).

Below the glass transition temperature, semi-crystalline materials are frozen in the amorphous and crystalline regions. The molecular motion is not possible and the material is hard, fragile, and brittle.

When the glass transition temperature is exceeded, the first molecules that begin to move are those of the amorphous regions as intermolecular forces are less intense than in the crystalline regions. Above the glass transition semi-crystalline temperature, materials have toughness properties.

In the most common crystalline plastics, the glass transition temperature is below room temperature (T_R).

If the temperature continues to increase, the molecular chains of the amorphous areas are increasingly mobile and in the crystalline regions the molecules slowly begin to vibrate.

When the melting temperature (T_m) is reached, the molecules of the crystalline regions are released from the intermolecular forces and the crystallite melting occurs. The molecules of the crystalline areas slide against each other and all plastic begins to melt.

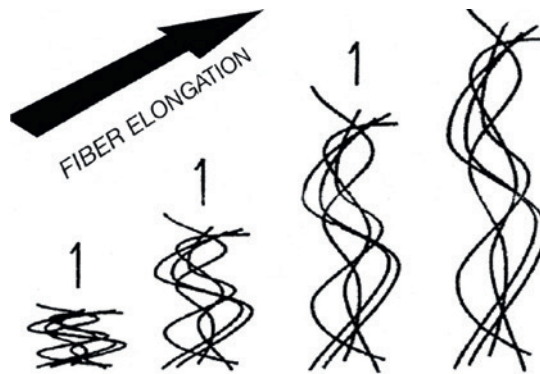
If the temperature continues to rise, the breaking of the atomic bonds will occur. Covalent bonds are destroyed, resulting in decomposition and degradation of the material. The molecular weight and the material properties (T_z) will drop and disappear.

1.7.1.9 Behavior under Load

1.7.1.9.1 Maxwell-Voigt Model

If a plastic is under a stress or load which does not exceed its strength, it will lengthen. If we remove the stress or load, the material will return to its original length. If this stress remains in time, by removing the stress or load the plastic material will recover only a fraction of the deformation suffered and the remainder will undergo a permanent deformation. This effect is called creep or cold flow.

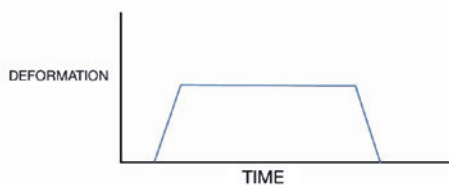
Creep is due to the tangled composition of plastics. Intermolecular forces hold the structure. If we apply a load, the tangle is stretched. If the stress ceases without having passed certain level, the shape of the tangle will recover. If the load remains, macromolecules slide against each other and the elongation is irreversible even when the load ceases.



SPRING

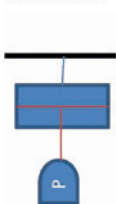


SPRING ELASTIC DEFORMATION

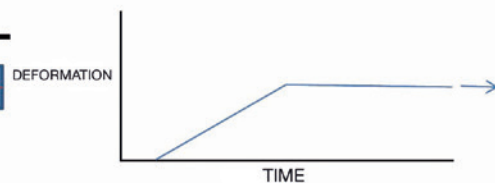


The deformation is fully recovered when the load ceases.

DASHPOT

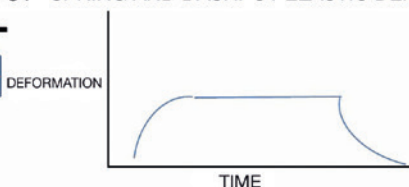
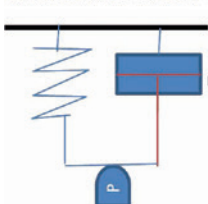


PISTON ELASTIC DEFORMATION

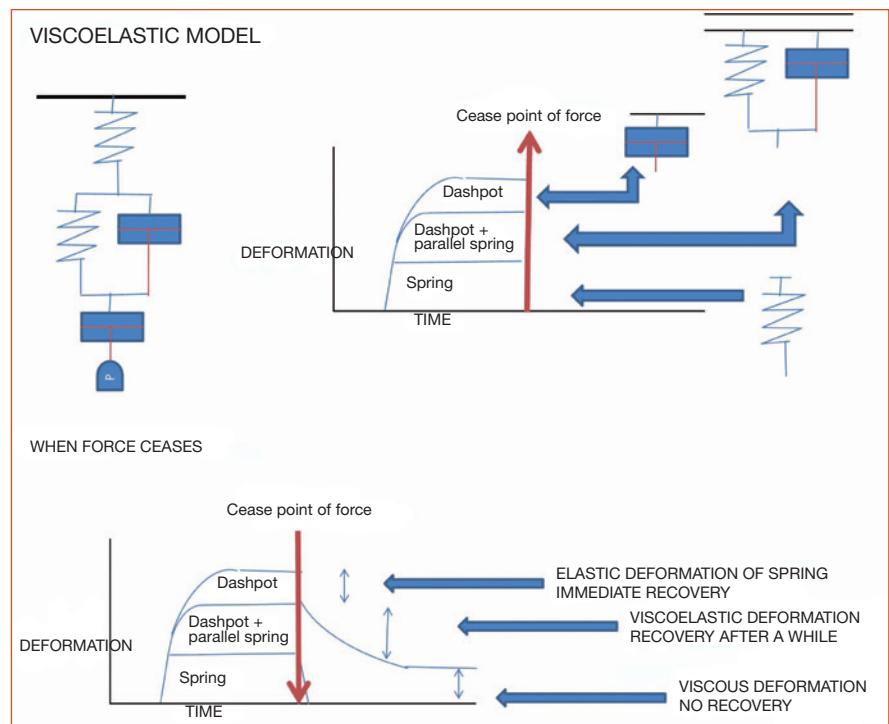


The deformation is not recovered when the load ceases.

SPRING AND DASHPOT SPRING AND DASHPOT ELASTIC DEFORMATION



The viscous component delays the deformation of the spring. Recovery is slow when the load ceases.



1.7.1.9.2 Creep and Relaxation

In Figure 1.10 we can see the tensile creep line with 5.5 MPa stress. Initially, the test module is 20 MPa. With a load of 5.5 MPa, the deformation obtained is 0.275%. About 10 hours later, the module is 50% of the initial value (10 MPa). The deformation then doubled the initial one (0.55%).

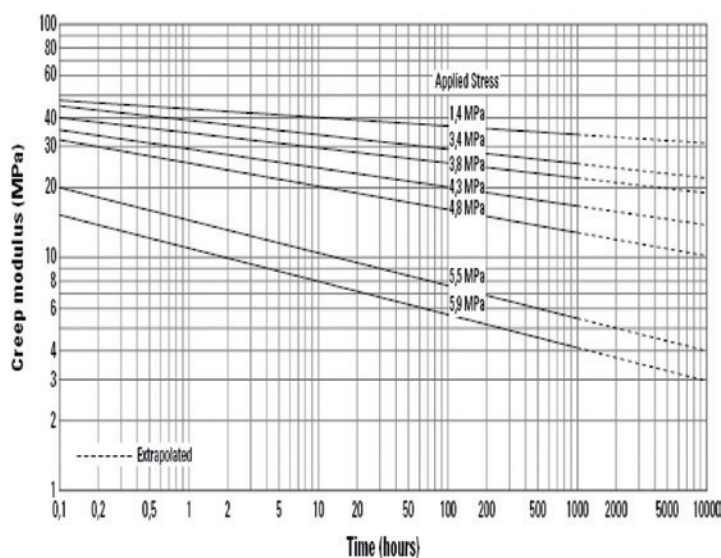


Figure 1.10 Creep graph: creep module example of a thermoplastic TPC ET (ASTM 2990) at 23 °C; source: DuPont

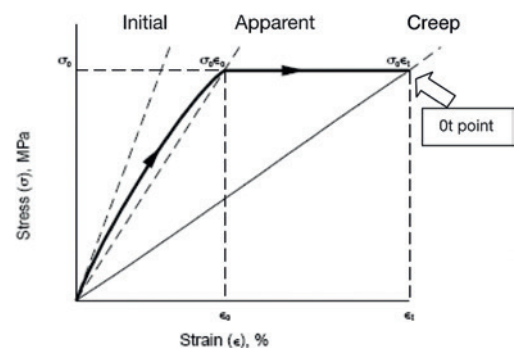


Figure 1.11 Creep graph; source: DuPont

When designing applications under stress and time, the creep modulus is the slope of the secant between the origin point and the $0t$ point.

We can see in Figure 1.11 the variation in the module (creep) between t and $0t$. By keeping the stress, increased stretching or deformation is produced and, therefore, the modulus decreases.

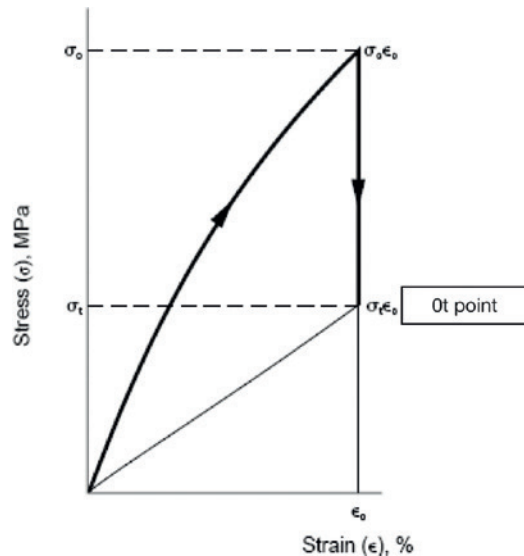


Figure 1.12 Relaxation graph; source: DuPont

When designing applications under relaxation and time (e.g., clippings), the relaxation modulus is the slope of the secant between the origin point and the $0t$ point.

In Figure 1.12 we can see how, keeping the deformation, less stress is necessary due to the relaxation of the polymer.

1.8 A Brief History of Plastics

Source: J. A. Brydson, *Plastics Materials*, Butterworth-Heinemann

Although the use of natural rubber was established in the early 20th century and the plastics industry experienced its highest growth from 1930 on, some considered plastic materials were used in ancient times.

In ancient Egypt, mummies were wrapped in bandages dipped in a solution of lavender oil or bitumen (called bitumen of Judea). Left under the sun, this bitumen hardened and became an insoluble substance. The process is very similar to the one applied for vulcanizing rubbers and thermosets. A similar substance (tar) was used, according to the Bible, for the basket of papyrus that carried Moses down the river.

In ancient Rome the electrical properties of amber were discovered. These properties let the amber attract dust and were highly valued at this time. The word *electricity* comes from *Elektron*, the Greek name of amber.

In the mid-17th century a new natural resin is introduced: gutta-percha, a kind of latex, similar to natural rubber, made from the resin of palauquium, an Asian tree. Gutta-percha was used as insulation for wire and as a molding material during the 19th century. It has been replaced by synthetic materials only since 1940.

Many years before, Christopher Columbus and his crew watched as natives played with rubber shapes obtained from coagulation of the resin or latex from trees as the Hevea.

In 1820, Thomas Hancock found that if gum was sheared or agitated strongly, it became plastic and it was able to flow and take shapes although with a loss of molecular weight.

Charles Goodyear discovered that heated rubber with sulfur held its elasticity in a wide temperature range and improved the properties of solvent resistance of the initial raw material. This reaction with sulfur was called vulcanization.

Christian Friedrich Schöbein established the conditions for controlling the nitration of cellulose. The product served as an explosive and was used in the manufacture of collodion (a mixed solution with alcohol and ether). In 1850, the English Alexander Parkes found that the solid residue left on evaporation of wet photographic collodion produced a hard, elastic, and waterproof substance. In 1856 he patented the process for its application in fabrics, carpets, etc.

In 1862, at the London International Exhibition, Parkes received the bronze medal for his Parkesine, a substance obtained after preparing and dissolving cellulose nitrate. This mixture was placed in a hot roller and a part of the solvent was removed. Even in a plastic state, the mixture was formed through presses to give the final shape.

In 1866, the Parkesine Company was founded. Although later it went bankrupt, the company was the first to start an industrial process for the operation of a polymer chemically modified as a thermoplastic.

A collaborator of Parkes, Daniel Spill, founded Xylonite, a company dedicated to manufacturing Ivoride and Xylonite, two products similar to Parkesine.

In 1865, in America, John Wesley Hyatt developed a method for making billiard balls of an ivory substitute material. In 1869, he patented the use of collodion to cover billiard balls even though it was a flammable material.

Kaufman, in his *History of Plastics*, tells the story of Hyatt receiving a letter from the owner of a pool hall in Colorado. In the letter he described how sometimes, when the balls collided, a burst similar to the detonation of a gun was produced. This burst was not dangerous, but it caused everyone to draw their weapons immediately.

The use of camphor as a plasticizer for cellulose nitrate led to celluloid.

1.8.1 1900–1930

In 1900, shellac, gutta-percha, ebonite, and celluloid were the only plastics available. In 1872, Adolf von Baeyer reported that phenols and aldehydes react by producing resinous substances. In 1899, Arthur Smith patented in England his first phenol-aldehyde resin, which replaced Ebonite in electrical insulations.

In 1907, Hendrik Baekeland discovered certain techniques to control and modify the phenol-aldehyde reaction. In 1907 the first of his 119 patents was registered. In 1910, he founded the Bakelite Company in the United States. This material was used in the electricity sector for many years. When Baekeland died, close to 175,000 tons of Bakelite were being consumed per year.

While celluloid was the first plastic material obtained and manufactured by chemical modification, phenolic resins were the first commercially successful synthetic resins. During the decade of 1930–1940, PS, PVC, polyolefins, and PMMA were born. In 1930, IG Farben in Germany and Dow Chemical in the United States initiated the manufacture of PS.

In 1912, the Russian Ivan Ostrominlensky patented the polymerization of vinyl chloride, but its easy decomposition was a problem that took 15 years to resolve. Today PVC is one of the most consumed plastics in the world.

In 1931, the Imperial Chemical Industries' Alkali Laboratories Division (ICI) designed a device to investigate the effects of pressure up to 3000 atm. E. W. Fawcett and R. O. Gibson discovered that, in one of the experiments carried out with ethylene, a small amount of a substance or white wax had formed. Analyzing it, they saw that it was an ethylene polymer. When trying to reproduce this process, they found that small amounts of oxygen, present in the first experiment by chance, were essential.

The excellent insulating properties of polyethylene, its outstanding chemical resistance, etc., made it to be traded on a large scale. The first sheet of PE appeared in September 1939, shortly before World War II began. During the conflict, ICI launched other plastics such as Perspex or PMMA. This latter was discovered by R. Hill and J. W. C. Crawford. PMMA is a rigid and transparent thermoplastic that can be produced at reasonable cost. This material was highly valued during World War II to build aircraft cockpits.

From 1939 on, new materials such as nylon appeared. Developed by W. H. Carothers and his research team at DuPont as a fiber, it started to be used for molding in 1941. Also this year the PTFE and the manufacturing process developed by DuPont were patented. In 1943, the company launched a pilot plant to produce the material under the trade name Teflon.

In 1937, Dow Chemical manufactured PS in the United States. A few years earlier, in 1930, BASF developed the manufacture and marketing of PS in Europe.

1.8.2 1950s

In 1950 many plastics were created: LDPE was manufactured with Ziegler and Phillips processes, and polypropylene was discovered and commercialized.

Polyacetals were discovered by the German chemist and Nobel Prize winner Hermann Staudinger. In 1920, Staudinger studied the polymerization and the structure of POM, but this one was not commercialized because of its low thermal stability. It was later, in 1952, when it was introduced by DuPont. In 1956 the company patented POM homopolymers.

In 1962, the Hostaform POM copolymer was introduced. In those years other plastics also appeared, like high impact polystyrenes, ABS, and polycarbonates, developed simultaneously but separately in U.S.A. and Germany.

In 1954, the manufacture of PP was developed. In 1963, Karl Ziegler and Giulio Natta received the Nobel Prize for their discoveries in catalyzing polyethylene as well as the so-called Ziegler-Natta catalysis. They managed to increase the size of the molecular chains and, therefore, the molecular weight of the PE by adding titanium tetrachloride. Natta, at the Polytechnic Institute of Milan, found that if he varied catalysis, different types of polypropylene were obtained.

1.8.3 1960s

In 1960, the PSU, PPSU, PPO, aromatic polyesters and polyamides, ionomers, among others, appeared.

Thermodynamic Behavior of Plastics: PVT Graphs

2.1 Thermodynamics

Specific volume: volume occupied by a given mass (unit: cubic centimeter/gram).

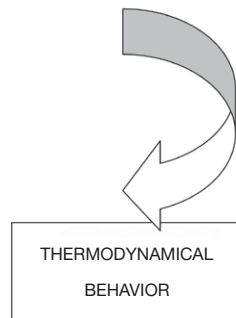
Density: mass of a given volume (unit: gram/cubic centimeter).

Specific volume is the inverse of density.

2.2 PVT Graphs

These graphs reflect the behavior of plastic in different situations depending on the variables.

PRESSURE ----- SPECIFIC VOLUME ----- TEMPERATURE



2.2.1 PVT Graphs Related to Amorphous and Crystalline Materials

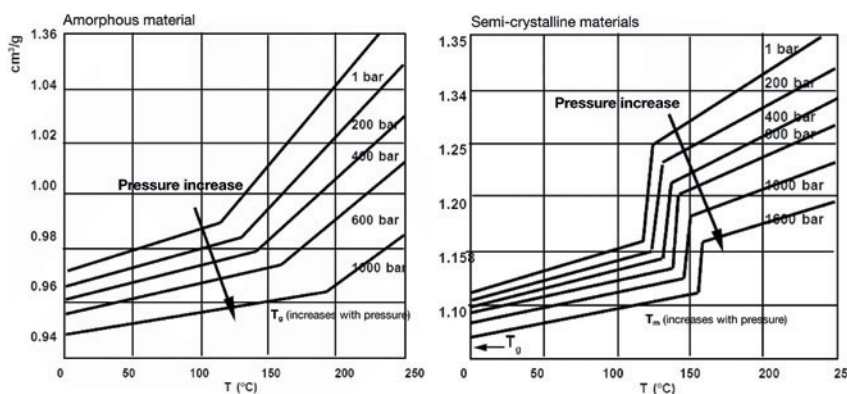


Figure 2.1 PVT diagrams;
source: Ascamm

PVT graphs (pressure, specific volume, temperature) show the strong relationship between the specific volume of a polymer, the pressure, and the temperature. The graph allows us to represent the injection process and get an idea of the effects on the polymer. In other words, we can understand the behavior of the polymer under certain conditions.

2.2.1.1 Dosage Stage, Plastification, Melting

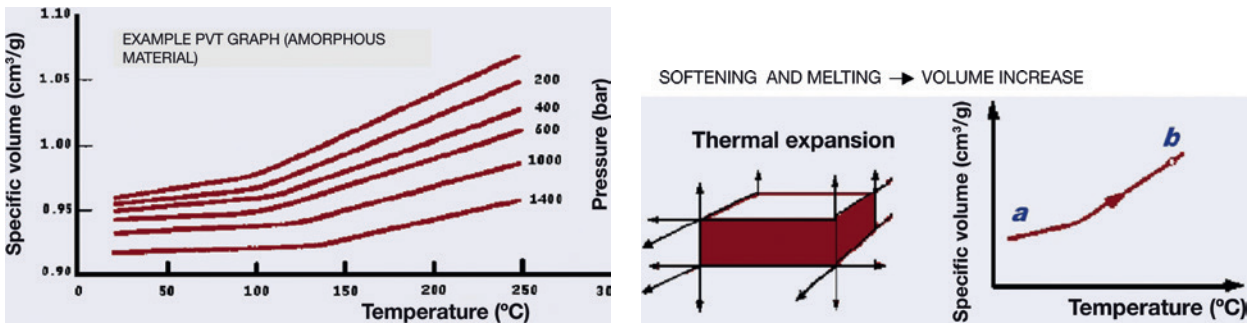


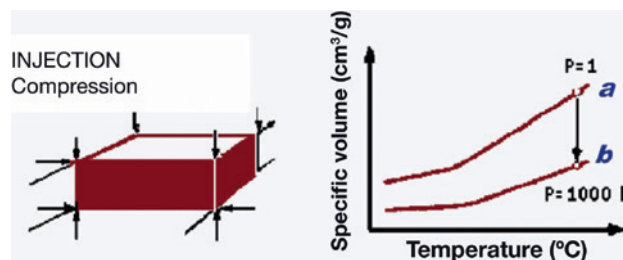
Figure 2.2 Specific volume changes during melting stage

When the material is subjected to an injection process, it melts as the temperature rises and it passes from a solid state (at room temperature) to a molten state (at the temperature it is being processed). During this process, the specific volume increases and the density decreases.

In Figure 2.2, a and b represent:

- Room temperature
- Temperature during the process

2.2.1.2 Injection Stage, Filling the Mold or Cavities



At this stage, an increase of the pressure applied on the material occurs. This increase allows the polymer to flow through distribution channels, gates, cavities, etc., overcoming the pressure drops in the nozzle.

The material undergoes an increase of pressure when it leaves the plasticizing chamber and is subjected to injection pressure (compression). During this process, the specific volume decreases and the density increases. Sometimes, the temperature also increases due to heat generated by friction and shear effect.

2.2.1.3 Hold Pressure Stage

HOLDING

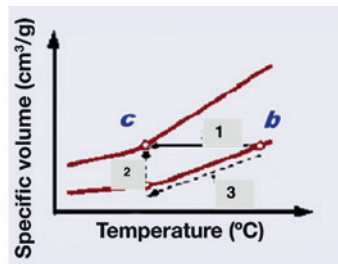


Figure 2.3 Temperature, volume, and pressure effects during hold pressure stage

In Figure 2.3, points 1, 2, and 3 represent:

1. Temperature decrease produced by cooling (SHRINKAGE)
2. Pressure decrease (EXPANSION)
3. Best result (CONSTANT VOLUME)

When the filling ends, the volume of material in the cavity corresponds to the cavity volume. At that time, the pressure inside the mold is balanced (pressurization phase). If further compaction pressure is not applied (holding phase), the pressure in the cavity would drop suddenly, we would have a back flow effect, and high shrinkage of the material.

The hold pressure softens the drop cavity pressure and reaches the atmospheric pressure curve at the required shrinkage level.

The ideal process would be to cool the material with a constant specific volume and steadily decreasing pressure (3) to be equated with atmospheric pressure.

2.2.1.4 Cooling Stage

At the end of the previous phase of holding pressure, cooling is initiated when decreasing flow speed. The heat produced for the shear stress is not enough and the cooling system extracts heat from the mold. After the compacting stage, the part continues to cool and will continue to do so when removed from the mold until its temperature is balanced with their environment. The cooling is produced with a decreasing pressure (into the mold) and with a constant atmospheric pressure (out of the mold).

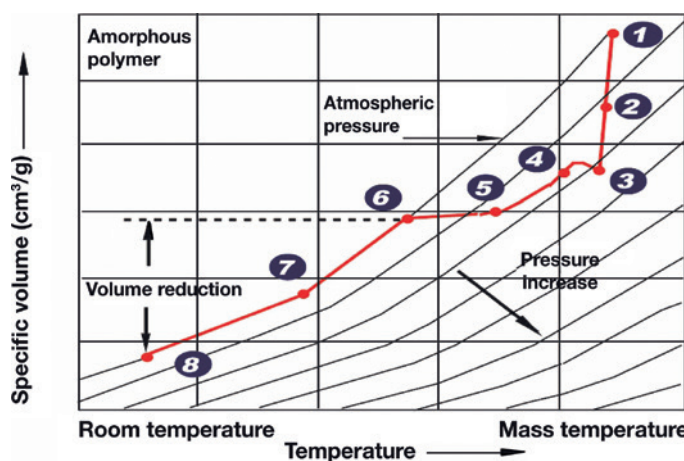


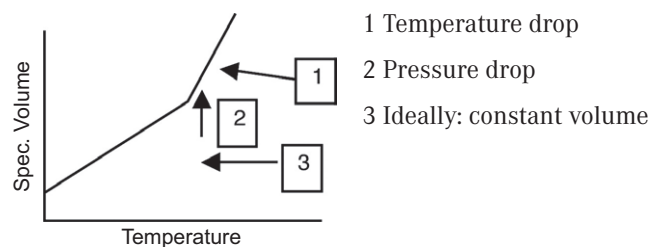
Figure 2.4 PVT graph; source: Ascamm

The stages in Figure 2.4 are:

1	Start filling: the specific volume corresponds to the temperature reached and the back pressure applied.
1-2	Filling the mold cavity: the pressure increases and the temperature may increase too.
2	Specific volume at the end of filling: the pressurizing of the cavity begins.
2-3	Pressurizing of cavity phase until the switching point.
3-4	Switching point: a little drop of pressure may occur by back flow.
4	Start of compaction phase.
4-5	Pressure is reduced by increasing the cold layer as the part cools. The gate begins to close.
5	Gate is sealed. It is not possible to apply pressure in the cavity.
5-6	Cooling causes a pressure drop. The residual shrinkage is caused by a not compensated decrease in specific volume.
6	Point of atmospheric pressure. The dimensions will be affected by molding shrinkage.
6-7	Isobaric cooling (i. e., at constant pressure).
7	Opening of the mold and ejection of the part.
7-8	Isobaric cooling out of the mold. The post-molding shrinkage starts.

Dosage	Transition from solid to liquid → Melting ↑ Specific volume ↓ Density ↑ Change from ambient temperature to melting temperature
Filling	High flow volume ↑ Pressure ↑ Temperature depending shear stress ↓ Specific volume ↑ Density
Holding phase	Every corner of the part has been filled.
Hold pressure stage	At the end of filling, the pressure inside the mold is balanced. If pressure is not supplied, internal pressure drops due to shrinkage. The hold pressure stage should soften the pressure drop and end on the atmospheric pressure curve.

Effects:



Cooling

During hold pressure stage, the flow stops. There is no shear that provides heat.

The mold cools the material.

Phase 1 Cooling with closed mold

Phase 2 Cooling out of the mold

Cooling starts at the outer surface and moves toward the core.

Recommended extraction temperature: 10–15 °C below Vicat temperature.

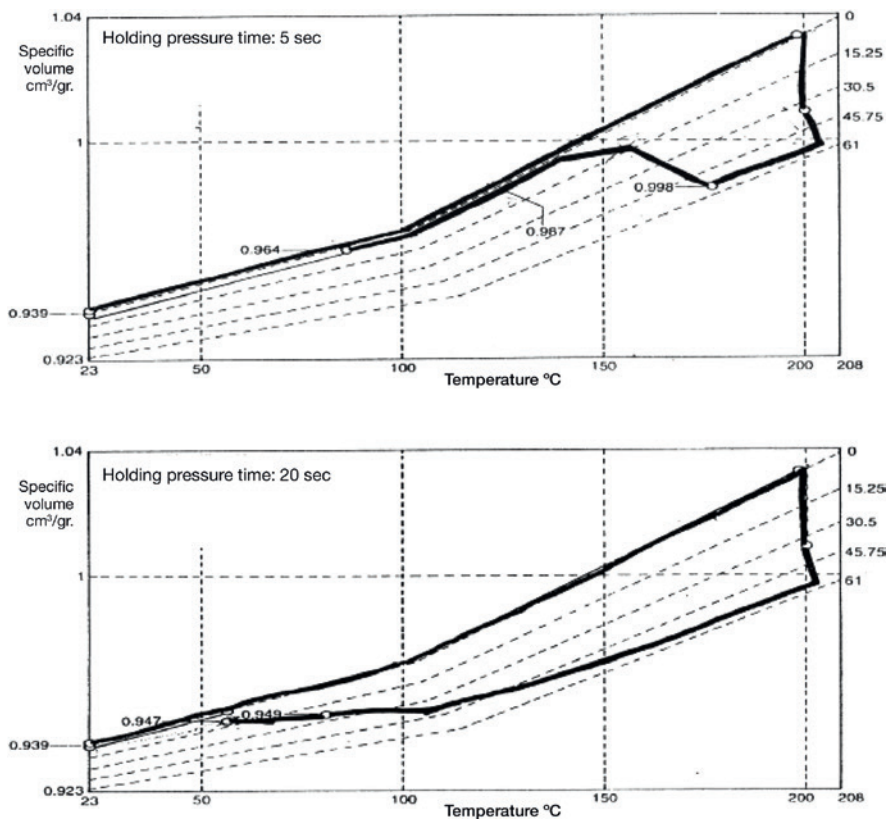


Figure 2.5 PVT graphs: they differ in the hold pressure time or holding pressure time; source: AITIIP Technical Report

In the first PVT graph in Figure 2.5 we can see that the holding pressure time (5 sec) is insufficient and creates a sharp drop in pressure.

In the second PVT graph, the compaction time is 20 seconds, until the entrance is sealed and the pressure drop is much more progressive. The cavity pressure is held during more effective time and the shrinkage of the molded part is lower.

2.2.1.5 Influence of Injection Molding Parameters Reflected in PVT Graphs

Variation of Parameters and Their Consequences

Higher back pressure $\uparrow$	A different constant pressure curve means: → Higher density → Higher mass dose
Temperature	Higher barrel temperature means higher material temperature and: → Higher specific volume → Lower mass dose
Filling pressure	Increased filling pressure and holding means: → Lower volumetric shrinkage
Injection speed	Higher friction means: → Higher shear → Temperature increase → Higher specific volume → Higher shrinkage
Holding pressure	Short = pressure drop = higher shrinkage Long = lower pressure drop = lower shrinkage = higher weight
Cooling	Two phases: 1 Closed mold Decreasing pressure 2 Open mold Constant atmospheric pressure → Molding shrinkage → Post molding shrinkage

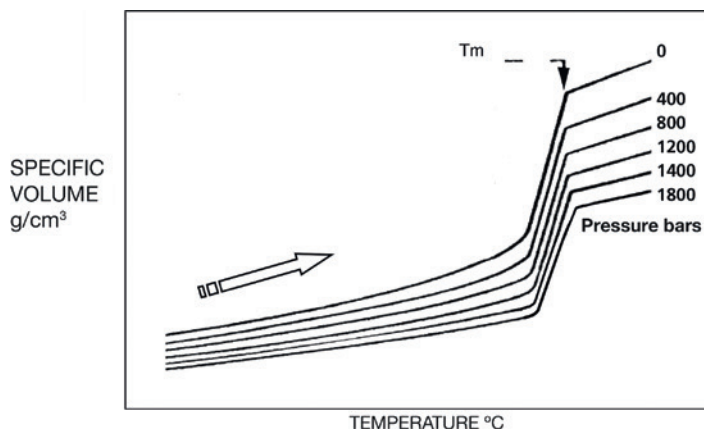
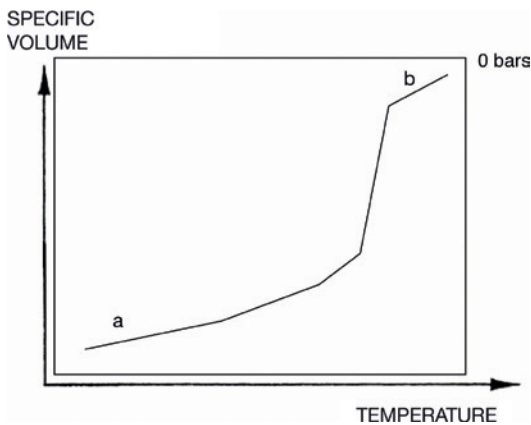


Figure 2.6 PVT graph of a POM h semi-crystalline material (DuPont technical information brochures)

In the following two graphs we can see the evolution of the specific volume in a range of temperatures applied. We can also see this evolution of specific volume with different pressures exerted.

The material being a semi-crystalline polymer, in the temperature range between 180 and 200 °C the melting of crystals occurs, generating this effect with a rapid increase of the specific volume in the thermal range.

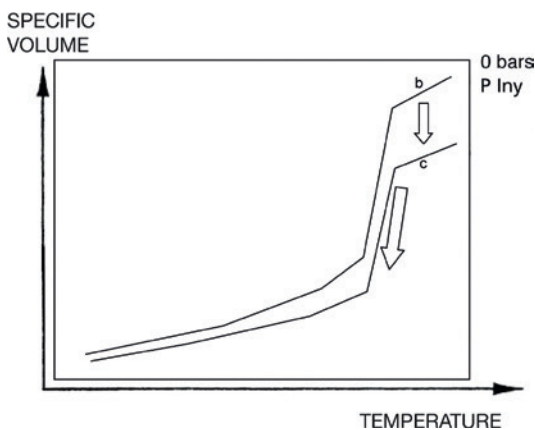
POM h semi-crystalline PVT graphs



Dosage

Transition from room temperature (a) to process temperature (b).

During melting, the transition from solid to liquid increases the specific volume of the polymer (16% in the case of POM).



Injection – Crystallization

b: specific volume before injection stage

c: specific volume after mold filling

- Crystallization.
- Volume shrinkage.
- Molecular reorganization.
- They generate voids that should be filled with more melted material.
- Crystallization under constant pressure.
- When injecting, we compress the melted materials and crystallization begins.

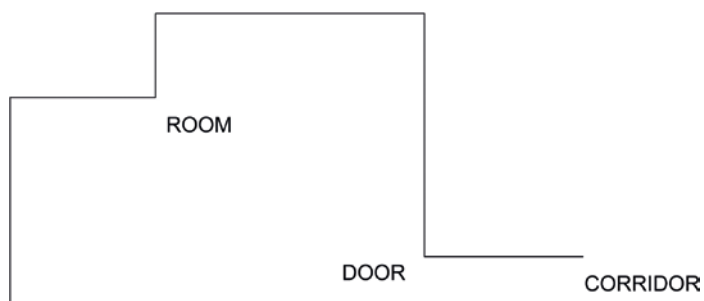
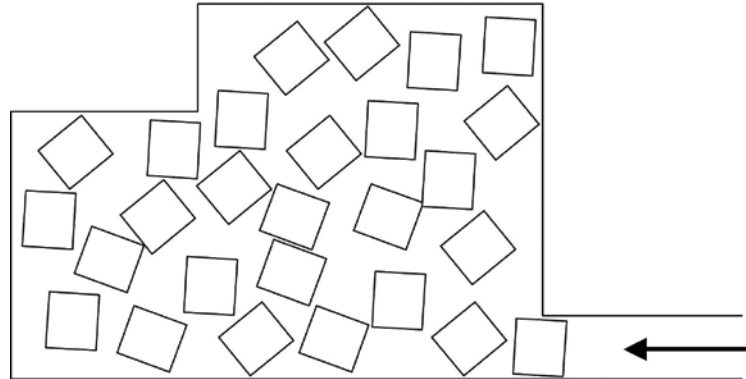


Figure 2.7 Allegory of a semi-crystalline material during the filling, hold, and crystallization phases; source: DuPont

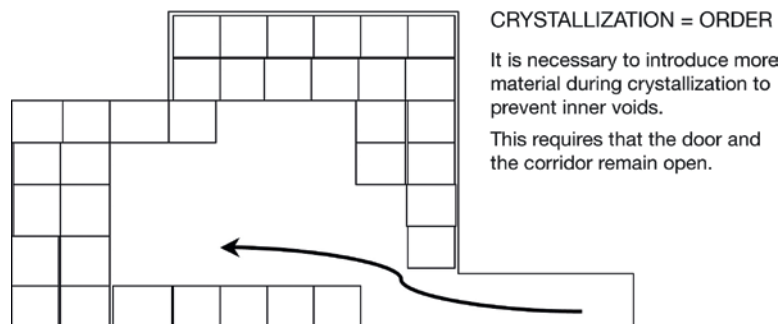
Imagine the cavity to fill is a room, the door is the cavity gate, and the corridor is the runner or distribution channel (see Figure 2.7).

During filling, we fill the room haphazardly and chaotically to fill the entire volume, as happens when filling the cavity with the molten polymer.

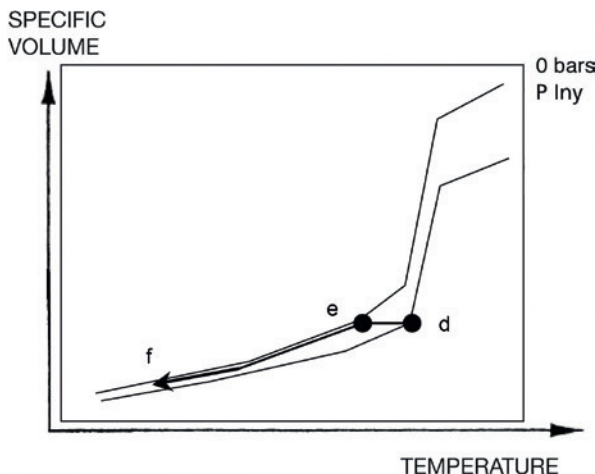
VOLUMETRIC FILLING PHASE



During cooling, the molecules are reorganized and seek their thermal and physical balance, so they take up less volume than the initial volume. This creates an empty space, a volume that we should compensate or fill to obtain parts with better quality.



During the holding pressure stage we compensate this loss of volume.



Specific volume evolution during hold pressure stage

d: specific volume after filling mold

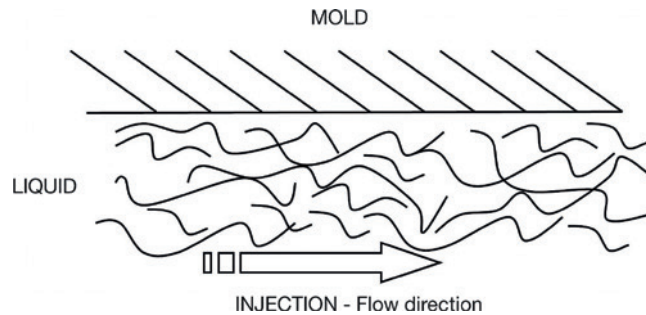
e: volume and temperature during cooling stage

f: specific volume after cooling out of the mold

- Do not over-compact
- Ejection of the part in solid and hot state
- Final shrinkage depends on the material

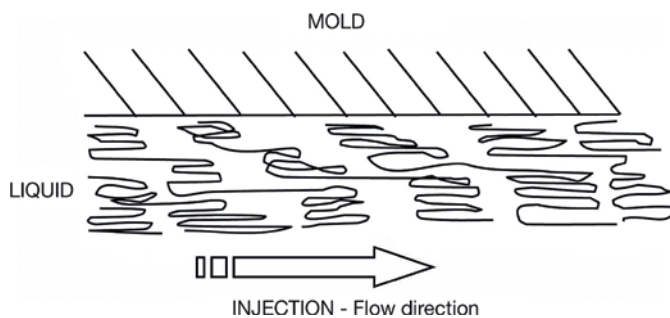
2.2.1.6 Crystallization Stages

2.2.1.6.1 First Zone Skin



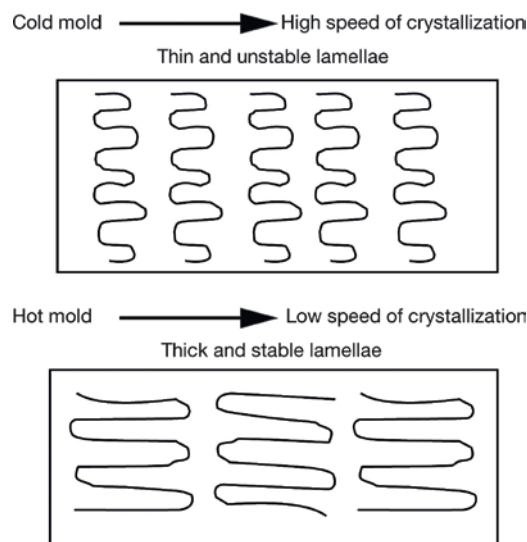
In this first stage, the material, when in contact with the mold, cools generating a solid skin. Below, the crystallization of the areas closest to the cold skin occurs. Thus, the thickness of this skin progressively increases.

2.2.1.6.2 Generation of Lamellae in the First Zone or Skin



The skin or outer layer cools and its thickness increases: it will begin to generate lamellae as crystalline structures.

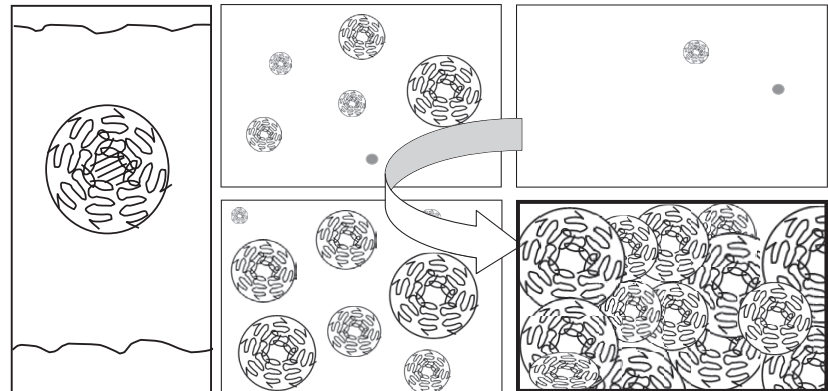
2.2.1.6.3 Intermediate Zone



The mold temperature is very important in this intermediate zone. The cooling rate influences the generation and size of these lamellae or crystalline structures. Structures obtained in cold molds will be weaker than those obtained with hot molds that have a slower crystallization rate.

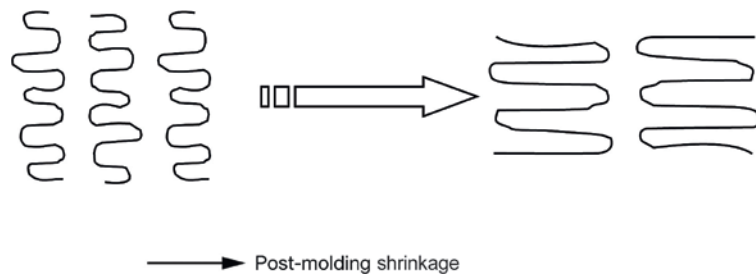
2.2.1.6.4 Central Zone

Spherulites are formed because of a slower cooling.



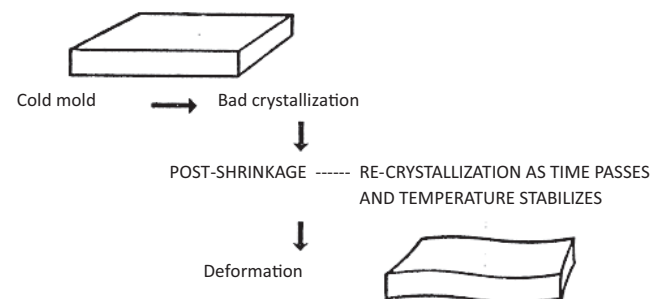
2.2.1.6.5 Defects or Errors Caused During Crystallization Stage

A too low mold temperature generates thin and unstable lamellae, which will become thicker and more stable as time passes and temperature stabilizes.



2.2.1.6.6 Semi-crystalline Polymers

Post-molding deformation



This weak crystallization may lead to a post-crystallization or post-shrinkage of the polymer structure, causing warps, cracks, or deformations.

Burn Test

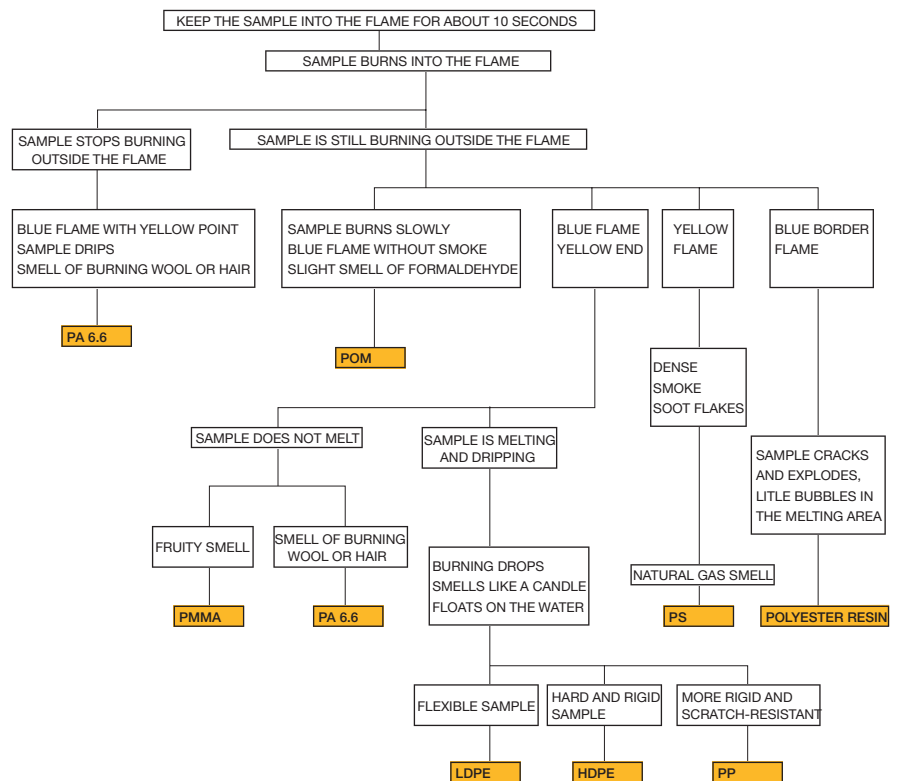
3.1 Identification of Various Types of Plastics

The burn test is one of the most common procedures to recognize and identify plastics. This method consists in maintaining a part or a portion of plastic over an open flame, like a lighter flame.

Variables can be the color of the flame, the fact that the material continues to burn after removing it from the flame, the presence of soot and smoke and their color, the remaining smell when the flame extinguishes, etc.

Material	Burns inside and outside the flame	Drips	Color and type of flame	Color and smell of the smoke
PE	yes	yes	bright blue center	wax, paraffin
CA	yes	yes, and burning	sparkling green yellow	black, acid, vinegar
PS	yes	no	bright, black flakes	styrene, leaves black soot
PMMA	yes	no drips	bright yellow, blue center	fruity, sweet
PC	inside only	yes	bright, bubbles, carbonizes	phenol
PA	yes	yes, and trickles	blue flame, yellow halo	bubbles and tickles
POM	yes	yes	non-luminous blue flame	acid, formaldehyde
ABS	yes	yes	yellow flame	black smoke, acid smell
SAN	yes	yes	yellow flame	black, with black soot
PPO	no	no	bright flame	soot, acid smell
PBT PET	no	yes	bright flame	soot

3.2 Recognition and Identification of Plastics by Burn Test



Source: Dietrich Braun, *Simple Methods for Identification of Plastics*, Hanser, 1999

Water and Plastics, a Difficult Friendship

Source: Tech Topics DuPont

Thermoplastics can be in solid or molten state. Water influences and reacts differently in thermoplastics according to their physical state. The resin, when melted, is very sensitive to many external influences like water. Therefore, we must protect it from moisture both in the molten state and during processing; said protection not being necessary during the normal life of the finished parts.

4.1 Exposure on Duty

Table 4.1 Effects of Water Exposure

Effect	Outcome	Reversibility
Absorption	Changes in weight and dimensions	Reversible
Plasticization	Changes in properties	Reversible
Hydrolysis	Loss in properties	Irreversible

If a significant amount of water is absorbed, swelling or dimensional variation will occur and its percentage will depend on the type of polymer. These dimension changes are reversible by drying or dehumidifying the polymer. When humidity decreases by removing water, the piece shrinks and loses the corresponding weight. In some polymers (such as polyamides, see Table 4.2), this absorption of water acts as a plasticizer, significantly changing properties such as softening, elasticity, toughness, impact resistance, etc.

This influence of water in polyamides causes the glass transition temperature T_g to change depending on the humidity. For example, in dry polyamides, the glass transition temperature T_g is above room temperature. Consequently, at room temperature, dried polyamides are fragile and brittle. However, a wetted or conditioned polyamide has a T_g below room temperature, so its behavior is more ductile and plastic.

The extreme effect that can occur in use is hydrolysis, a chemical reaction with water. Hydrolysis is a slow process at room temperature, but may be faster at higher operating temperatures. This reaction causes a loss of molecular weight, molecular chain breakage, and therefore a loss of polymer properties (especially toughness).

This process is irreversible. Drying of plastic will not restore the initial molecular weight or properties. Hydrolyzed parts cannot be ground and reused because their properties have not been recovered.

Table 4.2 Effects of Moisture on Polyamides

Moisture on pellets	Dimensional changes	Flex module (MPa)	Tensile strength (MPa)	Impact resistance (kJ/m)
0.2% dry	No changes	2830	83	53
2.5% moisture	0.5–0.7%	1210	59	112

4.2 Water and Polymer in Molten State

At melt temperature, the polymer can react to moisture or water in different ways.

Effect	Outcome	Reversibility
Plasticization	Increased fluidity, viscosity breakdown	Reversible
Vaporization	Bubbles, bursts, explosions	Reversible
Hydrolysis	Loss in properties, increased flow	Irreversible, fast

The plasticization of melt causes an increase in flow. This is reversible if the polymer is dried and reprocessed.

Vaporization occurs when the melt pressure is reduced by water. Bubbles, streaks, and small explosions are signs of vaporization. Streaks are bubbles that have been pressed against the mold surface by effect of pressure, popping bubbles leaving a streak shaped sign.

Hydrolysis occurs at melt temperatures. It is a quick and severe process, but not reversible. A loss of molecular weight and properties as well as a drastic reduction in polymer viscosity occurs (and thus, a substantial increase in fluidity). This effect, at melting temperature, does not need a lot of water and is a fast process. This results in flashes, drips, and changes affecting its size and appearance. Hydrolysis does not need large amounts of water when the melting temperature is reached.

4.3 Water-Sensitive Plastics

Water is a polar substance; this makes that polar plastics have an affinity to water and they tend to associate with it, being the opposite in the case of non-polar plastics.

When we consider the interaction of moisture and plastics, we can distinguish the following behaviors:

- **Hydrophobic:** No affinity to water. They are non-polar materials, while water is a polar material. (Oil and water are an example of polar and non-polar materials which do not interact.)
- **Hydrophilic:** Polar materials that attract water and must be dried. These materials can react absorbing water or with breakage of molecular chains (hydrolysis).

Some plastics do not absorb water significantly nor are they affected by water at processing temperatures. This group includes those containing only hydrogen atoms, like the acetals.

Others, although they are not degraded by water, can absorb enough of it to cause vaporization during the melt. Although this may cause streaks, the absorption of enough water to affect mechanical properties does not occur.

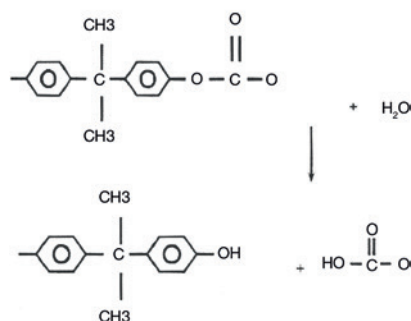
A third group exists: one that is seriously affected and hydrolyzed by a very limited amount of water at melting temperature (e. g., polyesters). Relatively large amounts of water (0.5%) are required to alter the dimensions or properties of these materials at operating temperature in normal use. However, only really small quantities of water are required to produce serious effects during processing of this polymer family. These percentages can be absorbed in a very short time in an open hopper in a humid environment.

Some examples of reaction to the water are shown in Table 4.3.

Table 4.3 Water Reaction of Diferent Polymers

No hydrolysis	Absorption	Hydrolysis
Polyacetals	Acrylics	PC
Polyethylene	ABS	PA 6
Polypropylene	SAN	PA 66
Polystyrene	PPO	PBT PET TPU TPC EC

HYDROLYSIS OF POLYCARBONATE



In the hydrolysis of polycarbonate, the water molecule (H_2O) interferes in the polymer molecule by cutting it (with an irreversible loss of properties).

In the case of polycarbonate, molecular breakdown begins at approximately 70°C .



Figure 4.1 Dehumidifying dryer;
source: Wittmann-Battenfeld

Acronyms for Some Plastics, Reinforced Plastics, and Rubbers

Source: Ascamm

PLASTICS

ABS	acrylonitrile butadiene styrene
AMMA	acrylonitrile methyl methacrylate
ASA	acrylonitrile styrene acrylate
CA	cellulose acetate
CAB	cellulose acetate butyrate
CF	cresol formaldehyde
CMC	carboxymethyl cellulose
CN	cellulose nitrate
CP	cellulose propionate
CPE	chlorinated polyethylene
CPP	chlorinated polypropylene
CPVC	chlorinated polyvinyl chloride
CSM	chlorosulfonated polyethylene rubber
CTA	cellulose triacetate
DAIP	diallyl isophthalate
DAP	diallyl phthalate
EC	ethyl cellulose
EEA	ethylene ethyl acrylate
EEMA	ethylene ethyl methacrylate
E/P	ethylene propylene
EP	epoxy
EPE	enhanced polyethylene
EPP	expandable polypropylene
EPS	expandable polystyrene
ETFE	ethylene tetrafluoroethylene
EVA	ethylene vinyl acetate
EVOH	ethylene vinyl alcohol
FEP	fluorinated ethylene propylene
HDPE	high density polyethylene
HIPS	high impact polystyrene

HMWPE	high molecular weight polyethylene
LCP	liquid crystal polymer
LDPE	low density polyethylene
LLDPE	linear low density polyethylene
MBS	methyl methacrylate butadiene styrene
MDPE	medium density polyethylene
MC	methyl cellulose
MF	melamine formaldehyde
MPF	melamine phenol formaldehyde
PA	polyamide
PA 6	polyamide 6
PA 66	polyamide 66
PA 69	polyamide 69
PA 610	polyamide 610
PA 612	polyamide 612
PA 11	polyamide 11
PA 12	polyamide 12
PA 66/610	polyamide 66 and polyamide 610 copolymer
PA 6/12	polyamide 6 and polyamide 12 copolymer
PA 6-3-T	polytrimethylene hexamethylene terephthalamide
PAI	polyamide imide
PAN	polyacrylonitrile
PAS	polyarylsulfone
PB	polybutylene-1
PBT	polybutylene terephthalate
PC	polycarbonate
PCTFE	polychlorotrifluoroethylene
PDAP	polydiallyl phthalate
PE	polyethylene
PEBA	polyether block amide
PEEK	polyetheretherketone
PEK	polyetherketone
PEI	polyetherimide
PEOX	polyethylene oxide
PESU	polyethersulfone

PET	polyethylene terephthalate
PEX	reticulated polyethylene
PF	phenol formaldehyde
PI	polyimide
PIB	polyisobutylene
PIR	polyisocyanurate
PMI	polymethacrylimide
PMMA	polymethyl methacrylate
PMP	polymethylpentene
POM	polyoxymethylene
PP	polypropylene
PPE	polyphenylene ether
PPO	polyphenylene oxide
PPOX	polypropylene oxide
PPS	polyphenylene sulfide
PPSU	polyphenylsulfone
PS	polystyrene
PSU	polysulfone
PTFE	polytetrafluoroethylene
PUR	polyurethane
PVAC	polyvinyl acetate
PVAL	polyvinyl alcohol
PVB	polyvinyl butyral
PVC	polyvinyl chloride
PVDF	polyvinylidene difluoride
PVF	polyvinyl fluoride
PVFM	polyvinyl formal
PVK	poly <i>N</i> -vinylcarbazole
PVP	poly <i>N</i> -vinylpyrrolidone
RF	resorcinol formaldehyde
SAN	styrene acrylonitrile
SB	styrene butadiene
SI	silicone
SMA	styrene maleic anhydride
SMMA	styrene methyl methacrylate copolymer

SMS	styrene- α -methylstyrene
SP	saturated polyester
UF	urea formaldehyde
UHMWPE	ultra high molecular weight polyethylene
UP	unsaturated polyester
VCE	vinyl chloride ethylene
VCMA	vinyl chloride ethylene methyl acrylate
VCEVAC	vinyl chloride ethylene vinyl acetate
VCMMA	vinyl chloride methyl methacrylate
VCOA	vinyl chloride octyl acrylate
VCVAC	vinyl chloride vinyl acetate

REINFORCED PLASTICS

AFRP	aramid fiber reinforced plastic
BFRP	boron fiber reinforced plastic
CFRP	carbon fiber reinforced plastic
GFRP	glass fiber reinforced plastic
MFRP	metallic fiber reinforced plastic
MWRP	metal whiskers reinforced plastic
SFRP	synthetic fiber reinforced plastic

RUBBERS

ABR	acrylate butadiene rubber
ACM	polyacrylate rubber
AFMU	terpolymer of tetrafluoroethylene, trifluoronitrosomethane, and nitrosoperfluorobutyric acid
ANM	acrylate rubber
AU	polyester polyurethane elastomer
BIIR	bromobutyl isobutylene isoprene rubber
BR	butadiene rubber
CFM	polychlorotrifluoroethylene
CIIR	chlorobutyl isobutylene isoprene rubber
CM	chlorinated polyethylene rubber
CO	epichlorohydrin rubber
CR	chloroprene rubber

CSM	chlorosulfonated polyethylene rubber
ECO	epichlorohydrin rubber (ethylene oxide copolymer)
EPDM	ethylene propylene diene monomer rubber
EPM	ethylene propylene monomer rubber
EU	polyether urethane
FPM	fluoroelastomer polymer
FSi	fluorosilicone rubber
IIR	isobutylene isoprene rubber
IM	polyisobutylene rubber
NBR	acrylonitrile butadiene rubber
NCR	acrylonitrile chloroprene rubber
NIR	acrylonitrile isoprene rubber
NR	isoprene rubber (natural)
PBR	pyridine butadiene rubber
PO	propylene oxide elastomer
PSBR	pyridine styrene butadiene rubber
Psi	methyl silicone elastomer
SBR	styrene butadiene rubber
SCR	styrene chloroprene rubber
SIR	styrene isoprene rubber
VPSi	methyl silicone elastomer with phenolic and vinylic groups
VSi	methyl silicone elastomer with vinylic groups

General Features of Some of the Most Used Thermoplastics

6.1 Polyolefins

6.1.1 Polyethylene (PE)

Discovered by ICI in 1933, initially it was used for insulation of electrical cables. The first industrial plant of high density polyethylene (HDPE) was developed by Hoechst in 1955. P. Phillips started its HDPE production in 1955.

6.1.1.1 High Density Polyethylene (HDPE)

This is a polymer with rectilinear molecular chains, short branches, and little mobility, which gives it rigidity and crystallinity (60–80%).

HDPE Properties

General properties

- Good stiffness
- Dimensional stability
- Good surface hardness
- Resistant to boiling
- Sterilizable

Physical properties

- Density: 0.94–0.97 g/cm³
- Shrinkage: 1.2–2.4%
- Molecular weight: approx. 50,000–100,000 g/mol

Processing

- Molding temperature: 220–260 °C (max.: 300 °C; min.: 200 °C)
- Melting temperature: 125 °C (softening) at 350 °C

Chemical properties

- HDPE resists acids, alkalis, solvents, alcohol, gasoline, oil, juices
- Not resistant to aromatic substances or chlorinated hydrocarbons

6.1.1.2 Low Density Polyethylene (LDPE)

LDPE is polyethylene with lateral branches of its molecules that are far apart and mobile, making it a soft polymer. It has a glass transition at $T_g = 120$ °C.

LDPE Properties

General properties

- Good flexibility

- Good thermal resistance
- Low surface hardness

Physical properties

- Density: 0.86–0.92 g/cm³
- Crystallinity (40–45%)
- Shrinkage: approx. 1.5–3%
- Molecular weight: approx. 25,000 g/mol

Processing

- Molding temperature: 200–220 °C (max.: 260 °C; min.: 160 °C)
- Melting temperature: 112–115 °C

6.1.1.3 Linear Low Density Polyethylene (LLDPE)

LLDPE is an ethylene copolymer with butene, hexene, and octene.

Mechanical properties

	C ₂ H ₄ = ethylene			
comonomers added	butene	C ₄ H ₈	–	Mechanical properties increase proportionally with carbon.
	hexene	C ₆ H ₁₂	↓	
	octene	C ₈ H ₁₆	+	

LLDPE is a soft polymer because the short and lateral branches of its molecules are far apart and mobile.

LLDPE Properties

General properties

- Good flexibility
- Good thermal resistance
- Low surface hardness

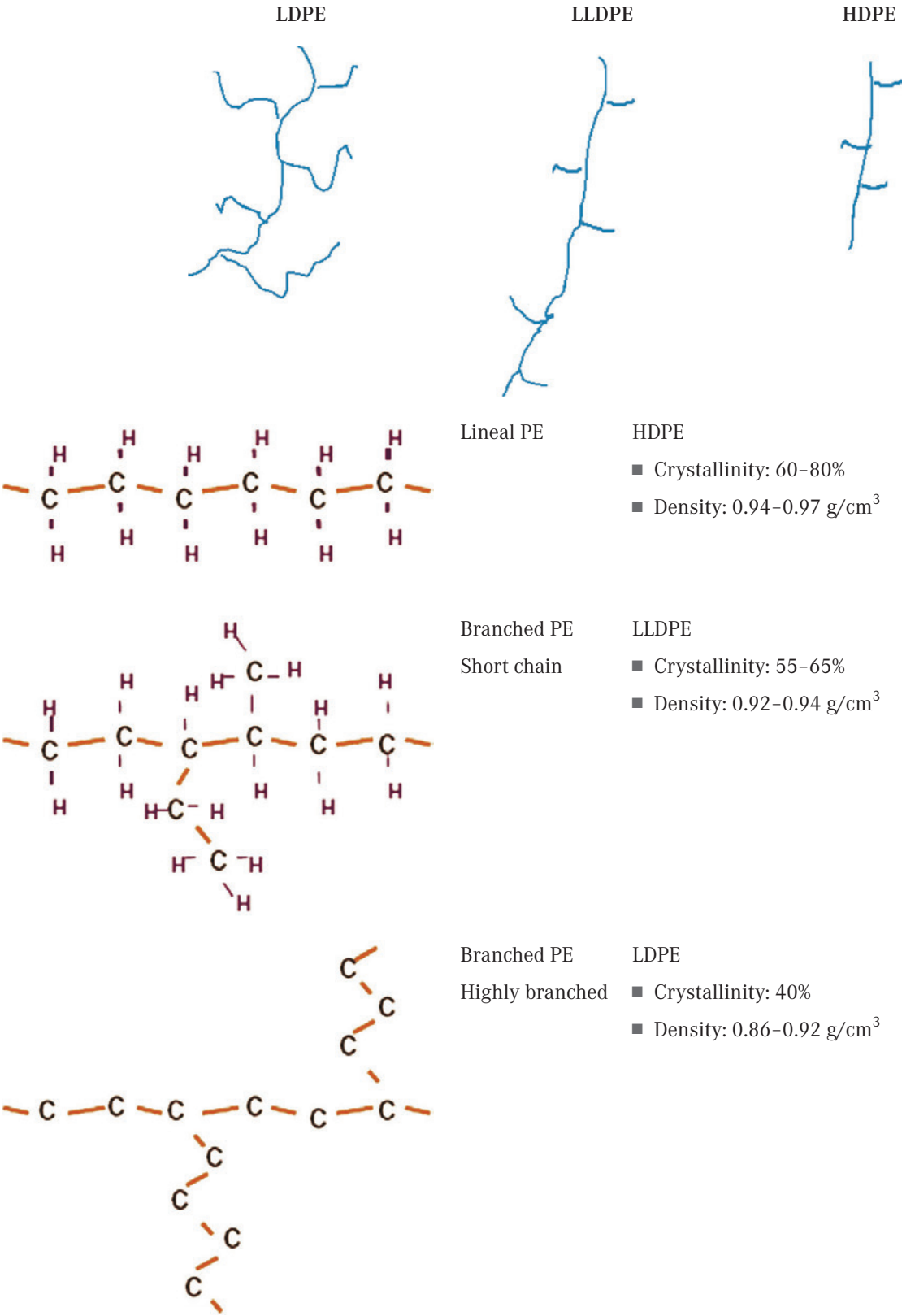
Physical properties

- Low crystallinity (55–65%)
- Density: 0.92–0.94 g/cm³
- Shrinkage: approx. 1.5–3%

Processing

- Molding temperature: 200–220 °C (max.: 260 °C; min 160 °C)
- Melting temperature: 115–120 °C

6.1.1.4 Comparison of Different Structures of Polyethylenes



6.1.2 Polypropylene (PP)

PP has been produced since 1954. It is more resistant than polyethylene, but with worse cold impact resistance (glass transition temperature: -10°C).

6.1.2.1 PP Homopolymer Properties

General properties

- Good hinge properties
- Good stiffness
- Hard and brittle
- Good dielectric properties

Physical properties

- Crystallinity: 60–70%
- Shrinkage: 1.2–2.5%
- Glass transition T_g : -50°C

Processing

- Melting temperature: 165°C

Chemical properties

- Chemical resistance to acids, alkalis, salt solutions, alcohols, gasoline, juices, oils, etc.
- No resistance to chlorinated hydrocarbons or copper

Advantages	Limitations
Low density	Poor impact resistance at subzero temperatures
Good impact resistance at room temperature	Little resistance to UV
Good soundproofing	Low resistance to scratches
Resistance to hinges and alternate bending	Painting is difficult due to its chemical resistance
Resistance to acids, solvents, and alkalis	
Resistance to gasoline and oil	

6.1.2.2 PP Copolymers

PP + Ethylene Properties

- Block copolymer or random copolymer

General properties

- More impact resistance at low temperatures than the homopolymer PP

Physical properties

- Glass transition T_g : -20°C
- Density: 0.9 g/cm^3

6.1.3 Ethylene Vinyl Acetate (EVA)

EVA Properties

General properties

- Random copolymer
- From 1 to 10% vinyl acetate: improved stiffness
- 30 to 40% vinyl acetate: used in adhesives

Physical properties

- Glass transition T_g : 60 °C
- Density: 0.95 g/cm³

Processing

- Melting temperature: 185–200 °C
- When it decomposes, it generates acetic acid

6.1.4 Ethylene Vinyl Alcohol (EVOH)

EVOH Properties

General properties

- Semi-crystalline regardless of the level of vinyl alcohol
- High barrier to oxygen
- Hydrophilic (it absorbs humidity)

6.2 Polyoxymethylene (POM)

POM is a semi-crystalline material with good mechanical properties and dimensional stability. There are two types of POM: homopolymers and copolymers, the homopolymers having better mechanical properties but a narrower process window.

The first polyacetal homopolymers were introduced in 1959 by DuPont with the tradename Delrin. They were the result of intensive research on polymers based on formaldehyde. In 1962, Celanese C introduced the copolymer resin POM.



Homopolymer: ionic reaction of formaldehyde.

Copolymer: ionic reaction of formaldehyde with ethylene oxide.

POM Properties

General properties

- Linear polymer with a regular structure; therefore, it crystallizes
- Hard, stiff, and tough down to –40 °C

- Because of its crystallinity it has no transparency
- Excellent friction and wear properties

Physical properties

- Density: 1.41–1.42 g/cm³
- Polymer with the highest crystallinity (70–80%)
- Shrinkage: 2%

Processing

- Subsequent annealing at 160 °C increases crystallization
- Melting temperature: 175 °C

Chemical properties

- Resistant to acids, moderately aggressive alkalis, gasoline, oils, benzene, alcohol
- Does not resist strong acids, oxidants
- Sensitive to copper; it acts as a catalyst and the polymer decomposes

Advantages	Replaces	Limitations
Little influence of temperature on the mechanical properties Spring properties Creep resistance Resistance to fatigue Petrol resistance Solvent resistance Food approved Chemical resistance Good electrical properties	Metal (weight, dimensional stability, spring effect) PA (dimensional stability)	Not possible to make it flame retardant RTI < 90–120 °C No hot water No matte colors Resistance to strong acids UV resistance

6.3 Polystyrenes (PS)

6.3.1 PS General Purpose

Dow Chemical and BASF began PS production in 1930.

PS Properties

General properties

- High stiffness, surface gloss, and dimensional stability
- Transparent
- Sensitive to UV
- PS easy flow typically contains 2–4% mineral oil to lubricate

Physical properties

- Density: 1.05 g/cm³
- Shrinkage: 0.4–0.6%
- Glass transition T_g : 90–100 °C

Processing

- Molding temperature: 200–210 °C (max.: 270 °C; min.: 170 °C)

Chemical resistance

- Sensitive to stress cracking
- Resistant to grease, oil, salt solutions, alcohols
- Not resistant to benzene, gasoline, solvents

6.3.2 Medium or High Impact PS (HIPS)

According to the content of polybutadiene, impact polystyrenes are classified as medium impact (5% rubber), high impact (5–10% rubber), and very high impact or super impact (10–15% rubber).

HIPS Properties

There are polystyrenes with a syndiotactic structure with excellent properties (mechanical, electrical, thermal, etc.).

General properties

- Good impact because its molecular structure is typically modified with butadiene

Physical properties

- Shrinkage: 0.5–0.6%

Processing

- Molding temperature: 210–225 °C (max.: 260 °C; min.: 190 °C)

6.4 Acrylonitrile Butadiene Styrene (ABS)

ABS Properties

General properties

- Hard and tough down to –40 °C

Physical properties

- Shrinkage: 0.4–0.6%
- Density: 1.02–1.22 g/cm³

Advantages	Limitations
Stable against weak acids, petrol, oils, fats Easy to paint and chrome plate Good resistance to impacts Good toughness High bright	Continuous work temperature: 60–80 °C Unstable against strong acids, hydrocarbons, chlorinated, ketones Regular resistance against UV

Influence of the different combinations of the three ABS components: acrylonitrile, butadiene, styrene

- | | |
|-----------------|-----------------------|
| + Acrylonitrile | + Rigidity |
| | + Chemical resistance |
| + Butadiene | + Impact |
| + Styrene | + Gloss |
| | + Flow |
| | + Rigidity |

A fourth monomer is used to modify ABS: metacrylate.

- | | |
|---------------|----------------------|
| + Metacrylate | + Weather resistance |
|---------------|----------------------|

6.5 Blend ABS-PC

General properties

- Increases resistance to temperature of ABS and impact resistance
- More resistance to stress cracking than PC

Physical properties

- Density: 1.15 g/cm³
- Shrinkage: 0.5–0.7%

Chemical resistance

- Not resistant to ketone, esters, and chlorinated hydrocarbons

6.6 Styrene Acrylonitrile (SAN)

SAN Properties

General properties

- Good mechanical strength, stiffness
- Transparent with slight yellowing
- Higher HDT than PS
- Excellent brightness
- Dimensional stability

Physical properties

- Shrinkage: 0.4–0.6%
- Density: 1.05 g/cm³

Processing

- Molding temperature: 180–225 °C (max.: 250 °C; min.: 170 °C)
- Chemical resistance
- Resists organic acids, animal and vegetable fats, mineral oils
- Not resistant to concentrated mineral acids, hydrocarbons, ester, ether, and ketone

6.7 Acrylonitrile Styrene Acrylic Rubber (ASA)

ASA is an amorphous terpolymer. It improves the weather resistance of ABS because it does not use butadiene as rubber on the SAN matrix, but acrylate rubber, more resistant to weathering (Figure 6.1).

ASA Properties**General properties**

- Dimensional stability
- Brightness, gloss

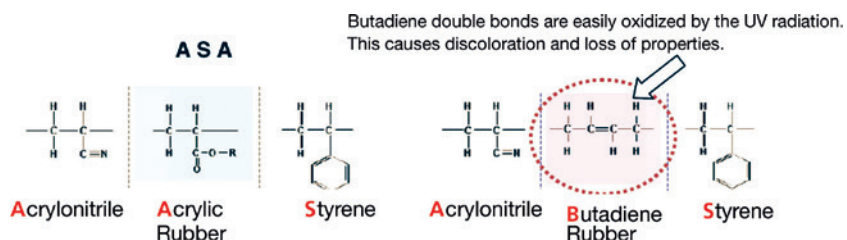
Physical properties

- Density: 1.07 g/cm³
- Shrinkage: 0.4–0.7%



ASA is similar to ABS in terms of molecular structure, physical properties, and processing except that a different rubber or elastomer is used for improving weatherability.

Figure 6.1 In ASA a different elastomer (acrylic rubber) is used, compared to the ABS (butadiene); butadiene has double bonds and, therefore, is very sensitive to UV radiation



6.8 Polyamides (PA)

Industrial production of polyamides started in 1939 by DuPont as synthetic fiber. In 1941 the first molding grades appeared.

Polyamides are semi-crystalline polymers. They are designated in terms of numbers that correspond to the carbon atoms of the diamide part and of the diacid part sequentially.

Polyamides are hygroscopic materials (they absorb humidity). The water absorbed by the molded parts after injection works as a plasticizer providing toughness and impact, and lowering the flexural modulus (they absorb up to 3% of water).

They are materials with low viscosity at molding temperature. Molding temperature: 265 °C (PA 66); 233 °C (PA 6); 228 °C (PA 6.10).

Advantages	Replaces	Limitations
Good mechanical strength Impact resistance and toughness Slip, friction, and wear resistance Density: 1.06–1.2 g/cm ³ Shrinkage: 0.7–2% (PA 6); 0.7–2% (PA 66) Glass transition: 50–70 °C Resistant to oils, gasoline, benzene, alkalis, solvents, esters, ketones, water, etc. Not resistant to ozone, hydrochloric acid, sulfuric acid, hydrogen peroxide Service temperature: 120–180 °C Creep resistance Electrical insulation class F	PP (temperature) PC (stress cracking, solvents, flammability rate)	UV resistance Fragile at low temperatures Changing characteristics in presence of humidity Dimensions and mechanical features

Polyamide humidity levels

DAM (dry as molded)

0.2% humidity on mass

Conditioned

1.5 to 2.5% humidity on mass

PA 6 and PA 66 High hardness, stiffness, and toughness; resistance to wear

PA 11 Low water absorption (fans and hydraulic accessories)

PA 4.6 Stiffness at high temperatures, high resistance to impact and abrasion

PA 12 Low water absorption, better impact than PA 6 but worse than PA 11 (bearings)

Melting points of crystalline part

PA 66 254 °C

PA 6 220 °C

PA 6 12 215 °C

PA 11 185 °C

PA 12 175 °C

6.9 Polyesters

General properties of polyesters polymers

Semi-crystalline polymers	Chemical resistance
Dimensional stability	Resistant to oil, gasoline, alcohol
Creep resistance	Not resistant to benzol, strong acids, alkalis, chlorinated hydrocarbons
Electrical properties	
Surface appearance	

6.9.1 Polybutylene Terephthalate (PBT)

PBT Properties

General properties

- Dimensional stability
- Mechanical properties

Physical properties

- PBT density: 1.3 g/cm³
- Shrinkage: 1.4–2%
- Glass transition T_g : 43 °C

Processing

- PBT: 250–260 °C
- Melting temperature: 225 °C

Chemical resistance

- Resistant to oils, grease, fuel, alcohols, weak acids, weak alkalis
- Not resistant to benzene, ketone, strong acids, strong alkalis

Advantages	Replaces	Limitations
Dimensional stability at 130–180 °C No absorption of humidity UV resistance Creep resistance Electrical insulation class F Resistant to solvent High surface gloss	PA (moisture absorption, dimensional stability) POM (temperature resistance) PC (temperature resistance, faster cycles, chemical resistance)	No water > 60 °C Alcohol and acid Predrying critical Benzene, ketone

6.9.2 Polyethylene Terephthalate (PET)

PET Properties

General properties

- Tough, hard, stiff

- Good dimensional stability
- Thermal resistance
- Mechanical properties

Physical properties

- PET glass transition: 70 °C
- Density: 1.35 g/cm³
- Shrinkage: 1.2–2%

Processing

- PET molding temperature: 260–280 °C
- Melting temperature: 254 °C

Advantages	Replaces	Limitations
Dimensional stability from 155 to 200 °C Excellent UV resistance Color stability Creep resistance Electrical insulation class H Surface gloss Adhesion to epoxy Barrier effect	PBT (temperature and color resistance) PA (temperature, color, and dimensional stability)	No water > 50 °C Acids Benzene, ketone

6.10 Polyphenylene Oxide (PPO)

PPO is a material with a difficult processability, so it is used usually modified and blended with PS or PA.

PPO Properties

General properties

- Hard, stiff, good sliding properties
- High dimensional stability
- Does not absorb humidity

Physical properties

- Density: 1.05–1.1 g/cm³
- Shrinkage: 0.5–0.7%

Chemical properties

- Resistant to acids, alkalis, alcohols, fats, and oils
- Not resistant to benzene, chlorinated hydrocarbons

6.11 Polycarbonate (PC)

PC is an amorphous material introduced by Einhorn in 1898. Its production began in Germany by Bayer and in USA by General Electric in 1958.

PC Properties

General properties

- High transparency (transmittance: 89%)
- High impact resistance
- Viscous
- Good dimensional stability
- Good scratch resistance
- Inflammability V2 without additives (UL94)

Physical properties

- Molecular weight: approx. 150,000 g/mol
- Density: 1.2 g/cm³
- Shrinkage: 0.6–0.8%
- Glass transition T_g : 150 °C

Processing

- Melt temperature: 267 °C

Chemical resistance

- Resistant to oil, gasoline, acid, alcohol
- Not resistant to strong acids, alkalis, benzene

Advantages	Limitations
High transparency	Not resistant to methyl alcohol
High impact resistance down to –150 °C	Regular against UV
Difficult inflammability V2 without additives	Sensible to stress cracking
Low thermal dilatation	Sensible to hydrolysis with hot water
Good electrical and dielectric abilities	Less resistant to fats, oils, ketones
Chemical resistance to mineral acids and bases	

6.12 Polymethylmethacrylate (PMMA)

PMMA Properties

General properties

- Hard, brittle, scratch-resistant
- Good optical properties

- Good UV resistance
- Transparent

Physical properties

- Density: 1.18 g/cm³
- Shrinkage: 0.4–0.7%

Advantages	Limitations
Extremely high transparency (92%)	Impact resistance
Very good UV resistance	Does not resist aromatic hydrocarbons, esters, ketones, strong acids, and alkalis
Dielectric	Low resistance to continuous temperature (70 °C)
Chemical resistance to detergents, acids, and alkalis	High expansion coefficient
Resistant to fats and oils	Susceptible to stress cracking
Surface hardness	

6.13 Liquid Crystal Polymer (LCP)

LCP Properties

General properties

- Excellent thermal resistance
- Dimensional stability

Physical properties

- Density: (LCP 30% fiberglass) 1.68 g/cm³
- Shrinkage: –0.07% to 0.8% (caution: possibility of negative shrinkage)

Advantages	Replaces	Limitations
Service temperature: 240 °C	Ceramics	Hydrolysis > 120 °C
VO flame retardant inherent	Metal (RTI)	Weld lines
Excellent chemical resistance	PPS (RTI and processed)	
Low CLTE		
Low emission		
Food approved grades		

6.14 Elastomers

6.14.1 Thermoplastic Elastomer (TPE–V)

TPE Properties

General properties

- Thermoplastic elastomer vulcanized

- Polyolefin-based and rubber combined
- Mixture of PP and EPDM vulcanized
- Excellent compression set

Physical properties

- Hardness: Shore A and Shore D
- Density: 0.92–0.98 g/cm³
- Shrinkage: 2% according to the Shore hardness and wall thickness

Advantages

Work temperature: –60 °C to +135 °C (1,000 hours)
 Cable work temperature: –60 °C to +125 °C (25,000 hours)
 Good sealing
 Very good chemical resistance to liquids
 Very good in weather resistance
 Very good compression set

6.14.2 Elastomer Thermoplastic Vulcanized (ETPV)

ETPV Properties

General properties

- Thermal resistance

Physical properties

- Density: 1.08 g/cm³
- Shrinkage: 1.2–4.4% (the harder, the less shrinkage)

Advantages

Excellent oil resistance
 Excellent temperature resistance
 Work temperature: 150–160 °C

Replaces

PU, EPDM
 TPEV, TPU

Limitations

Bad compression
 Less mechanical properties at 200 °C

6.14.3 Thermoplastic Copolymer Elastomer Ether Ester (TPC ET)

TPC ET Properties

General properties

- Good aesthetic surface
- Good recovering behavior

Physical properties

- Density: 1.19 g/cm³
- Shrinkage: 1.4%

Advantages	Replaces	Limitations
Excellent fatigue Flexible at low temperatures Low impact of temperature in its flexibility Oil and solvent resistance High impact resistance at low temperatures	TPU (process) Rubber (process, recycling)	Polar liquids as alcohol UV resistance Resistant to abrasion Degrees > 55D hydrolysis resistance up to 70 °C

6.14.4 Polyurethane (TPU)

TPU Properties

General properties

- Excellent wear behavior
- Good tear resistance
- Good impact resistance
- Elastic and flexible when cold
- Good recovery
- Resistant to abrasion
- Resistant to weathering
- Flexible -40 to +125 °C

Physical properties

- Density: 1.08 to 1.23 g/cm³
- Shrinkage: 1 to 1.5% based on wall thickness and hardness (the harder, the less shrinkage)
- Halogen-free flame retardant grades
- Vicat: 70–90 °C; with fiberglass, 90–130 °C
- HDT: 60–100 °C; with fiberglass, 140–170 °C

Chemical resistance

- Resistant to hydrolysis, microorganisms, and saltwater (ether grades)
- Resistant to oils and fats

6.14.4.1 Composition

TPU have three components: polyols, diisocyanates, and diols. Polyols are part of the flexible material. The union of the diol and the diisocyanate forms the rigid part.

Polyols used: base ester and base ether.

Base Polyester Polyol

- Good mechanical properties
- Temperature resistance, tear strength
- Mineral oils and hydraulic resistance

Base Polyether Polyol

- Increased resistance to hydrolysis
- Increased resistance to microorganisms
- Greater flexibility at low temperatures

6.15 Styrene Butadiene Copolymer (SBC)

SBC Properties

- Styrene butadiene block copolymer

General properties

- Transparent
- Good impact

Physical properties

- Density: 1.01 g/cm³
- Shrinkage: 0.5–0.6% to a thickness of 2.5 mm

Advantages	Replaces	Limitations
Clarity Surface gloss Impact resistance Best transparence Approved to medical uses Printability Food contact approved Approved for toys EN71-3 Rigidity Lower density than PET, PVC, etc. Sterilizable (except for steam) Low density = low cost Blood contact compatible No predrying needed Paintable	PS (improved processability, better density) PS (greater impact)	Scratch resistance UV resistance Max. use T.: 65 °C Resistance to solvents and oils Stress cracking No long term contact with chocolate and food fats

6.16 Ionomer

Ionomer Properties

General properties

- Transparent
- Good chemical resistance

Physical properties

- Density: 0.94–0.96 g/cm³
- Shrinkage: 0.3–0.8%

Advantages	Limitations
Transparency Chemical resistance Impact Scratch and wear Flexibility Low density Resistance to fragrances and alcohols Resistance to oils and fats	Thermal resistance

6.17 Polyphenylene Sulfide (PPS)

6.17.1 Properties

General properties

- Excellent mechanical properties, held to almost the melting temperature
- High temperature resistance
- Dimensional stability
- No water absorption (< 0.05%)
- Autoextinguishable flame retardant without additives
- Good creep resistance

Physical properties

- 65% crystallinity
- Shrinkage 40% glass: 0.3–0.5%
- Low post-molding warpage
- Density 40% glass: 1.65 g/cm³
- Density 70% glass: 1.95 g/cm³

Chemical properties

- Excellent chemical resistance, not attacked by known solvents below 200 °C
- Resistant to all fluids normally used in automotive

6.17.2 Features

Glass transition	88 °C
HDT 1.8 MPa	260 °C
UL94	Vo
	5V
	5VA
Shrinkage	0.1–0.6%
Postshrinkage	At temperatures above the glass transition, depending on the mold temperature used.
Annealing	To crystallize the entire structure, the piece could be put at 200–230 °C for two hours.

6.18 Polysulfones

6.18.1 Polyphenyl Sulfone (PPSU)

PPSU Properties

General properties

- High thermal stability: 207 °C (HDT)
- High dimensional stability
- High impact resistance
- Inherent flame retardant

Physical properties

- Glass transition T_g : 220 °C

6.18.2 Polyethersulfone (PESU)

PESU Properties

General properties

- High thermal stability: 204 °C (HDT)
- High dimensional stability
- High impact resistance
- Inherent flame retardant

Physical properties

- Glass transition T_g : 220 °C
- Density: 1.29 g/cm³
- Shrinkage: 0.7%

6.18.3 Polysulfone (PSU)

PSU Properties

General properties

- High thermal stability: 174 °C (HDT)
- High dimensional stability
- High impact resistance
- Inherent flame retardant

Physical properties

- Glass transition T_g : 190 °C
- Density: 1.24 g/cm³
- Shrinkage: 0.7%

A pyramidal classification of polymers can be found in Chapter 1, see Figure 1.5.

Chemical Resistances



Plastics may be attacked by different chemical substances. When an attack occurs, symptoms are usually quite obvious.

- Dissolution
- Absorption
- Chemical reaction
- Cracking
- Loss of properties
- Softening
- Swelling
- Turbidity
- Crazing



It is always advisable to perform a test of chemical resistance of the polymers used with the chemical substances with which they will be in contact, at the temperature at which they will be used, to determine real compatibility.

7.1 Chemical Substances

7.1.1 Ethers



Ethers are abundant in plant life: we can find them in some plants' resins, flowers' color pigments, and others. Ethyl ether is a central nervous system depressant; for this reason, it is used as an anesthetic.



- Solvent of organic substances
- Strong glue
- Anesthetics

7.1.2 Alkalis

Alkalis are more destructive than acids to human tissue. They dissolve fat.



Sodium hydroxide (caustic soda)

Ammonia

Potassium hydroxide

Hydroxide and potassium carbonate

Sodium peroxide

Atropine

Morphine

Nicotine

Quinine

Cocaine

Strychnine

Calcium hydroxide

Potassium hydroxide

Trisodium phosphate

Pipe deblocking



7.1.3 Esters

Esters derive from the reaction between fatty acids and alcohols. Esters of low molecular weight are liquid and are usually used as solvents (especially acetates of methyl, ethyl, and butyl alcohols).

They are also used as raw material in perfume and flavor essences, confectionery, solvents, and synthetic agents for preparation of plastics. Many esters have a characteristic odor and are used to give flavors (pineapple, raspberry, banana, etc.).



Acetate

Fats

Glycerol esters

Fatty acid esters

Methyl butanoate (pineapple)

Methyl salicylate (mint)

Heptyl octanoate (raspberry)

Isopentyl ethanoate (banana)

Pentyl pentanoate (apple)

Ethylhexyl acetate (soft, sweet smell)

Penil butonate (pear)

Octyl ethanoate (orange)

Isoamyl acetate (banana)

Butyl butyrate (pineapple)

Aromas and synthetic perfumes

Analgesics

Insect repellents

7.1.4 Ketones



The suffix *-one* is added to the hydrocarbon from which the ketones come. Hydrocarbon combustion is an uncontrolled system of oxidation of hydrocarbons which results in ketones.

Hexane ————— Hexanone

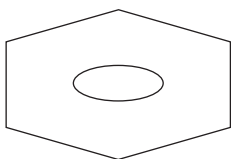
Heptane ————— Heptanone

The name can also be formed by adding *ketone* to the chemical substance name; for example, methylphenyl ketone.

Ketones are produced on a massive scale as solvents and pharmaceuticals. The most important are the ketones which are widely spread in nature. Acetone and methylethyl ketone are used as solvents in industry.



Acetone
Methylethyl ketone
Cyclohexanone
Carbohydrate fructose
Cortisone
Testosterone
Progesterone
Camphor
Acetone (nail cleaner)



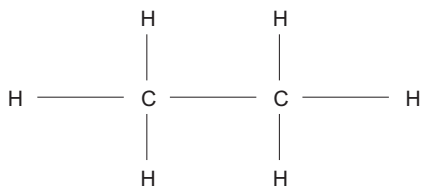
Benzene-based ketones can be carcinogenic.



Perfumes
Organic dyes
TNT
Toluene
Xylene
Ethylbenzene
Carbon
Oil
Aromatic compounds

7.1.5 Aliphatic Compounds

Aliphatic compounds are contained in products used to dissolve fat, oil, rubber, resins, etc.



Aliphatic hydrocarbons

Hexane

Heptane

Octane

7.1.6 Halogenated Hydrocarbons

Halogenated hydrocarbons are compounds of hydrogen, carbon, and halogen elements in group 7 of the periodic table (iodine, bromine, fluorine).

7.1.7 Halogenated Compounds

Halogenated compounds are iodine, bromine, fluorine compounds. They are used for swimming pool water treatment, for example.



Sodium hypochlorite



7.1.8 Amines

Amines are derived from ammonia.



Methylamine (or aminomethane)

Dimethylamine (or methylaminomethane)

Ethylpropylamine (or ethylaminopropane)

Trimethylamine (or dimethylaminomethane)

Ethylmethylpropylamine (or methylaminopropane)

7.1.9 Other Chemicals that May Attack Plastics

Oils



Fatty acids



Alcohols



Detergents



Acids

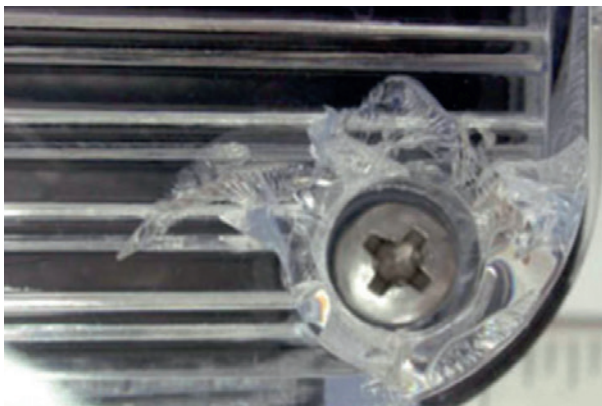


Environmental stress cracking (ESC) is a major cause of failures in plastics, especially amorphous plastics.

Exposure of polymers to chemicals tends to accelerate the process of cracking or crazing. This process begins with stress much lower than that needed to produce cracks simply in contact with air. The mere effect of both conditions separately, stress or contact with an aggressive chemical, need not necessarily result in ESC. This phenomenon usually occurs when a combined action of both effects occurs.

ESC depends on multiple factors such as crystallinity, surface roughness, residual stress, presence of chemical agents, temperature, and strain level or molecular stretching.

The ESC effect can be minimized by lower residual stress and molecular stretching during the injection process. The use of cold molds should be avoided, as they cause residual stresses that will accelerate the ESC. Polymers of higher molecular weight should be used, because they are more resistant to ESC.



Chemical resistances

	LIMITED RESISTANCE, MINOR OR MODERATE ATTACK. USE BRIEFLY
	GOOD RESISTANCE, MINOR ATTACK
	EXCELLENT RESISTANCE, WITHOUT ATTACK
	LOW RESISTANCE. NOT RECOMMENDED

	LDPE	HDPE	PP	PP C	PS	PC
DILUTED ACIDS						
CONCENTRATED ACIDS						
ALCOHOLS						
ALDEHYDES						
BASES						
ESTERS						
ALIPHATIC HYDROCARBONS						
AROMATIC HYDROCARBONS						
HALOGENATED HYDROCARBONS						
KETONES						
MINERAL OIL						
VEGETAL OIL						
MAX TEMPERATURE °C	80	120	135	121	70	130
MIN TEMPERATURE °C	-50	-100	0	-40	0	-135
AUTOClave STERILIZATION						
MICROWAVES						
GAS STERILIZATION						
DRY HEAT STERILIZATION						
GAMMA RAY STERILIZATION						
CHEMICAL STERILIZATION						
NITROGEN PERMEABILITY	20	3	4.4	4.2	3	
CO ₂ PERMEABILITY	280	45	92	65	75	
OXYGEN PERMEABILITY	60	10	25	24	15	

Chemical resistances														
	LDPE		HDPE		PP		PC		PS		SAN		ABS	
	20	50	20	50	20	50	20	50	20	50	20	50	20	50
TEMPERATURE														
ACETALDEHYDE														
ACETIC ACID														
ACETONE														
AMMONIUM HYDROXIDE														
AQUA REGIA														
BENZENE														
WATER BROMINE														
BUTYL ACETATE														
BUTYL ALCOHOL														
CHLORINE WATER														
CHLOROFORM														
CYCLOHEXANE														
ETHYL ACETATE														
ETHYL ALCOHOL														
ETHYL OXIDE														
FORMALDEHYDE														
FORMIC ACID														
FUEL OIL														
METHYL ALCOHOL														
METHYLETHYL KETONE (MEK)														
MINERAL OIL														
SODIUM OXIDE 50 %														
SODIUM CHLORIDE 20 %														
SULFURIC ACID 10 %														
SULFURIC ACID 98 %														
TOLUENE														
VEGETAL OIL														

EXCELLENT RESISTANCE, WITHOUT ATTACK

LIMITED RESISTANCE, MODERATE ATTACK

GOOD RESISTANCE, MINOR ATTACK

POOR RESISTANCE (ATTACKED OR DISSOLVED), NOT RECOMMENDED

Chemical resistances														
	LDPE		HDPE		PP		PC		PS		SAN		ABS	
	20	50	20	50	20	50	20	50	20	50	20	50	20	50
TEMPERATURE														
ACETALDEHYDE														
ACETIC ACID														
ACETONE														
AMMONIUM HYDROXIDE														
AQUA REGIA														
BENZENE														
WATER BROMINE														
BUTYL ACETATE														
BUTYL ALCOHOL														
CHLORINE WATER														
CHLOROFORM														
CYCLOHEXANE														
ETHYL ACETATE														
ETHYL ALCOHOL														
ETHYL OXIDE														
FORMALDEHYDE														
FORMIC ACID														
FUEL OIL														
METHYL ALCOHOL														
METHYLETHYL KETONE (MEK)														
MINERAL OIL														
SODIUM OXIDE 50 %														
SODIUM CHLORIDE 20 %														
SULFURIC ACID 10 %														
SULFURIC ACID 98 %														
TOLUENE														
VEGETAL OIL														

NOT RESISTANT

NOT RECOMMENDED

RESISTANT

Chemical resistances

	RESISTANT						
	LIMITED RESISTANCE						
	NOT RESISTANT						
	IT DISSOLVES						
	NO DATA						
		PS	SMMA	PMMA	ACRYLONITRILES ASA SAN ABS	POLYOLEFINS PP PE	PC
AQUEOUS SALTS							
DETERGENTS							
DISSOLVED ACIDS							
ALKALIS							
ALCOHOLS							
DISSOLVED AMMONIA							
FATS AND OILS							
MONOUNSATURATED OILS AND FATS							
ALIPHATIC AMINES							
CONCENTRATED AQUEOUS ACIDS							
ESTERS							
ETHERS							
CONCENTRATED MINERAL ACIDS							
AROMATIC HALOGENATED HYDROCARBONS							
MEEK							
TETRA-HYDROFURANE							
TOLUENE							
DIMETHYL-FORMAMIDE							
VERY UNSATURATED OILS							
OXYGENATED MATERIALS							
HALOGENATED COMPOUNDS							
ALIPHATIC HYDROCARBONS							
KETONES							
AROMATIC HYDROCARBONS							
ESSENTIAL OILS							
AROMATIC SOLVENTS							
ORGANIC HALOGENATED							

Note: Information obtained from different chemical resistance guides and from several polymer manufacturers. This information does not replace tests necessary for the determination of the real chemical resistance in each case. The author assumes no responsibility for incidents or accidents, damage to equipment or people, or unfavorable results that may occur by use of this information.

Without the inclusion of additives, polymer macromolecules would not be processable and would not acquire their final properties. Additives are included in the polymer to form together what we call thermoplastics. In the plastics business, they are called the additives pack.

Types of additives

Process aids	Functional additives
Lubricants	Glass fibers, glass beads
Process stabilizers	Mineral fillers
Nucleating agents	Flame retardants
Antiblock agents	Heat stabilizers
Others	Color pigments
	Blowing agents
	Impact modifiers
	Softeners
	Antioxidants
	Demolding agents
	Hydrolysis stabilizers
	Antistatic agents
	Others (conductors, steel, natural fibers, nano particles, etc.)



POLYMER + ADDITIVE = PLASTIC

Some additives are necessary to reinforce mechanical properties, thermal and hydrolysis resistance, flammability, etc. Others, like stabilizers, plasticizers, etc., are needed to allow the thermoplastic material to be processed; for example, heat stabilizers to improve the residence time in the injection unit without degradation, etc.

It is considered an additive any organic or inorganic chemical compound added to polymers to modify some of their properties.

8.1 Stabilizers

Heat stabilizers and antioxidants protect the polymer during molding, but successive passages through the plasticizing unit can deplete this effect. The working temperature range is not unlimited: the addition of a considerable amount of stabilizer does not permit excessively increasing the process temperature.

Light stabilizers: The finished part requires light stabilizers, especially when it is exposed to the weather (UV). Polymers are sensitive to the action of sunlight, which can attack free radicals by breaking the molecular chains, causing the polymer to lose its properties.

Some stabilizers used are carbon black, TiO_2 , and HALS (hindered amine light stabilizers). Depending on the sensitivity of the polymer, high concentrations of additive will be necessary.

Light and oxygen are responsible for most of the degradation of plastics. Radiation (290 nm–400 nm) is one of the causes of weathering degradation of polymers.

In general, semi-crystalline polymers are more affected by radiation than amorphous polymers.

There are two forms of action for protection:

1. Reducing the amount of radiation on the polymer
2. Capturing radicals caused by degradation as soon as they occur

Families:

- UV absorbers: benzophenones, benzotriazole, oxanilide
- Radical catchers: HALS hindered amines

UV protection additives have a limited duration.

8.2 Lubricants

Polymers consist of high-weight molecules that maintain high melt viscosity when melted.

Internal lubricants improve the rheological behavior of the polymer reducing shear stresses and increasing the fluidity. They can provoke dispersed flows with contractions and tensions as collateral effects. Polymers, due to the great friction between molecular chains, degrade during the injection process when lubricant additives are not applied.

External lubricants also improve polymer passage through the machine and mold. They migrate to the surface also improving the sliding between finished pieces. They may have secondary effects that affect the weld lines strength of the material and surface finishes (serigraphy, pad printing, hot stamping, welding, etc.).

Families: hydrocarbons, alcohols, carboxylic acids, ketones, amides, polyethylene waxes.

PTFE	Slip-stick effect (10–20%)
Silicone	Migrates to the surface creating a lubricating protective layer Reduces the coefficient of friction. Wear factor gets lower and PV limit* gets higher

* The PV limit is used in tribology and is the product of the nominal pressure and the lineal velocity.

8.3 Antioxidants

Antioxidants prevent polymer degradation by the action of temperature both during processing and during the life of the final product. Oxygen combines with molecular chains to form compounds that accumulate. When this process occurs, the polymer becomes yellow and loses mechanical properties. This is called oxidation.

Some types of stabilizers:

- Radical catchers (lactones)
- Primary antioxidants (hindered phenols)
- Secondary antioxidants (phosphites and thioesters)

Radical catchers are able to give and absorb hydrogen radicals.

Antioxidants are derivatives of sulfur and phosphorus.

8.4 UV Protection

UV protection additives protect polymers against the action of ultraviolet radiation.

Types: absorbents, HALS.

8.4.1 Absorbents

UV radiation is transformed into heat (thermal energy), raising the temperature. Aside from protecting the polymer, absorbents protect the product stored, in the case of bags or packaging.

8.4.2 HALS

- They hinder the action of the free radicals formed by UV radiation.
- They do not protect the contents inside in the case of bags, packaging.
- No antioxidant is needed because they provide some thermal stability.

8.5 Plasticizers

Plasticizers are pastes whose purpose is to be placed between molecules to modify the stiffness and increase plasticity and impact resistance.

They are necessary to enable the processing of the polymer. It is normal to have a pack of plasticizer loss during passage through the machine. Thus, the use of reground material should be limited to avoid affecting remarkable properties of the finished pieces. These alterations can be caused by shear, excessive temperature, deposits in the mold marks, etc.

The functionality of these additives is to reduce internal friction and increase the moving of chains.

A plasticizer may be compatible with the process temperature but it can exude at using temperature.

Families:

- Phthalates (DOP, DIOP, DBP)
- Phosphates (trianil)
- Adipic acid esters
- Sebacic acid esters

8.6 Antistatic Compounds

Antistatic compounds are used for improving the surface conductivity of the finished part so as not to accumulate electrical charges and so that static discharges do not occur. They can also avoid dust deposition on the surface of the finished parts. The plastics, being insulating, attract static charges on the surface. Hygroscopic additives migrate to the surface and attract room humidity. This moisture increases the surface conductivity and neutralizes static charges. This migration effect has a limited time. If a permanent effect is required, a special black smoke additive or conductive additives such as graphite or metallic fillers can be used.

These additives that migrate to the surface may have a similar effect to that of external lubricants. If their heat resistance is poor, it can lead to effects such as gas, bubbles, or bursts.

Polymers with a low dielectric constant charge faster. Polymers with low resistivity help dissipate electrostatic charges.

Families:

Glycerol stearates, ethoxylated amines, fatty alcohols, alkylsulfonates.

Types:

Internal (incorporated into the dough, they act outward by migration) and external (applied on the outer surface by dissolution).

8.7 Flame Retardants

Polymers burn easily because they are organic substances. The function of flame-retardant additives is to:

- Retard combustion and polymer degradation
- Reduce smoke emission
- Prevent dripping

These additives reduce the flammability of the polymer and hinder its combustion. The mechanisms used to hinder combustion are complex: eliminating oxygen in the area affected by the flame, creating a charred outer layer to smother the fire,

or producing water during combustion, which autoextinguishes. These additives typically affect the polymer processing temperatures.

8.7.1 Combustion Mechanism of a Plastic

The combustion mechanism of a plastic starts with heating the material to the point of breakdown and autoignition. Combustible gases are formed. If there is oxygen, combustion starts and spreads.

Retardants may act in two basic ways: chemical and physical. The physical path can be broken down into two types of interference in the combustion process: the solid and gaseous phases.

8.7.1.1 Solid Phase

Two types of reactions may occur:

1. Molecular break accelerated by the flame retardant. In this way, the greater fluidity reduces the impact of the flame.
2. The flame retardant generates a calcined coating on the surface.

Intumescence

The amount of soot generated—instead of gas—increases, forming a double barrier to the passage of gases and to the flame advancing.

Families: ammonium salts, phosphates, polyphosphates, melamines, ureas.

8.7.1.2 Gaseous Phase

During the decomposition reaction, the flame retardants stop the combustion mechanism. There is a general cooling and the contribution of flammable gases is reduced or eliminated.

1. Formation of protective coatings

Flame retardants can form a layer of low thermal conductivity, so that the material is isolated.

Families: phosphorus, zinc borate.

2. Cooling

An additive generates endothermic processes that cool the substrate below the temperature needed for the combustion.

Families: metal hydroxides (aluminum).

3. Dilution

Inert substances such as talc and carbon black generate inert gases during decomposition.

Families: halogenated, chlorinated, brominated compounds based on phosphorus, zinc borate (new regulations ban halogenated compounds).

8.7.2 Some Types of Flame Retardants

Flame Retardants			
	Advantages	Limitations	Comments
Red phosphorus	Good performance	Process window Migration and corrosion Only red and black colors	Predominantly used in PA
Halogenated compounds	Glow wire performance Excellent performance with flame retardation Process window Freedom of colors	Environment, waste management Low CTI High density	Banned
Melamine cyanurate	Low toxicity of smokes Environmental impact Arc resistance	Low impact resistance High density Processability	
Organic phosphorous compounds	Excellent flame retardation Environmental impact It does not emit phosphine	Process window	

8.8 Halogen-Free Flame Retardants

Halogen-free flame retardants are used more and more in the market as additives in polymer compounds. The applications where halogen-free materials are needed are:

- Applications where an improved fire safety is needed
- Applications where continuously high temperatures are needed

8.8.1 Halogens

Halogens are five non-metallic elements forming the group 7 of the periodic table of elements.

The term *halogen* means “salt-formed”. Thus, the halogen-containing compounds are called *salts*.

Halogen	At room temperature
Fluor	Gas
Chlorine	Gas
Bromine	Liquid
Iodine	Solid
Astatine	Solid

8.8.2 Usual Names for Halogen-Free Materials

The term “halogen-free” means that the material does not contain any compound derived from these elements.

Terms used to indicate that a material does not contain any halogen substances:

- Halogen-free
- Zero halogen
- No halogen
- OH
- ZH

8.8.3 Contribution of Halogens in Plastics

Halogens provide polymers with excellent flame-retardant properties that are difficult to obtain with non-halogen substances with the same level of performance and cost. For example, fluoride results in Teflon (FEP). This material provides an extremely high resistance to heat and combustion and therefore provides high levels of security.

Chlorine is a PVC component. Chlorine is derived from salt and water, is very cheap, and is the most widely used component in providing low-cost PVC material.

The challenge is to find halogen-free materials with the same or better properties and costs of halogenated materials.

8.8.4 Need for Alternatives to Halogenated Materials

Halogenated materials may leak corrosive and toxic gases during their ignition in a fire. Their smoke can damage electronic systems and have a high toxicity. They can be potentially dangerous for people if they are not evacuated quickly: a very important issue for potential fires in confined and difficult rescue or evacuation areas as trains, tunnels, boats, etc.

Communication systems and data centers are particularly sensitive to corrosion. The biggest disaster known in the history of telecommunications happened in Illinois in May 1988: fire cut 35,000 suburban telephone lines in the Chicago area. The rebuilding of the central telephone network had a cost a millions of dollars. Although the telephone station was not damaged by the fire, it had to be reconstructed because of the effect of corrosive gases.

8.9 Foaming Agents

Foaming agents are used to obtain cellular structures with low densities. They can be exothermic (they emit heat) or endothermic (they absorb heat) additives. The latter are more useful to help reduce production cycles. A good thermal process control is recommended to avoid unwanted chemical reactions.

These products, as they decompose, produce a gas that expands the plastic.

The azodicarbonamides (an exothermic foaming agent) and the sodium borohydride and sodium bicarbonate (endothermic foaming agent) are widely used foaming agents.

8.10 Hydrolysis Stabilizers

Hydrolysis is a chemical reaction with water. It is a slow process at room temperature but can be faster at higher operating temperatures. This reaction causes a loss of molecular weight, chain breakage, and loss of polymer properties (especially toughness). Hydrolysis stabilizers reduce water reaction at high temperatures.

8.11 Slips and Antiblocking

8.11.1 Slips

Slips reduce friction, improve the process and/or the application or end functionality.

Types: metal esters, amines and esters of fatty acids, natural and synthetic waxes, amides, etc.

8.11.2 Antiblocking

Antiblocks make the polymer surface rough to prevent that sheets or films stick together and make processing difficult.

Types: synthetic and natural silica.

8.12 Nucleating Agents

Nucleating agents increase polymer crystallinity and reduce overall shrinkage because they form more but smaller spherulites. They usually improve the cooling cycle.

When using nucleating materials, they can produce most of the shrinkage in the mold. The post-shrinkage will be reduced. This effect can minimize subsequent warpage but also make difficult to remove the pieces by shrinking against the cores.

They increase clarity and brightness.

Families: sales of acids, sorbitols, talc, mica, silica, etc. The ratio is usually 0.5%.

8.13 Compatibility Agents

Compatibility agents promote adhesion and improve it between phases of different materials. When they are used to improve the adhesion between polymers and fillers, they are called coupling agents.

8.14 Impact Modifiers

Impact modifiers promote the addition of some kind of elastomer in the polymer matrix, acting on three different types of changes in the polymer structure:

- Incorporation of an elastomer during polymerization
- Dispersion of an elastomer during processing
- Incorporation of core shell particles (particles with thermoplastic elastomeric core encapsulated in shells)

8.15 Fillers and Reinforcements

Fillers are used to obtain or enhance polymer properties. Often they influence the rheology, viscosity, and material behavior during processing, so it is important to know the type of filler used.

Reinforcements

The most common reinforcements are:

- Glass fibers (long or short)
- Glass spheres or balls
- Carbon fibers
- Mineral fillers (talc, calcium carbonate, silicates, graphite, etc.)

Fibers: Typically, they are glass or carbon fibers. These increase the tensile and flexural modules, providing higher mechanical strength. In return, there is a loss of impact strength, a loss of fluidity due to increased viscosity, and an increased tendency to warp due to differential shrinkage caused by the orientation of the fiber in the flow and the different contraction in the flow direction and in the transversal axis of flow (anisotropy).

Glass microspheres: They increase mechanical properties and do not generate as much differential shrinkage and warping. They also reduce the overall shrinkage of the final part.

Mineral fillers: Usually mica. They increase mechanical properties. Also, contraction will be reduced and will be isometric, equal in the flow direction and in its transversal axis. (isotropy). These fillers can act as nucleating agents to increase crystallization of smaller crystals.

Mineral reinforcements may induce abrasion effects in the mold and the plasticizing unit. Therefore, this must be taken into account when programming the injection parameters in order to also avoid breaks in the fibers.

8.16 Mineral Additives

- Talc
- Calcium carbonate
- Walastonites (reduce stress-related white lines)
- Carbon fibers
 - They are obtained charring polyacrylonitriles in high-temperature furnaces without oxygen
 - A carbon filament = 5 to 8 micrometers in diameter
 - Carbon fibers are amorphous
 - Structure similar to graphite but, unlike graphite, it is cross-linked
 - Graphite: irregularly parallel sheets of carbon
 - Carbon: randomly foliate, tightly, and integrated leaves

Property	Glass fiber	Mineral filler
tensile modulus	increase	slight increase
mechanical resistance	increase	little variation
creep resistance	increase	slight increase
impact resistance	decrease	decrease
ductility	decrease	significant decrease
notching sensibility	increase	significant increase
fatigue resistance	increase	–
thermal resistance	increase	increase
coefficient of thermal expansion	decrease	decrease
electrical properties	little variation	improvement
flame retard	increase	increase
fluidity	decrease	decrease
density	increase	significant increase
shrinkage	anisotropic	significant decrease
aesthetic properties	decrease	decrease

8.17 Antifriction Lubricants

- Recommended for combating friction and wearing
- Parameters: friction coefficient (static and dynamic), wear factor, and PV limit
- **PTFE (polytetrafluoroethylene)**
 - 10–20% of charge usually used
 - Slip-stick effect
- **Silicone**
By migration, it creates a protective lubricant layer on the surface, reducing the friction coefficient and getting a very low wear factor and a higher PV limit
- **Carbon fiber**
Increases electric conductivity
- **Graphite**
Isotropic; reduces thermal expansion
- **Molybdenum disulfide**
It is a nucleating agent that creates a crystalline layer on the surface, enhancing the properties of the compound; used in semi-crystalline polymers

8.18 Dyes and Pigments

Natural polymers have a wide range of colors: from cream, beige, blue, transparent, to brown and green tones. Pigments or dyes are necessary to color them.

There are different types of pigments:

- Organic and inorganic
- Stable or heat-sensitive
- With or without a tendency to migrate

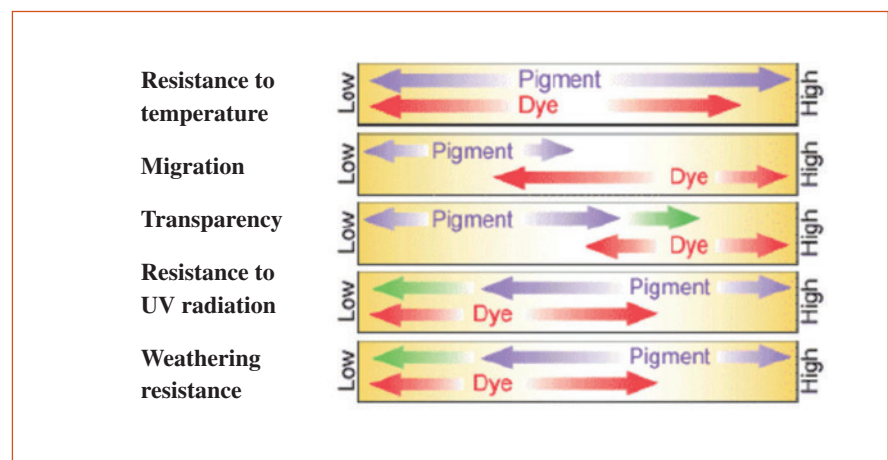


Figure 8.1 Differences between pigments and dyes

Titanium dioxide is used for white and black carbon is used for black.

inorganic pigments	titanium dioxide, ultramarine blue, green oxide, iron oxide, lead chromate
organic pigments	diarylide (yellow), calcium lacquer (red), copper phthalocyanines (blue)

Table 8.1 Properties of Pigments

Properties	Inorganic pigments	Classic organic pigments	High-performance organic pigments
opacity	high	more or less transparent	
color strength	weak	better than inorganic pigments	
resistance to temperature	< 500 °C	165–200 °C	200–300 °C
light strength	good	medium	good or difficult

When using masterbatch or color concentrates, the carrier bearer of the pigment must be of the same base or compatible with the polymer to be colored.

8.19 Masterbatch

A masterbatch is a color concentrate and additives dispersed in a polymer or carrier. The color concentrate is mixed with the natural polymer to color it or modify it. It can be used for coloring or for other characteristics.

Basic Requirements of a Masterbatch

1. Chemical compatibility with the polymer to be modified
2. Good dispersion of its components
3. Easy coloring and spreading of pigments

Chemical compatibility

Good chemical compatibility between the polymer and the masterbatch. The carrier polymer must be the same polymer we want to color. If not, it must be a compatible polymer.

Dispersion

Dispersion increases color performance (the pigment is more effective). It is very important in transparent colors. Organic pigments are harder to disperse because they tend to agglomerate.

Spreading

Spreading is the ease with which the masterbatch colors the piece uniformly.

Masterbatch Composition

Dyes

- Organic and soluble

- Recommended for polymers with high glass transition temperature T_g (PS, SB, PMMA, PC, PA6, PET, ABS)
- Good resistance to light
- Thermal resistance
- Used for transparent and bright colors (and opaque in combination with titanium dioxide colors)

Pigments

- Organic and inorganic
- Insoluble in the polymer
- They are more commonly used

Pearl pigments

They provide a similar appearance to pearls thanks to the different refraction of light by the different pigments they contain. They are typically mica particles coated with titanium dioxide.

These pigments are transparent and can be used in PVC, PE, PP, PS, and PMMA. They are stable to acids, bases, and to temperature.

Metallic pigments

- Provide a metallic appearance
- These are sheets of aluminum, copper, zinc, and mixtures of copper and zinc
- Sensitive to acids and antioxidants

Optical brighteners

- They are organic
- Absorb UV radiation between 300 and 400 nm to convert it into visible light (400–600 nm); the polymer reflects light and makes it whiter and brighter
- Solid at 300 °C
- Good dispersion

Examples of pigments

- White: titanium dioxide, zinc sulfide
- Colored: iron oxides, cadmium pigments
- Metallic: aluminum particles
- Pearly: iron oxides of mica
- Fluorescent: zinc sulfide silver
- Phosphorescent: copper zinc sulfide
- Pearlescent: bismuth oxychloride and mica coated with titanium dioxide

Other additives in the form of masterbatch

- Packages for laser marking: they can be marked with color laser
- Antimicrobial and antibacterial packages (usually silver-based): to prevent the appearance of microbes or bacteria

Antibacterial packages, according to their mode of operation, can be of two types:

- **Bacteriostatic:** they inhibit the growth and reproduction of bacteria
- **Bactericide:** they kill a kind of bacteria depending on the type of additive

8.20 Applications

- Interior of refrigerators
- Toiletries
- Garbage bags
- Coffee
- Baby bottles

The incorporation of antimicrobial agents into polymers is a common practice. They are added to protect degradation by microbes or to provide protective properties.

The silver-based antimicrobial additives are becoming more common because they are very effective against a wide range of microorganisms.

8.20.1 Action Mode

Silver is one of the most effective bactericidal agents. It is very effective against bacteria, fungi, and yeasts, and can act on a large number of pathogens.

Silver nanoparticles are incorporated into the inorganic matrix and released in the presence of moisture, inhibiting the respiratory enzyme of the microorganism, preventing its breathing and causing its death.

8.20.2 Addition Mode

Antimicrobial agents can be added as an additive, a masterbatch, or another component in the formulation. The polymeric products may contain antimicrobial active agent concentrations (0.05–3%).

8.20.3 Some Products

Colloidal silver, Collargol, proteinate, vitelinate, Targesine, Fosfargol, Zeargol.

Tests on Plastics

9.1 Mechanical Tests

9.1.1 Tensile Test ISO 527 1-2

Stress-strain relations are the most important mechanical property for a part subjected to a tensile stress, when comparing materials.

This tensile test is performed on a sample of multipurpose test or specimen (MPTS) according to ISO 527 1-2.

MPTS sample

150 mm length, 110 mm width, and 4 mm thickness

Test speed

A = 1 mm per minute

B = 5 mm per minute for resins reinforced with glass fibers

C = 50 mm per minute for unreinforced resins

In the initial test area, where the module is determined, lower speeds are normally used. Then, the tensile curve is developed at the speeds mentioned.

Stress	load/cross unit area	MPa
Strain	elongation/original length $\times 100$	%
Modulus	stress/strain	MPa
Stress to yield limit	initial maximum stress	MPa
Stress at break	stress to break	MPa
Deformation to break	deformation at breaking point or maximum elongation	%
Proportional limit	linear correlation breaking point	
Elastic modulus	modulus below the proportional limit	MPa

9.1.2 Flexural Test ISO 178

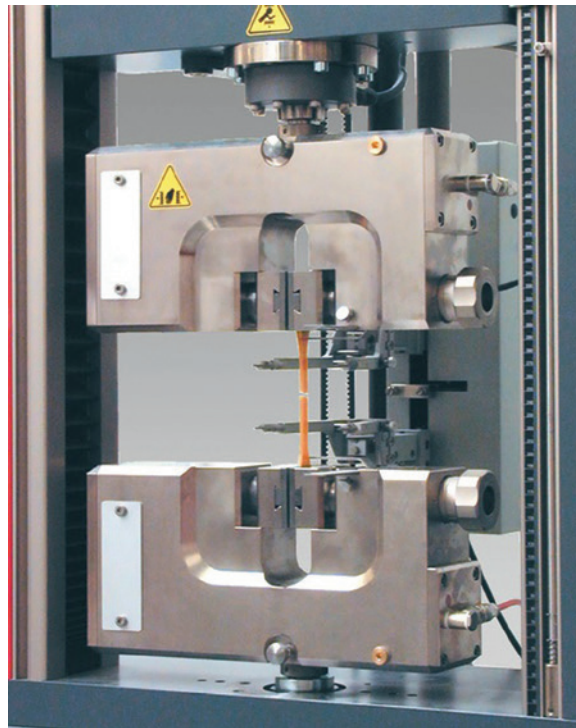


Figure 9.1 Universal testing machine; source: Zwick-Roell

This flexural test measures the extent of bending resistance of a material and its stiffness. To carry it out, a specimen is placed so that it rests on two points. Then, pressure is applied at its midpoint.

Test speed: 2 mm per minute.

To calculate the flexural modulus, the load/deflection curve is drawn. The flexural modulus is determined by the slope of the line tangent to the stress-strain curve in the region where the plastic has not yet been permanently deformed or where elastic strain occurs.

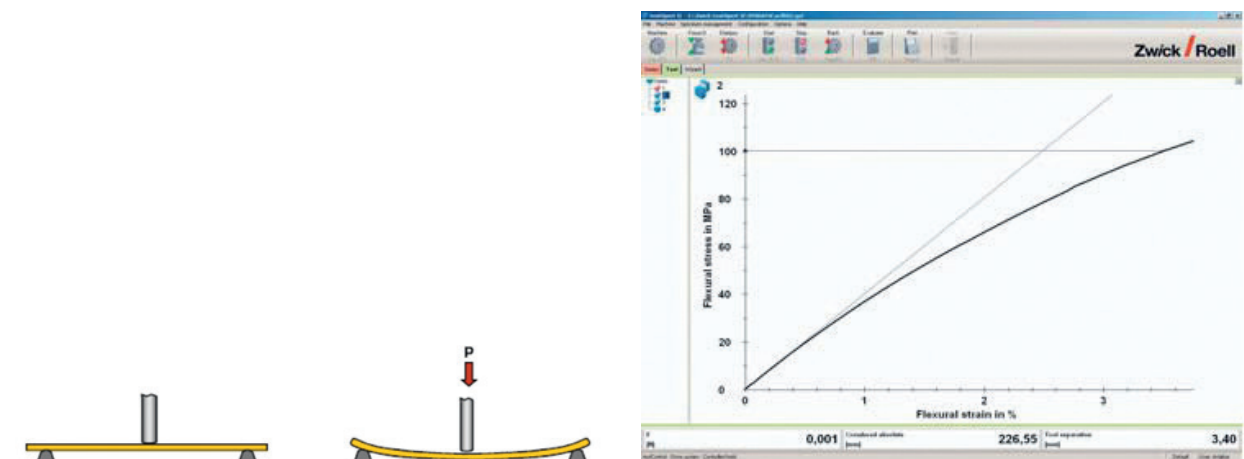


Figure 9.2 Graph of flexural stress; source: Zwick-Roell

9.1.3 Wear Resistance Test TABER ASTM D1044



Figure 9.3 TABER machine;
source: Neurtek

This wear resistance test measures the amount of material loss by abrasion or wear.

The sample is mounted on a turntable which rotates at 60 rpm. Loads are applied as weights that push the abrasive wheels against the sample. After a certain number of cycles the test is stopped.

The mass lost by abrasion is indicated in mg/1000 cycles.

9.1.4 Hardness Tests

9.1.4.1 Ball Pressure Hardness Test ISO 2039-1

A 5 mm diameter ball of hardened and polished steel is pressed at 358 N on a sample surface with a minimum thickness of 4 mm. 30 seconds after, the depth of impression is measured.

Hardness pressure is calculated by dividing the load applied by the mark area (N/mm^2).

9.1.4.2 Rockwell Hardness Test ISO 2039-2

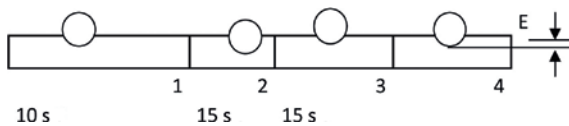
The diameter of the ball depends on the Rockwell scale used. The indenter is made of hardened and ground steel. The sample is subjected to a lighter load. A heavier load is then applied and, finally, the lighter load is applied again.

The measurement is based on the total penetration depth achieved. The values are always between 50 and 115 (in Rockwell units).

The scale increases in severity R to M through L.

Table 9.1 Rockwell Hardness Test

Rockwell hardness scale	Lower load (N)	Higher load (N)	Ball diameter (mm)
R	98.07	588.4	12.7
L	98.07	588.4	6.35
M	90	980.7	6.35

**Figure 9.4** Rockwell hardness conditions and sequence**Figure 9.5** Rockwell hardness test machine; source: Zwick-Roell

Rockwell hardness calculation = $130 - E$ (see Figure 9.4).

Units: 0.002 mm (one unit per each 0.002 mm of the mark depth).

9.1.4.3 Shore A and Shore D Hardness Test ISO 868

The Shore A test is intended for soft materials. The Shore D test is intended for harder materials.

Pressure is applied on the sample for 15 seconds. Hardness is read on the durometer scale. Values range from 0 (total penetration: 2.5 mm) to 100 (no penetration).

Shore A hardness ranges from 10 to 90. Shore D hardness ranges from 20 to 90.

Shore A values over 90 require switching to the Shore D scale. Shore D values under 20 require switching to the Shore A scale.

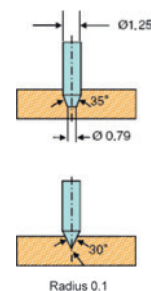




Figure 9.6 Shore A durometer;
source: Zwick-Roell

9.1.5 Impact Charpy Test ISO 179 IZOD, ISO 180

The sample specimens are different between ISO and ASTM. See Table 9.2.

Table 9.2 Sample Dimensions for Charpy Impact Test

	Thickness	Length
ISO sample	4 mm	80 mm
ASTM sample	3 mm	60 mm

The impact Charpy test is used to estimate the degree of weakness or strength of material samples subjected to impact. We can thus compare the toughness of different materials.

The sample is placed in the specimen holder. Then, a pendulum hammer (with a hardened steel tip of a certain radius) is dropped from a certain height. The impact causes shearing of the sample material due to the sudden load.

The height difference between the baseline and the residual height reached by the hammer represents the energy absorbed by the sample.

This test can be performed at different temperatures. It can also be performed with or without notches in the sample.

9.1.5.1 Izod Test ISO 180

The result of this test is obtained by dividing the energy required to break the sample by the initial area. The result is expressed in kilojoules per square meter, kJ/m^2 .

9.1.5.2 Charpy Test ISO 179

One important difference between the Charpy and the Izod tests is that, while in the Charpy test the specimen is in a horizontal position and not fixed, in the Izod test the specimen is fixed in a vertical position.

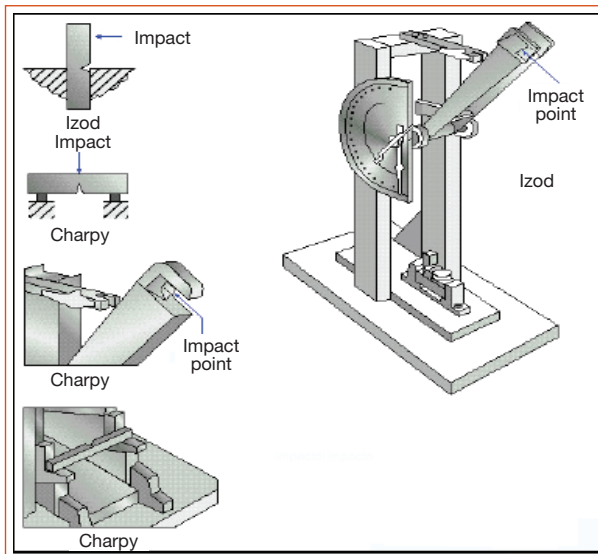


Figure 9.7 Specimen positions and details of impact tests; source: Ascamm



Figure 9.8 Impact test machine; source: Zwick-Roell

9.1.6 Scratch ASTM D3363

This test evaluates surface hardness using a range of pencils, each harder than the previous one (6B, 5B, 4B, 3B, 2B, B, HB, F, H, 2H, 3H, 4H, 5H, 6H). The pencil is applied to the surface at an angle of 45° and with constant load. The result is given by the hardness of the last pencil that does not scratch the surface.

6B
5B
4B
3B
2B
B
HB
F
H
2H
3H
4H
5H
6H



Figure 9.9 Hardness scale levels

9.1.7 Compression Set Test

Compression Stress Relaxation



Figure 9.10 Compression test: scheme of procedure; source: Exxon Mobil

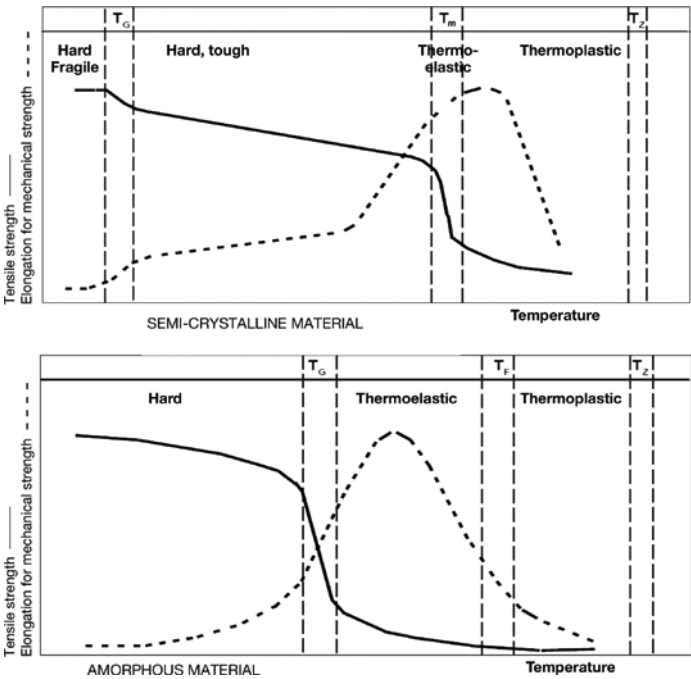
The sample to be tested is compressed 25% for a certain time (the test can also be performed at different temperatures). Then, the compression is released, resulting in a partial recovery of the original shape. The amount not recovered is the compression set.

9.2 Thermal Tests

9.2.1 Definitions

Glass transition temperature (T_g): temperature at which the material goes from a glassy state (hard and brittle) to a rubbery state (tough and flexible). T_g depends on the flexibility of the molecular chains and the interactions between them. Below T_g , molecular motion is very limited.

Melting temperature (T_m): temperature at which, in semi-crystalline polymers, the fusion of the crystalline regions occurs, leading to a significant increase in specific volume. See Section 1.7 in Chapter 1.



9.2.2 Vicat Test ISO 306

This test measures the temperature at which a plastic starts to soften rapidly. It is particularly suitable for amorphous materials.

A cylindrical flat-tipped needle with a cross section of 1 mm^2 penetrates the surface of the plastic sample under a specific load. Temperature increases at a uniform rate.

The Vicat temperature is that at which the needle penetrates 1 mm. The loads applied are:

Vicat A: 10 N

Vicat B: 50 N

The temperature can be increased at two speed rates: 50°C/h or 120°C/h . The strictest test is the Vicat B at a 50°C/h rate of temperature increase.

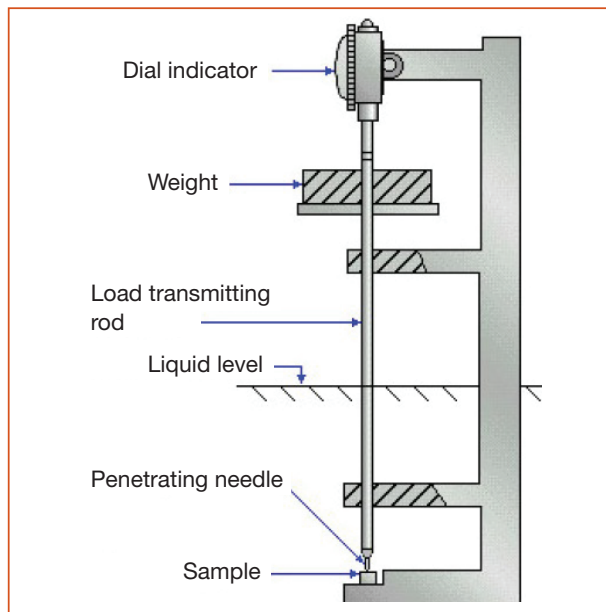


Figure 9.11 Vicat test scheme; source: Ascamm

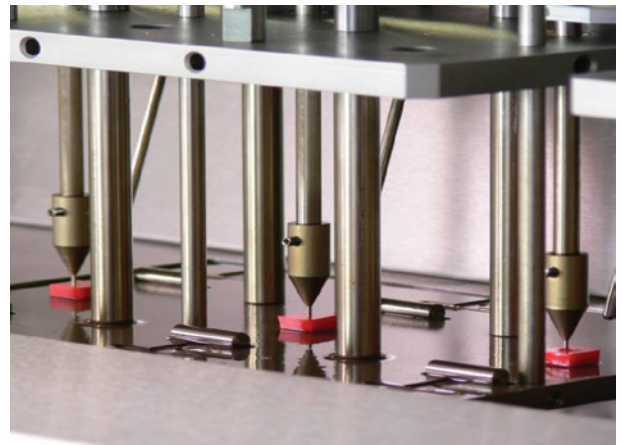


Figure 9.12 Vicat test machine; source: Zwick-Roell

9.2.3 HDT ISO 75

The HDT (heat deflection temperature) test measures the ability of a material under load to provide service for a short time at an elevated temperature.

To perform the test, the workpiece is immersed in thermal silicone oil. The loads applied are 0.45 MPa (HDT A) and 1.8 MPa (HDT B).

The load acts for 5 minutes. Then, the bath temperature is increased at a rate of 2°C per minute. When the deflection reaches 0.32 mm (ISO) or 0.25 mm (ASTM), it is expressed as deflection temperature under load or HDT.

In amorphous polymers the HDT is close to the T_g .

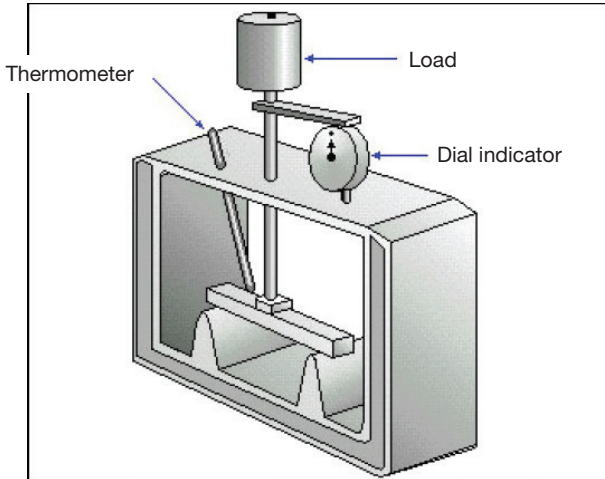


Figure 9.13 HDT test scheme; source: Ascamm

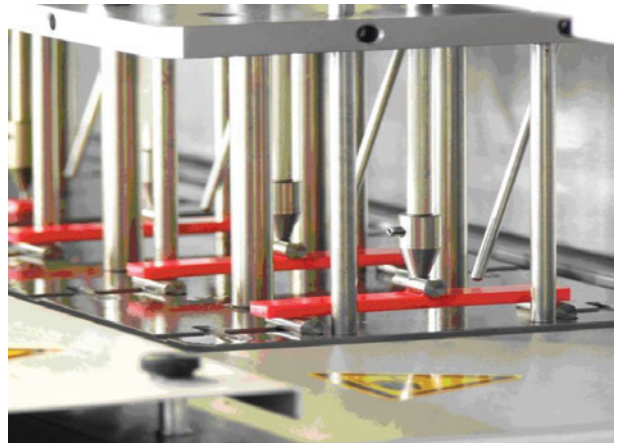


Figure 9.14 HDT test machine; source: Zwick-Roell

9.2.4 Hot Ball Pressure Test

This test determines the softening temperature. The sample is placed horizontally on a stand inside a heating cabinet. A 20 N force is applied on a steel ball of 5 mm of diameter. One hour later, the ball is removed and the sample is cooled in water for 10 seconds. Then, the impression left by the ball is measured. If the diameter of the mark is less than 2 mm, the ball pressure test at the indicated temperature has been passed.

Test temperature:

- 75 °C for parts used in devices where there is no electric current
- 125 °C for parts used in devices with electric charge

EC 335-1: Two types of tests (ball radius: 25 mm):

- 100 °C for parts used in devices where there is no electric current
- 125 °C for parts used in devices with electric current

9.2.5 Relative Temperature Index (RTI) Test

The RTI test measures the maximum operating temperature at which the basic properties of the material are kept within acceptable limits for a long time. It is also called the maximum temperature of continuous use of a material.

The material is subjected to accelerated aging and then subjected to tests to determine the loss of properties.

There are three classifications:

Electrical RTI	electrical strength
Mechanical with impact RTI	mechanical and impact resistance
Mechanical without impact RTI	mechanical tensile strength

The useful life term is the time after which a material property has degraded to (max.) 50% of its original value after 60,000 hours (7 years approximately). The loss of initial values is less than 50%.

9.2.6 Coefficient of Linear Thermal Expansion (CLTE) Test

The CLTE test determines the expansion of the material when heated.

Amorphous polymers tend to have uniform expansion speeds for the entire temperature range. Crystalline polymers typically have higher rates of expansion for temperatures above their T_g .

Table 9.3 Calculation Example

	Coefficient of thermal expansion (CTE) $\alpha \times 10^{-5} \text{ K}^{-1}$	PA66 example
POM	8–13	Length: 100 mm Temperature increase: from 23 °C to 90 °C (i. e., 67 °C) T increase = 67 °C $\Delta l = l_0 \times \alpha \times \Delta T$ $\Delta l = 100 \times (11 \times 10^{-5}) \times 67$ Length increase: 0.737 mm
PA 66	7–15	
PC	6–7	
PP	15–20	
PA 66 GV	3–4.5	
PC GV	2.3–4.5	
PP GV	3–6	
Steel	1.1	
Copper	1.7	

9.2.7 Flammability Test UL94

The flammability test UL94 determines the ability of a material to extinguish a flame once ignited.

Materials are classified according to the burning rate, the extinction time, the ability to resist dripping, and if droplets burn or not.

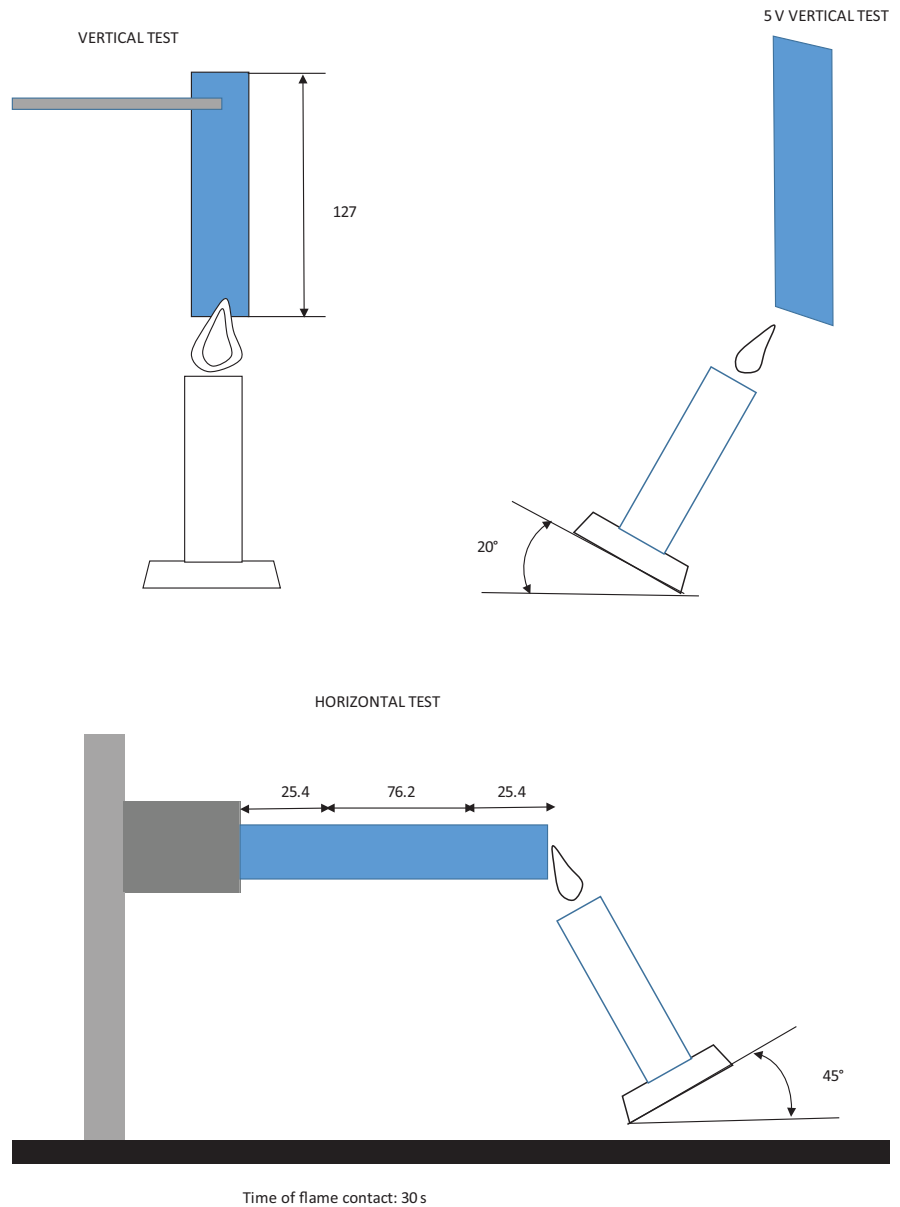
The burning times are recorded when dripping occurs and if the cotton placed underneath the material lights or not.

The UL classification must always indicate the thickness of the test.



HB materials are not recommended when flammability is a safety requisite.

UL testing standard



Classification

- Horizontal HB flame at 45 °C
- Smoldering
- < 76 mm per minute for thickness < 3 mm
- < 38 mm per minute for thickness > 3 mm

2 × 10 s flame	V-0	Combustion stops within 10 seconds. No dripping.
2 × 10 s flame	V-1	Combustion stops within 30 seconds. No dripping.
2 × 10 s flame	V-2	Combustion stops within 30 seconds. Burning particles dripping allowed.
5 × 5 s flame	5V	Combustion stops within 60 seconds after applying a flame for 5 seconds five times. No dripping.
5 × 5 s flame	5VA	Like 5V. No burning hole. No dripping.
5 × 5 s flame	5VB	Like 5V. Plate can have a burning hole.

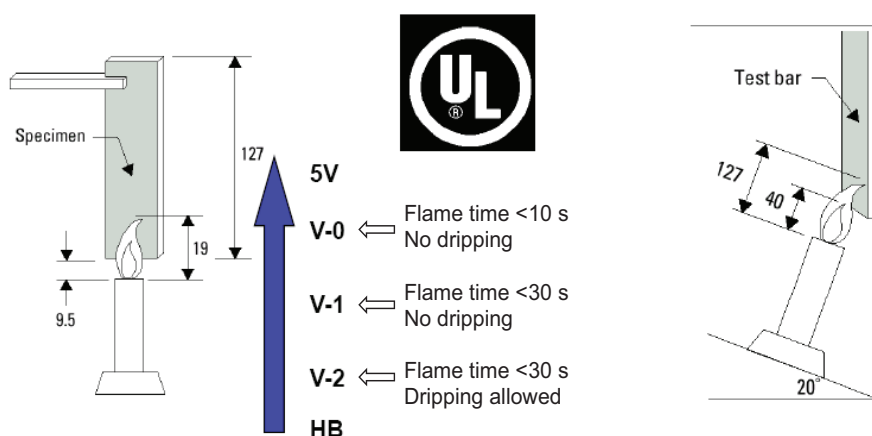


Figure 9.15 UL 94 levels scheme; source: UL Lab

9.2.8 Limited Oxygen Index (LOI) Test ISO 4589 1.2

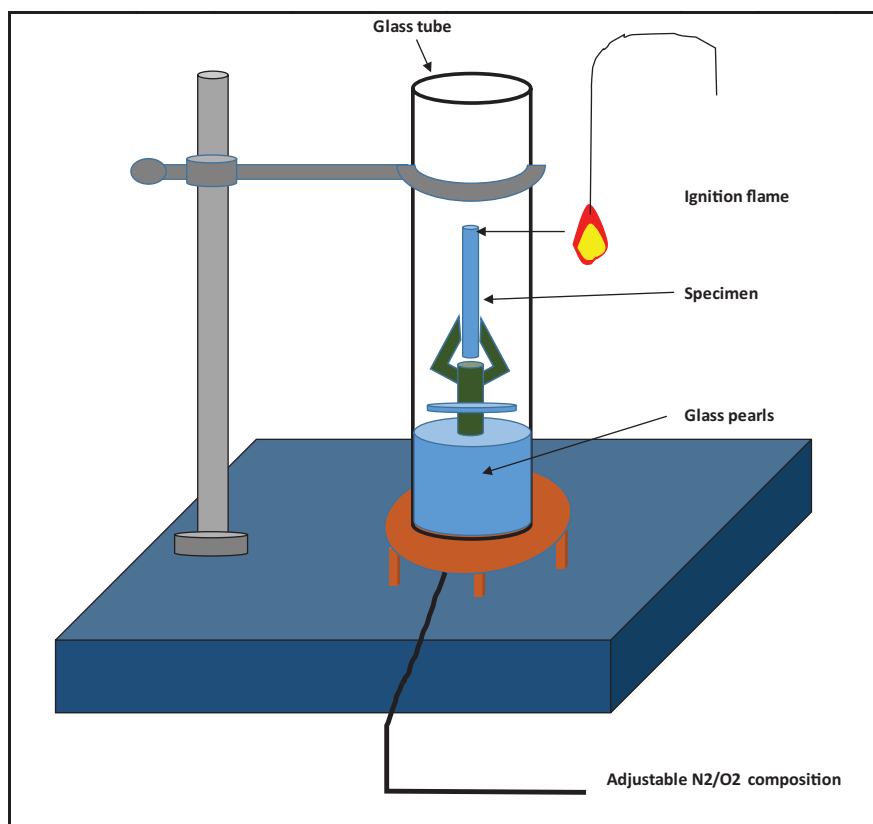
The LOI test is used to measure the relative flammability of materials, making them burn in a controlled environment. It represents the minimum level of oxygen in the atmosphere in which a material can burn at least 3 minutes.

The test atmosphere is a controlled mixture of nitrogen and oxygen. The sample is ignited by a pilot flame, which is then removed. In the following stages of testing, oxygen concentration is reduced until it reaches a point where the sample no longer burns.

The relative oxygen index is defined as the minimum concentration of oxygen needed to burn a material for 3 minutes.

The higher the LOI, the lower the probability of combustion occurring.

The Earth's atmosphere is 21% oxygen.



9.2.9 Incandescent Glow Wire IEC 60695-2-13 and 2-12

The incandescent glow wire test simulates thermal stresses that can cause heat sources (e.g., overloaded resistors, overloaded cables, or glowing elements).

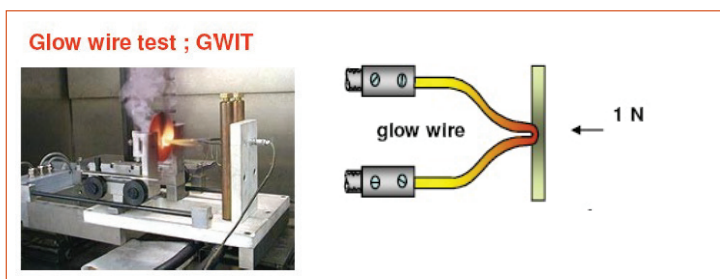
A vertical sample is placed against the tip of an electrically heated incandescent wire for 30 seconds with a force of 1 N. The following items are recorded: the presence or absence of ignition, the time it takes to extinguish the flames, and the presence or absence of burning drips.

The sample will pass the test in these cases:

- No flame or glowing combustion
- The flame is extinguished within 30 seconds after removing the hot wire

According to the environment of the piece, priority is given to the following temperatures: 550 °C, 650 °C, 750 °C, 850 °C, and 960 °C.

9.2.10 Glow Wire Ignition Test (GWIT) IEC 60695-2-13, 2-12



The GWIT determines the glow wire ignition temperature (IEC 60695-2-13). This is the temperature at which the flames are extinguished after removing the hot wire (time elapsed: 5 seconds). Paper placed under the specimen must not ignite.

Temperature (°C)	500	600	650	700	750	800	850	900	960
Contact time	30 s								

9.2.11 Glow Wire Flammability Test (GWFT) IEC 60695-2-12

Temperature (°C)	500	600	650	700	750	800	850	900	960
Contact time	30 s								

The GWFT determines the temperature at which the ignition does not last more than 30 seconds after applying a hot wire for 30 seconds. Paper placed under the specimen must not ignite.

9.2.12 Reaction to Fire: Classification

Ceramic building materials are considered M0 class. They have no heat energy input, or gassing or fumes in contact with the flame.

They represent the highest security level for users in case of fire. They are completely inorganic.

Reaction to fire:

Regarding the reaction to fire of materials, they are classified as M0, M1, M2, M3, and M4. This classification indicates the capacity of materials to favor the development of a fire.

The number of each class name indicates the magnitude.

- M0: non-combustible material according to the test-standard thermal action.
- M1: combustible but not flammable material. Its combustion is not maintained when the heat input from an external focus ceases.
- M2: material with moderate flammability.

- M3: material with medium flammability.
- M4: material with high flammability.

9.3 Electric Tests

9.3.1 Dielectric Strength ASTM D149 IEC 60243-1

This test reflects the electrical resistance of the insulating materials in network frequencies from 48 Hz to 60 Hz. The voltage applied just before the break is divided by the sample thickness and the value is given in kV/mm.

The surrounding medium may be air or oil.

9.3.2 Dissipation Factor ASTM D150 IEC 60250

In a perfect dielectric environment the voltage and current intensity waves are out of phase exactly 90 °C. When the dielectric is no longer 100% effective, the intensity wave begins to delay the voltage in direct proportion. The amount by which the current wave deviates from being 90 °C out of phase with the voltage wave is called loss angle or dielectric loss.

In case of high-frequency equipment, radar, or microwaves, it is important that this dissipation factor is as low as possible. The lower the value of the dissipation factor, the better will be the material as dielectric.

Conversely, regarding welding capabilities it is important that the dissipation factor be high.

9.3.3 Dielectric Constant ASTM D150 IEC 60250

The dielectric constant is the insulation value of a polymer. Air has a dielectric constant value of 1. Water has a dielectric constant of 80.

Polymers loaded with graphite-type conductive fillers can reach dielectric constants from 10 to 13. Materials that will be used as insulation should have a low dielectric constant. Conversely, materials that will be used as dielectric, for example on a capacitor, must have a high dielectric constant.

9.3.4 Comparative Tracking Index (CTI) IEC 60112

The CTI measures the relative resistance of electrically insulating materials to tracking when their surface is exposed to the action of water with contaminants under a voltage.

This test evaluates the safety of components bearing electrically charged parts. The CTI is defined as the maximum voltage that the material resists, pouring 50 drops of ammonium chloride dissolved in water between two electrodes.

Materials used in electrical applications need to have a high CTI. When they have a CTI of 600 volts, they are called high-tracking resins.

CTI values may be affected and reduced when additives (carbon black, flame retardants, glass fibers) are added to the polymers. It is not recommended to use black materials, flame retarded, or glass-fiber reinforced when the tracking index is important. Type-TiO₂ minerals tend to increase the CTI values.

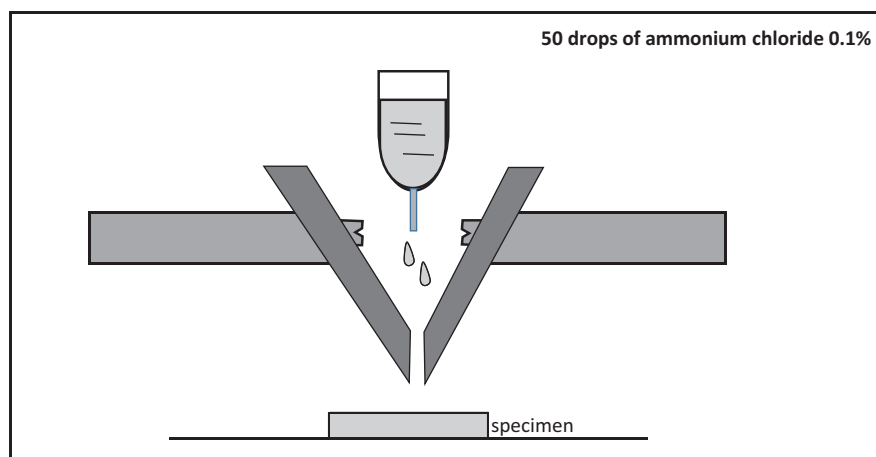
Test:

The test is performed with two platinum electrodes placed with the slightly rounded “chisel” edge flat on the test sample. A potential difference is applied between the electrodes (usually a minimum of 175 volts). The voltage is applied in steps of 25 volts; the maximum voltage is 600 V.

The surface of the test specimen is wetted by 50 drops of a solution of 0.1% ammonium chloride in distilled water falling between the two electrodes. When no current is flowing at the chosen voltage, the test is repeated with a 25 V higher voltage, until there is a flow of current. The voltage then, decreased by 25 V, is called CTI.

Classification used:

0	≥ 600 V
2	275 to 400 V
3	175 to 250 V
4	100 to 175 V
5	0 to 100 V



9.3.5 Surface Resistivity (SR) ASTM D527 IEC 6009 3

Surface resistivity is a measure of the material's ability to resist an electrical current through its surface.

The test consists of two parallel electrodes with conductive paint (silver) of a particular size. They are applied at a distance on the test plate surface. Then, the resistance between the electrodes is measured.

9.3.6 Volume Resistivity (VR) ASTM D527 IEC 6009 3

Volume resistivity is the electrical resistance of a material when an electrical current is applied between electrodes mounted on opposite faces of the test specimen's thickness. It is reported in ohms per square centimeter.

9.4 Rheological Tests

9.4.1 Melt Flow Rate (MFR), MFI ISO 1133

This test measures the flow of a molten polymer through an extrusion plastometer at a specific temperature and load. The plastometer consists of a cylinder with an outlet diameter of 2 mm and an inner piston.

Temperatures and loads are applied according to the standard used and the material to test. The amount of polymer exiting the nozzle after 10 minutes is weighed.

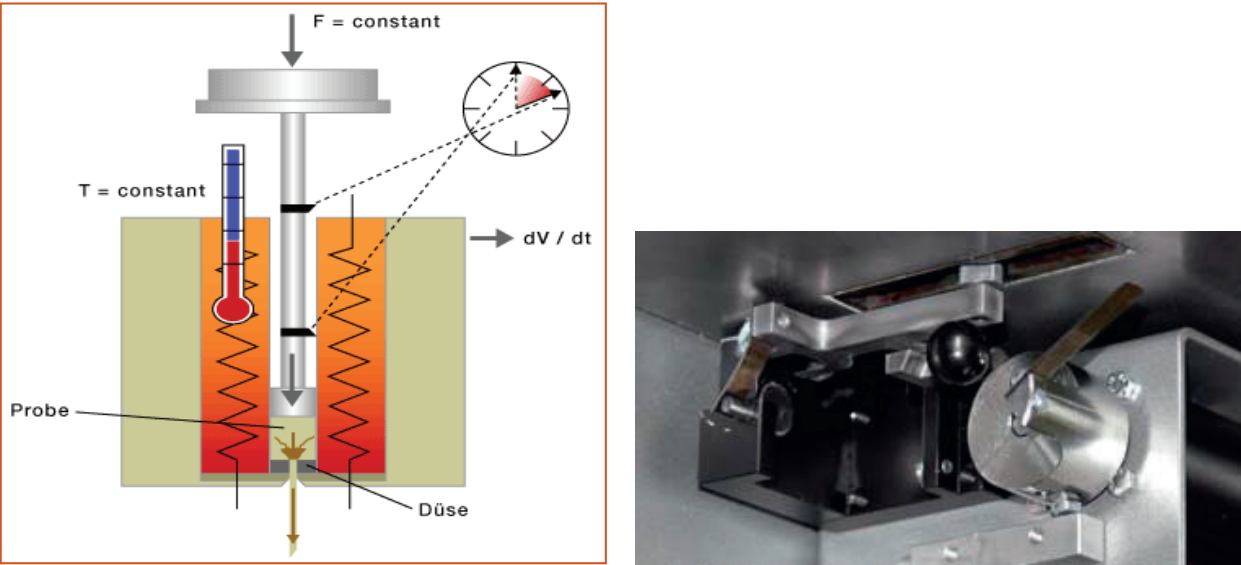


Figure 9.16 Detailed scheme of MFI test (left); photo (right) source: Zwick-Roell

Table 9.4 ISO 1133

International Standard (see ISO section 2)	Materials	Conditions (code)	Temperature (°C)	Load (kg)
ISO 1622-1	PS	H	200	5.00
ISO 1872-1	PE	D	190	2.16
ISO 1872-1	PE	E	190	0.325
ISO 1872-1	PE	G	190	21.60
ISO 1872-1	PE	T	190	5.00
ISO 1873-1	PP	M	230	2.16
ISO 2580-1	ABS	U	220	10.00

International Standard (see ISO section 2)	Materials	Conditions (code)	Temperature (°C)	Load (kg)
ISO 2897-1	PS-I	H	200	5.00
ISO 4613-1	E/VAC	B	150	2.16
ISO 4613-1	E/VAC	D	190	2.16
ISO 4613-1	E/VAC	Z	125	0.325
ISO 4894-1	SAN	U	220	10.00
ISO 6402-1	ASA, ACS, AES	U	220	10.00
ISO 7391-1	PC	W	300	1.20
ISO 8257-1	PMMA	N	230	3.80
ISO 8986-1	PB	D	190	2.16
ISO 8986-1	PB	F	190	10.00
ISO 9988-1	POM	D	190	2.16
ISO 10366-1	MABS	U	220	10.00

Conditions (code)	Temperature (°C)	Load (kg)
A	250	2.16
B	150	2.16
D	190	2.16
E	190	0.325
F	190	10.00
G	190	21.6
H	200	5.00
M	230	2.16
N	230	3.8
S	280	2.16
T	190	5.00
U	220	10.00
W	300	1.2
Z	125	0.325

9.4.2 MVI and MVR

These are the same tests as the MFI but the values used are referred to the volume coming through the nozzle after 10 minutes. Values are indicated in cubic centimeters per 10 minutes.

9.5 Weathering

There are some factors that influence the weathering of plastics: solar radiation, temperature, and humidity.

- *Solar radiation:* Solar radiation on Earth is the energy received from the Sun.

- *Temperature:* The areas subjected to high radiation also tend to be the most exposed to temperature. Both increase usually near the Equator and decrease with increasing latitude. High temperatures influence the effects of light and accelerate the degradation.
- *Humidity:* Humidity contributes to degradation through chemical reactions and by generating hydrolytic stress due to its absorption and loss.



Figure 9.17 Effect of weathering in plastics; source: Atlas-Aimplas

Table 9.5 Resistance to Aging of Some Plastics

	Destabilized degrees		Stabilized degrees	
Thermoplastics	Valuation	Years (approx.)	Valuation	Years (approx.)
PE	bad	1 year	good	some years
PTFE	very good	1 year		
PP	bad	1 year	good	10–30 years
POM	bad	¼ year	good	NDA
PS	bad	¼ year	moderate	NDA
PA	bad	1 year	good	some years
PC	bad	2 years	good	more than 5 years
ABS	bad	½–1 year	good	some years
SAN	moderate	1–2 years	moderate	NDA
PMMA	moderate	5–25 years	good	some years

9.5.1 XW Weather-Ometer

9.5.1.1 Accelerated Weathering

UV radiation is applied through xenon and carbon arc light lamps. The samples are wetted with water sprayed at 32 °C for 18 minutes and also with water sprayed at 63 °C for 102 minutes. Each cycle lasts 120 minutes.

A test of 400–1,000 hours equals to one year in Florida. This test is faster than natural tests.

These test sets (Figure 9.18) can simulate climate factors, radiation, heat, etc.

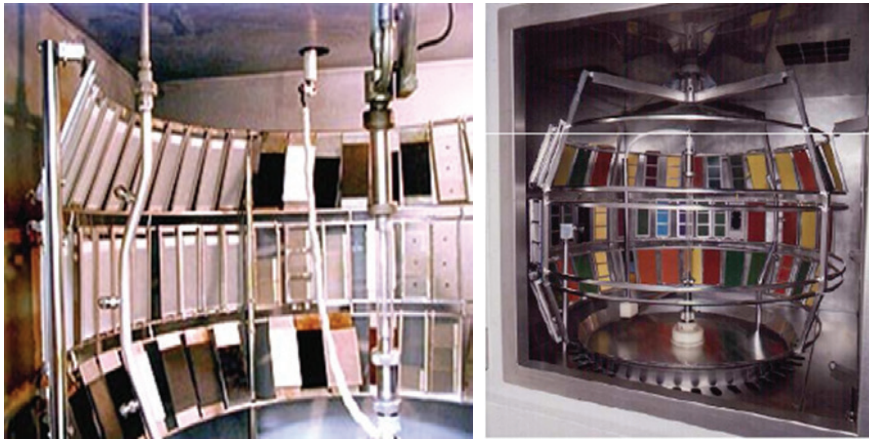


Figure 9.18 Interior of artificial light aging and weathering test machine; source: Atlas-Aimplas

9.5.1.2 Tests in Natural Environments

Environmental aging

These tests are performed in USA (Arizona and Florida) and the desert of Kalahari, in Africa. They are long time tests but bring good results.



Figure 9.19 EMMA: Equatorial Mount with Mirrors for Acceleration; source: Atlas-Aimplas

UV or weather resistance is the resistance to change of properties caused by the influence of sunlight, UV radiation, and environmental conditions.

Dry heat tests are performed in the desert of Kalahari and humidity hot tests, in Florida.

9.5.2 Radiation

Solar radiation has a wavelength from 100 to 400 nm.

- UVA: from 315 to 400 nm
- UVB: from 280 to 315 nm
- UVC: from 100 to 289 nm (this radiation does not reach the Earth)

UV radiation index:

Low	< 2	1-2: one can stay outside
Moderate	3-5	3-7: one has to stay in the shade around midday, wear shirts, sunscreen, hats
High	6-7	

Very high 8–10 8–11: protection is essential. One cannot go out around midday.
 Extreme > 11

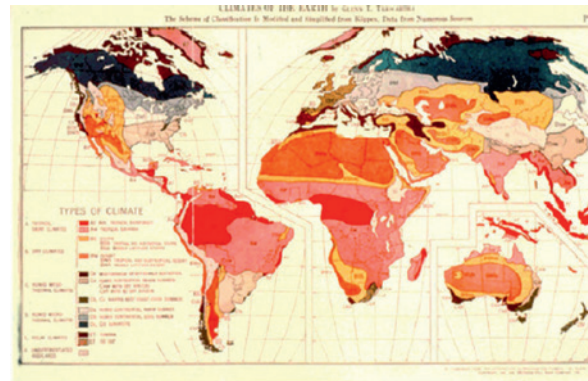


Figure 9.20 Radiation in the world;
 source: Atlas-Aimplas

9.6 Stress in Transparent Materials

9.6.1 Residual Stress Measurement in Transparent Materials

The residual stress and the molecular orientation of a product give us information on how this product will perform. The presence or absence of stress is decisive on the behavior of parts in applications such as packaging, medicine, cosmetics, etc. Stresses are usually generated by the polymers processing methods. Molecular chains are subjected to different contractions, cooling rates, flows, and so on. In some polymers the molecular orientations are intentionally induced to improve the biaxial orientation properties of PET or PS. In other cases, stresses should be avoided since the surface develops some susceptibility to cracking in the presence of solvents and detergents.

The method of evaluating stresses in transparent plastics is based on the concept of photoelastic response of transparent materials. The refractive index of a material is directional and its change of direction is proportional to the stress. Transformation methods produce plastic stress and generate birefringence (orientation in the refractive index). Birefringence is an optical anisotropy: the polarized rays passing through the piece under evaluation vibrate at different speeds depending on the internal stresses. This causes color differences due to the phase difference. Brewster's law states that the index of refraction of a material is directional. The change in this refractive index is proportional to stress.

9.6.2 Method

The most basic way to see the stresses of a transparent piece involves placing a sample of the piece between two sheets of polarized lenses illuminated. When these sheets are aligned, stresses become visible. In some cases the color can be used as evaluation, as each one corresponds to a degree of stress (see Table 9.6).

The measurement of birefringence can be made with a calibrated compensator. It is a graduated strip placed in series with the sample to be tested. The operator moves the strip until the observed area fades to black. The black color indicates that the slowdown of the control strip is equal and opposite value to the analyzed area of the sample. The scale compensator strip indicates the retardation value.

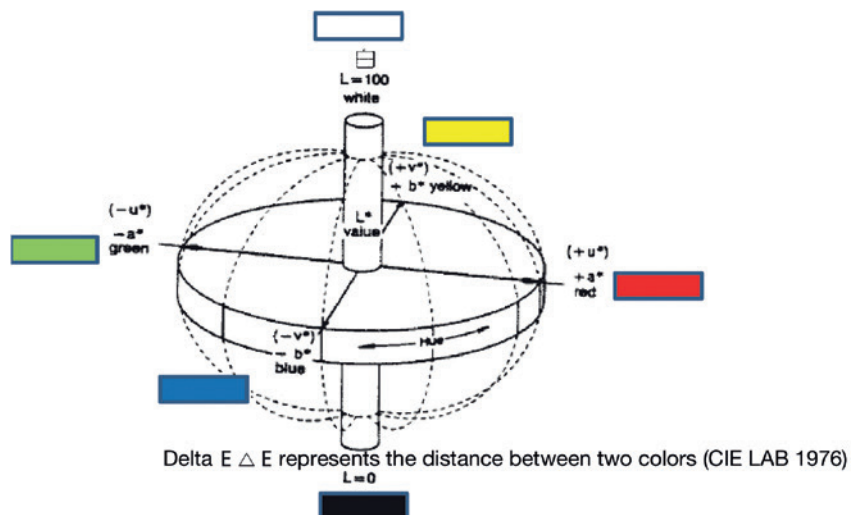
The compensator measurement is an ASTM standard procedure: ASTM D 4093-95 Standard

Table 9.6 Colors and Retardation on Polarized Lenses

COLOR	RETARDATION (nm)
BLACK	0
GRAY	150
WHITE YELLOW	250
YELLOW	300
ORANGE	450
RED	500
INDIGO VIOLET	570
BLUE	600
BLUE GREEN	650
GREEN YELLOW	750
YELLOW	850
ORANGE	950
RED	1050
INDIGO VIOLET	1140
GREEN	1300
GREEN YELLOW	1400
PINK	1500
VIOLET	1700
GREEN	1750

9.7 Colors: *Lab* System

L, a, b Color Coordinates



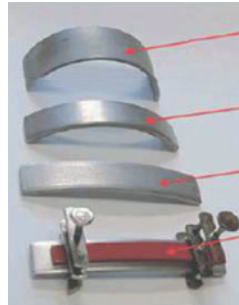
$$\Delta E = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2}$$

9.8 Chemical Resistance and Stress Cracking



The test specimen with a certain level of stress is placed through a radio shaped tool, so the specimen is fixed under stress. Then, various reagents or chemical substances are applied to see whether there is chemical resistance under stress.

Test Method



Test method

Bending test tubes in support

Radius 62 = 1.6% strain

Radius 110 mm = 0.9% strain

Radius 220 mm = 0.5% strain

Radius 1,000 mm = 0.1% strain



Regulations:

ASTM D1939-94

Determine stress in ABS

ISO 22088-3: 2006

Determine resistance to ESC

Underwriters Laboratories (UL); Yellow Card (Source: UL)

9.8.1 Electrical Properties

9.8.1.1 HWI: Hot Wire Ignition

Test specimens are heated with a hot wire that dissipates certain level of electric energy. The HWI classification corresponds to the time to ignite.

T in seconds	PLC Category
> 120	0
60–120	1
30–60	2
15–30	3
7–15	4
< 7	5

9.8.1.2 HAI: High Ampere Arc Ignition

The HAI represents the number of arcs needed to ignite the material both on its surface and at some distance of it.

The test reaches 200 arcs or ignition of the material. Arcs are intermittent.

Number of arcs	PLC Category
> 120	0
60–120	1
30–60	2
15–30	3
< 15	4

9.8.1.3 Time of Arc Resistance (TAR) ASTM D 495

The TAR is the time of resistance (in seconds) of a material before forming a conductive path when an intermittent high voltage and low current arc is applied to it.

TAR (Time of Arc Resistance) in seconds	PLC Category
< 420	0
360–420	1
300–360	2
240–300	3
180–240	4
120–180	5
60–120	6
< 60	7

The material can fail in different ways (being conductive on fire, starting a charred step for the current).

9.8.1.4 HVAR: High Voltage Arc Resistance to Ignition

The HVAR is the resistance time (in seconds) of a material to ignition when it is subjected to a high voltage and a low intensity.

TI (Time of Ignition) in seconds	PLC Category
> 300	0
120–300	1
30–120	2
< 30	3

9.8.1.5 HVTR: High Voltage Arc Tracking Rate

The HVTR is the ratio in millimeters per minute at which a conductive path occurs on the surface of a material.

MMPM in millimeters per minute	PLC Category
0–10	0
> 10–25.4	1
> 25.4–80	2
> 80–150	3
< 150	4

9.8.1.6 CTI: Comparative Tracking Index

As explained in Section 9.3.4, CTI is the voltage that causes a conductive path in a material after pouring 50 drops of ammonium chloride at 0.1%.

CTI (V)	PLC Category
> 600	0
400–600	1
250–400	2
175–250	3
100–175	4
< 100	5

9.8.1.7 RTI: Relative Temperature Index

In this test, after 60,000 hours, the tested material must maintain at least 50% of its initial properties.

Temperature aging

As explained in Section 9.2.5, there are three types of RTI temperature:

- Electrical RTI
- RTI with mechanical impact
- RTI without mechanical impact

Internal Stress Test for Injection Molding Parts

ASTM D1939 for ABS, ISO 21088-3: 2006

First part

Parts are submerged in glacial acetic acid (10% concentration) for 30 seconds. Then, they are rinsed with water. Finally, they are checked visually for stress marks.

Second part

Parts are submerged in glacial acetic acid for 2 minutes. Then, they are rinsed with water. Finally, they are checked visually for stress marks.

This test must be done with original specimens that have been injected at least a few hours in advance in order to allow time for their thermal and structural stabilization.

Properties of Plastics: Understanding Technical Data Sheets

Here are listed some of the most characteristic properties of plastic materials. These properties are used to compare materials and to help select the most appropriate one for each application:

- Density
- Melt flow index (MFI)
- Elastic modulus or tensile modulus
- Tensile strength
- Impact resistance
- Cold flow (creep)
- Creep modulus
- Softening temperature (Vicat)
- Heat deflection temperature (HDT)

These properties, along with some others, are characterized in the technical data sheet (TDS) by the manufacturers.

Data Sheet Example of a PA66 30% Fiberglass (Source: DuPont)

Zytel NC010 70G30HSL

Table 10.1 Mechanical Properties

Zytel® 70G30HSL NC010 is a 30% glass fiber reinforced, heat stabilized polyamide 66 resin for injection molding.

Property	Test Method	Units	Value	
			DAM	50%RH
Identification				
Resin Identification	ISO 1043		PA66-GF30	
Part Marking Code	ISO 11469		>PA66-GF30<	
Mechanical				
Stress at Break	ISO 527	MPa (kpsi)	195 (28.3)	125 (18.1)
Strain at Break	ISO 527	%	3.4	5
Tensile Modulus	ISO 527	MPa (kpsi)	10000 (1450)	7200 (1045)
Tensile Creep Modulus	ISO 899	MPa (kpsi)		
1h				6800 (990)
1000h				5100 (740)
Notched Charpy Impact Strength	ISO 179/1eA	kJ/m ²		
-30°C (-22°F)			10	10
23°C (73°F)			12	16
Unnotched Charpy Impact Strength	ISO 179/1eU	kJ/m ²		
-30°C (-22°F)			70	73
23°C (73°F)			82	93

Table 10.2 Thermal Properties

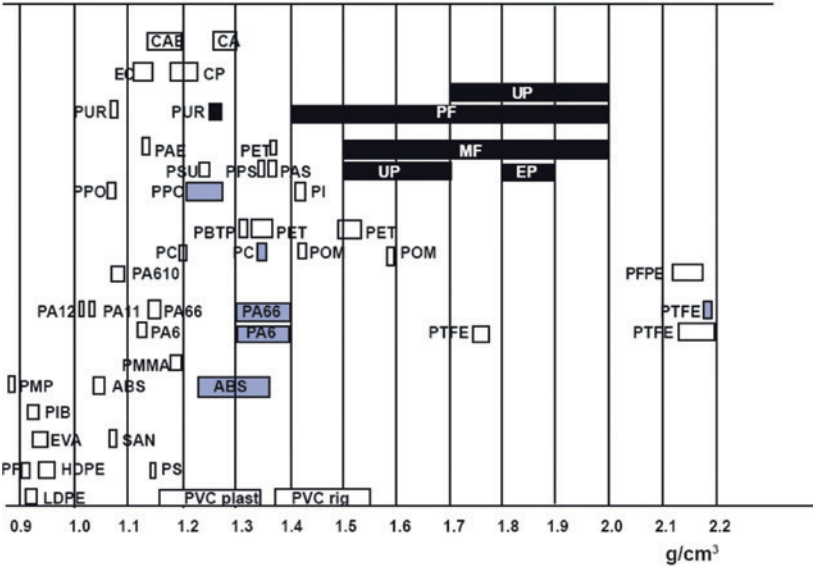
Property	Test Method	Units	Value	
			DAM	50%RH
Thermal				
Deflection Temperature	ISO 75f	°C (°F)		
0.45MPa			261 (502)	
1.80MPa			248 (478)	
Melting Temperature	ISO 11357-1/-3	°C (°F)		
10°C/min			263 (505)	
CLTE, Normal				
23 - 55°C (73 - 130°F)	ISO 11359-1/-2	E-4/C (E-4/F)	1.07 (0.60)	
CLTE, Parallel				
23 - 55°C (73 - 130°F)			0.22 (0.12)	
Vicat Softening Temperature	ISO 306	°C (°F)		
50N			250 (482)	

Table 10.3 Electrical Properties

Electrical				
Surface Resistivity	IEC 60093	ohm	>1E15	1E13
Relative Permittivity	IEC 60250			
1E2 Hz			4.4	10.8
1E6 Hz			4.1	4.6
Volume Resistivity	IEC 60093	ohm m	>1E15	1E9
Dissipation Factor	IEC 60250	E-4		
1E2 Hz			70	4600
1E6 Hz			150	650
Electric Strength	IEC 60243-1	kV/mm (V/mil)		
1.0mm			38 (964)	32 (812)
CTI	IEC 60112	V	400	
CTI	UL 746A	V		
3.0mm			400	

10.1 Density

The density of a material is the mass per unit volume, usually expressed in g/cm³.



Some Densities

HDPE:	LDPE:	PP:	PC:	PA12:	ABS:
0.94–0.98	0.89–0.93	0.85–0.92	1.2–1.22	1.01–1.04	1.04–1.22
PS:	PPO:	PA6:	PA66:	PMMA:	
1.04–1.08	1.05–1.07	1.12–1.15	1.13–1.16	1.16–1.2	

10.2 Bulk Density

Bulk density is the mass or amount of material in pellet form contained in a unit volume. It is often used in the comparison of materials as granulometry index. Expressed in kg/m^3 , it also serves to determine the amount of material contained in silos, dryers, hoppers, etc.

10.3 Flow Rates

10.3.1 Melt Volume Index (MVI)

The melt volume index is the most widely used reference to determine the fluidity of a material. A capillary rheometer is used to obtain it. A quantity of pellets (previously dried) is inserted into the device and is heated to the test temperature (depending on material; see Table 10.4). Once it melts, a weight is applied (also depending on the material to be tested, see Table 10.4) so that it flows through a calibrated outflow hole.



Figure 10.2 Plastometer to determine melt mass flow rate; source: Zwick-Roell

Thus, a certain amount of material flowing through the rheometer is obtained at a given time. The flow values are expressed in cubic centimeters per 10 minutes ($\text{cm}^3/10 \text{ min}$).

10.3.2 Melt Flow Index (MFI)

The melt flow index, expressed in grams/10 minutes, is obtained much like the MVI. It is necessary to multiply the value obtained by the volume density of the melt at the test temperature. It can also be obtained by weighing the amount of molten material through the capillary rheometer. (See Section 9.4.1 in Chapter 9.)

Table 10.4 Standard Conditions for MFI Test (ASTM D1238 and ASTM D3364)

Condition	Temperature (°C)	Load-Weight (kg)	Pressure (kg/cm ²)*
A	125	0.325	0.46
B	125	2.160	3.04
C	150	2.160	3.04
D	190	0.325	0.46
E	190	2.160	3.04
F	190	21.600	30.40
G	200	5.000	7.03
H	230	1.200	1.69
I	230	3.800	5.34
J	265	12.500	17.58
K	275	0.325	0.46
L	230	2.160	3.04
M	190	1.050	1.48
N	190	10.000	14.06
O	300	1.200	1.69
P	190	5.000	7.03
Q	235	1.000	1.41
R	235	2.160	3.04
S	235	5.000	7.03
T	250	2.160	3.04

*kg corresponds to kilogram-force here.

Polymer	Condition
Acetals (POM)	E, M
Acrylics	H, I
Acrylonitrile butadiene styrene (ABS)	G
Cellulose esters	D, E, F
Nylon (PA)	K, Q, R, S
Polychlorotrifluoroethylene (PCTFE)	J
Polyethylene (PE)	A, B, D, E, F, N
Polyterephthalate (PET)	T
Polycarbonate (PC)	O
Polypropylene (PP)	L
Polystyrene (PS)	G, H, I, P
Vinyl acetal (PVC)	C

Table 10.5 ISO 1133

Condition	Temperature (°C)	Load (kg)
A	250	2.16
B	150	2.16
D	190	2.16
E	190	0.325
F	190	10.00
G	190	21.6
H	200	5.00
M	230	2.16
N	230	3.8
S	280	2.16
T	190	5.00
u	220	10.00
W	300	1.2
z	125	0.325

Table 10.6 Melting Temperatures

Material	Temperature (°C)
PS	70–115
HDPE	125–140
LDPE	105–115
PMMA	120–160
PP	160–170
PA11	180–190
PA6	215–225
PBT	220
PC	220–230
PA66	250–260
PET	250–260

10.4 Tensile Stress, Mechanical Resistance

This test determines the stiffness of the material and its resistance to breakage when subjected to a tensile stress. It can be performed at different temperatures and stretch rates. In this way, different characteristics of the polymer can be obtained.

Yield Stress

Yield stress is the maximum stress level reached before the failure of the material. This peak occurs immediately before the break, and always with deformation.

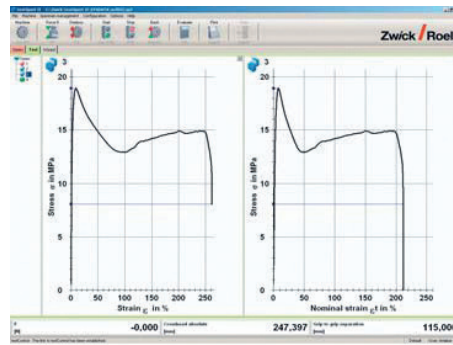
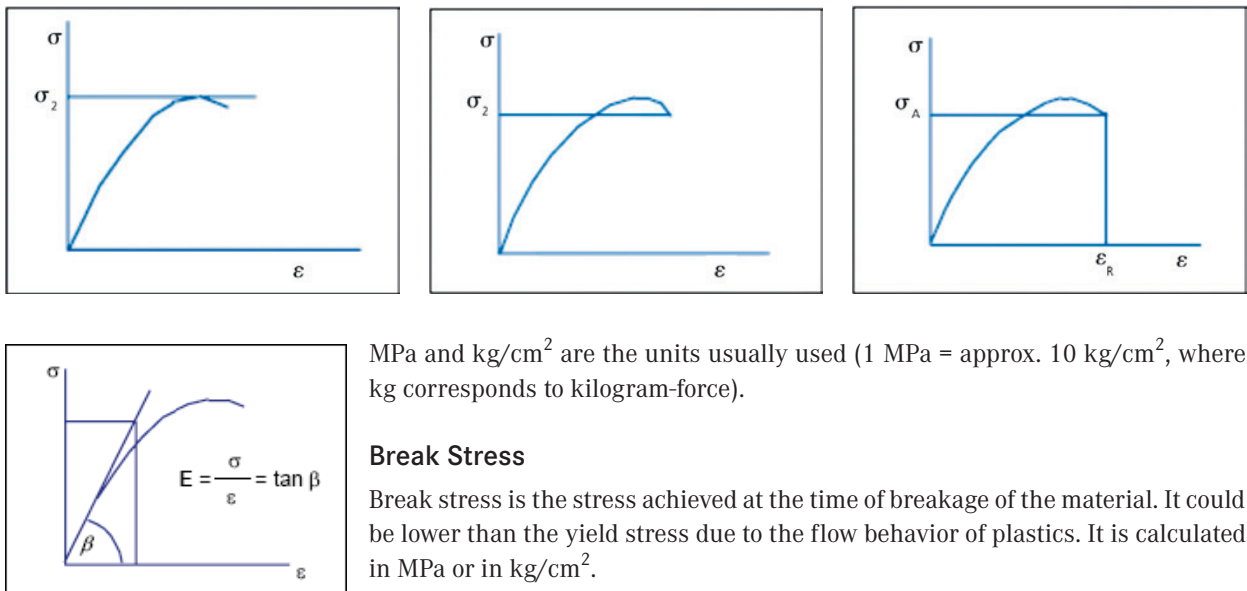


Figure 10.3 Tensile test curve;
source: Zwick-Roell



MPa and kg/cm^2 are the units usually used (1 MPa = approx. 10 kg/cm^2 , where kg corresponds to kilogram-force).

Break Stress

Break stress is the stress achieved at the time of breakage of the material. It could be lower than the yield stress due to the flow behavior of plastics. It is calculated in MPa or in kg/cm^2 .

Strain at Break

Strain at break is the elongation registered when the test piece breaks. This elongation is expressed as a percentage and indicates how the material can be stretched before it breaks.

10.5 Elastic Modulus and Tensile Modulus

During the tensile test, at the beginning of the stress-strain curve (Figure 10.4), we can see an area where the elongation is proportional to the tensile strength. The deformation stress of each material will set the slope of the curve. The tensile modulus is the relationship between stress and strain in the linear region and therefore directly proportional region.

During the tensile deformation of a plastic material, there is a zone where the strain produced by the applied stress could be fully recovered when the effort ceases. From a certain point of tensile deformation, it no longer recovers and is considered permanent. The yield point is the stress level necessary to obtain a permanent deformation of 0.2%.

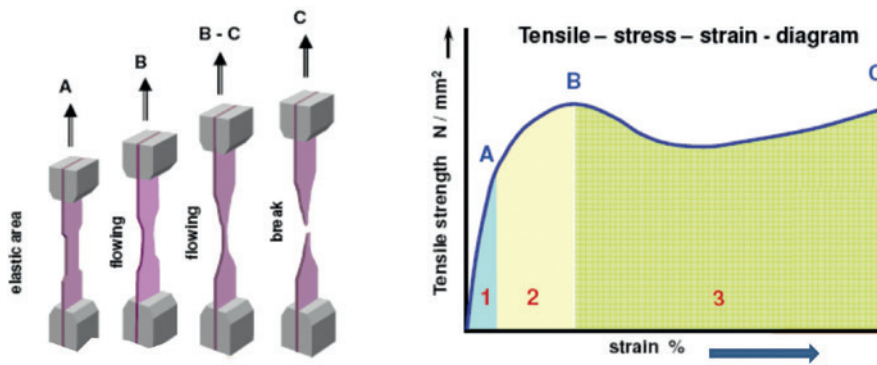


Figure 10.4 Tensile specimen elongation and tensile test curve

Areas in Figure 10.4:

- **Zone 1 (elastic zone):** (reversible) deformation until point A (proportional limit)
- **Zone 2 (stretching):** the material is stretched when pressure increases to point B (yield limit) = tensile stress at yield point
- **Zone 3 (cold flow, creep of material):** reduction or increase of the tensile strength to point C (tensile strength at break)

10.6 Impact Resistance

The impact resistance indicates the toughness of the material, its energy absorption capacity, and its deformation. The values are given in kJ/m^2 , kJ/cm^2 , and J/m .

There are two types of data (1: notched; 2: unnotched) and two types of tests (Izod and Charpy).

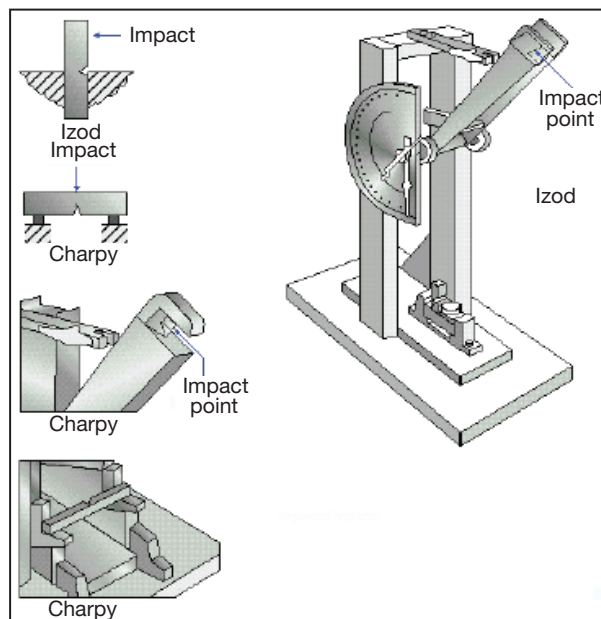
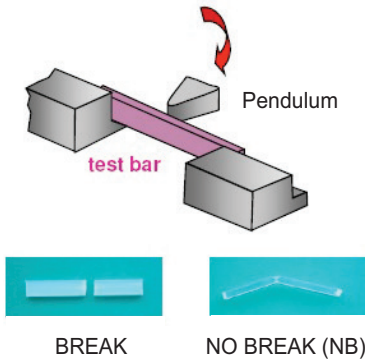


Figure 10.5 Impact test differences; source: Ascamm

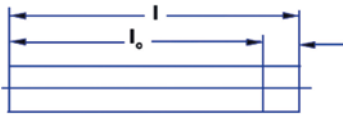
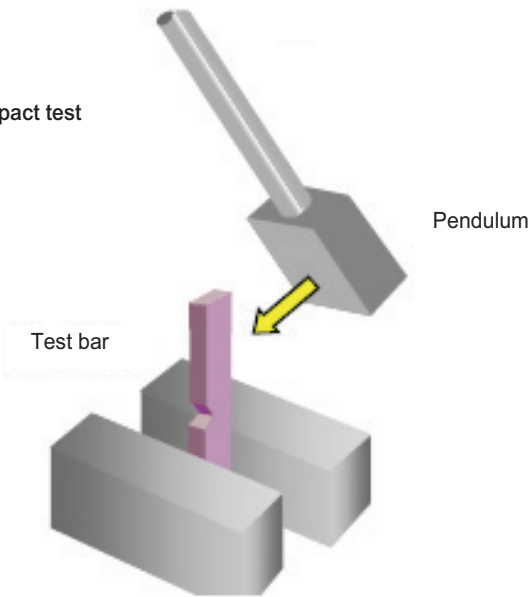
Figure 10.6 Pendulum impact test machine; source: Zwick-Roell



CHARPY IMPACT TEST
Pendulum impacts on test bar



Izod impact test



$$\alpha = \frac{\Delta l}{l_0} \cdot \frac{1}{(T - T_0)}$$

l_0 = length at temperature T_0
 l = length at temperature T
 $\Delta l = l - l_0$

10.7 Coefficient of Linear Thermal Expansion (CLTE)

The coefficient of linear thermal expansion (CLTE) indicates the expansion of the material (its length increases when temperature increases by a certain number of degrees). These values are important when different plastics are joined together or when assemblies with metals or other materials with different CLTEs are performed.

10.8 Vicat Softening Temperature

The Vicat softening temperature is the temperature at which a plastic material rapidly softens. In semi-crystalline thermoplastics, the Vicat temperature is close to the melting temperature, while in amorphous it is close to the glass transition. The test is performed by heating the test specimen and promoting the penetration with a weighed needle.

Vicat can be considered as the limit of short-term use of a material. This value can also indicate the temperature at which a part can be demolded by pushing the ejectors of the mold (Vicat -10°C).

There are different test scales depending on the type of material.

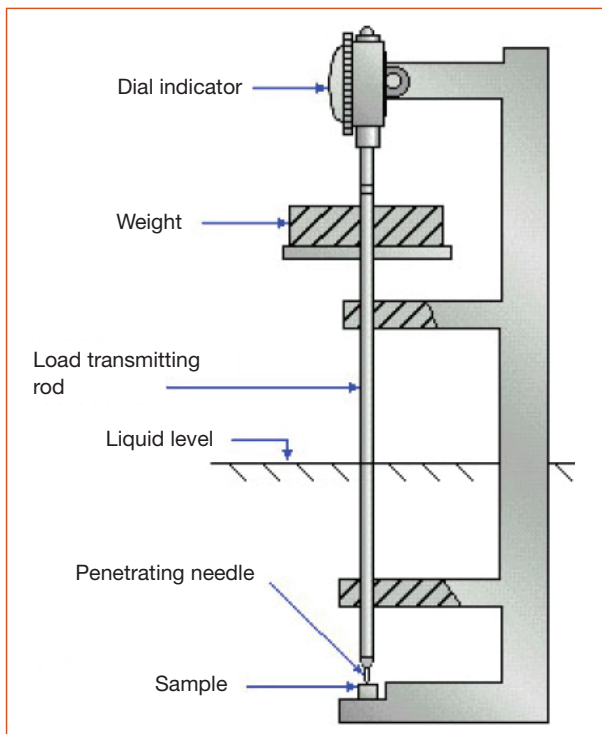


Figure 10.7 Vicat test scheme; source: Ascamm

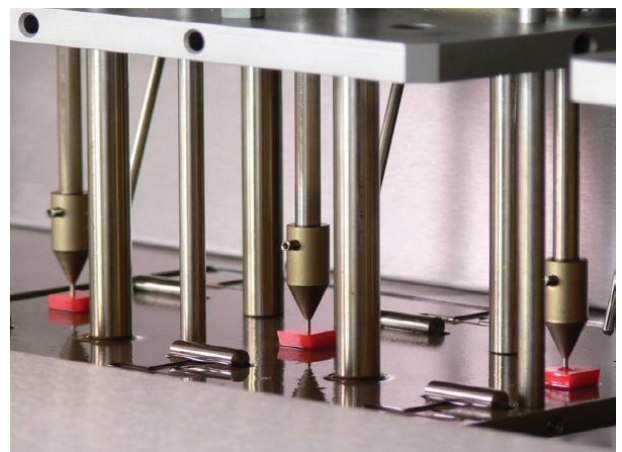


Figure 10.8 Vicat test machine; source: Zwick-Roell

	Load	Temperature increase rate
Vicat A50	10 N	50 °C/h
Vicat A120	10 N	120 °C/h
Vicat B50	50 N	50 °C/h
Vicat B120	50 N	120 °C/h

10.9 Heat Deflection Temperature (HDT or HDTUL)

The heat deflection temperature is the temperature at which a polymer sample test specimen deforms under a specific load. This temperature indicates the ability of a material to serve for a short time and under load.

By applying a permanent stress and increasing the temperature of the specimen at a uniform rate, we can see the effect of temperature on the material stiffness. (HDT/A for a load of 1.80 MPa, HDT/B for a load of 0.45 MPa; see Table 10.7.)

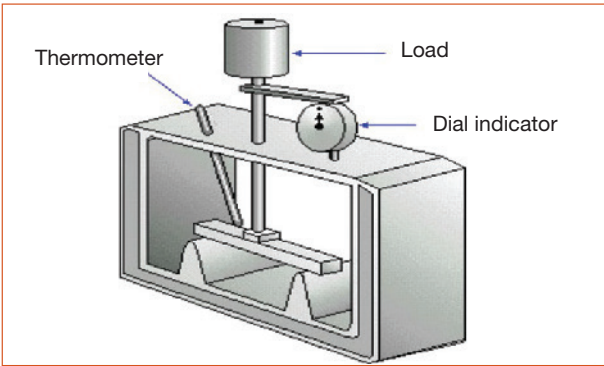


Figure 10.9 HDT test scheme; source: Ascamm



Figure 10.10 HDT machine test detail; source: Zwick-Roell

Table 10.7 Typical Temperatures of Some Materials

Material	HDT (°C)		Vicat (°C)
	A: 1.80 MPa	B: 0.45 MPa	B
PS	83	86	101
SB	83	91	95
SAN	86	95	99
ABS	91	98	101
PC	125–130	135–140	150
PC FV	145	150	155
PE	45	70	75
PTFE	50–60	130–140	110
PP	60	100	105
PA 6	95	190	200
PA 6 FV	200	200	215
PA 66	108	200	200
PA 66 FV	200	200	200
POM	85	150	155



Figure 10.11 Machine test for Vicat and HDT test; source: Zwick-Roell

10.10 Thermal Conductivity

Thermal conductivity indicates the ability of a material to conduct or insulate heat. The test calculates the perpendicular heat flow through a given surface by measuring the differential temperature on both sides of the surface.

Measurement units: $W/(m \cdot K)$

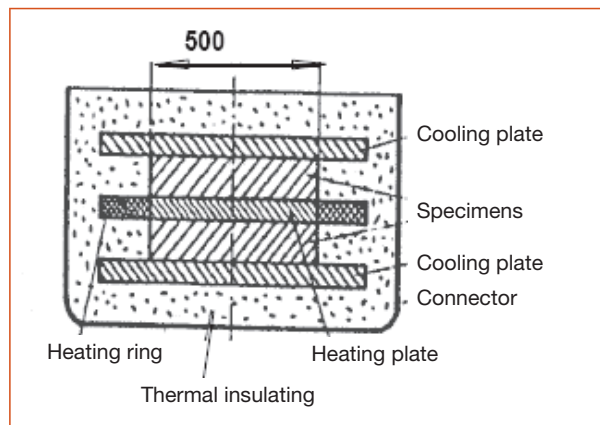


Figure 10.12 Scheme of thermal conductivity test; source: Ascam

10.11 Hardness

Penetration tests determine the hardness of materials to penetration. A weight or stress is applied during a given time.

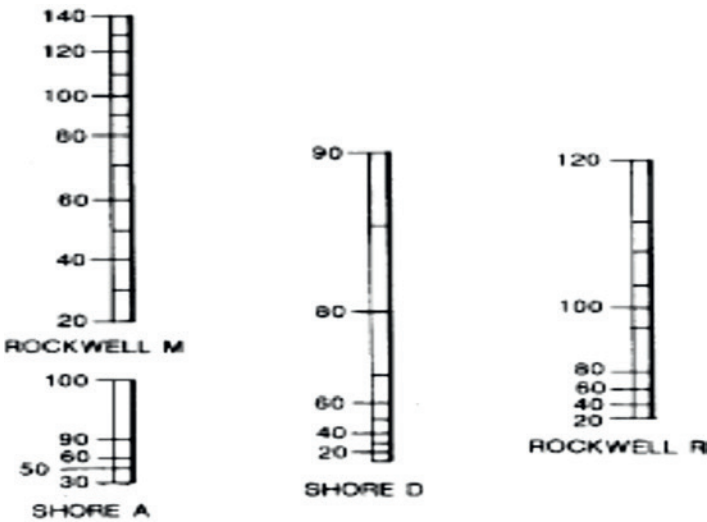
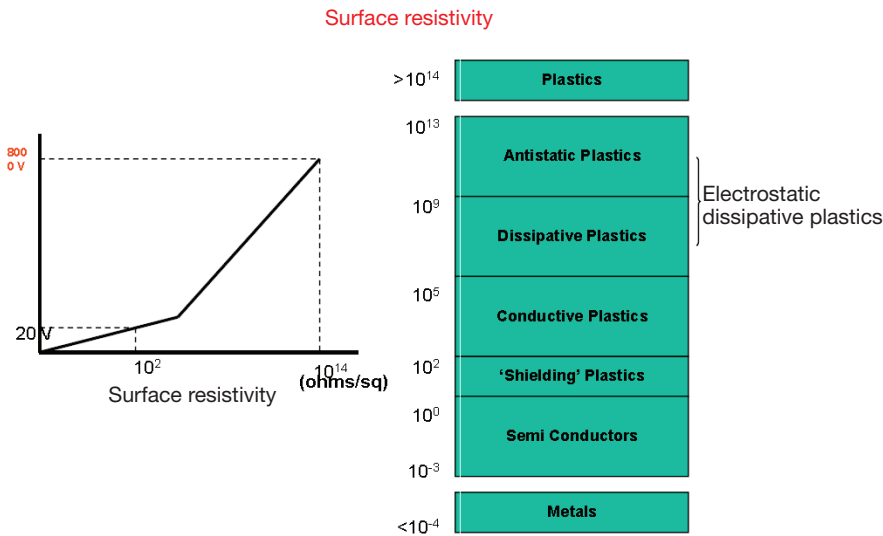


Figure 10.13 Different hardness levels; source: Ascamm

10.12 Surface Resistivity



Surface resistivity is the property of materials regarding their behavior to the passage of electric current. Plastics are generally poor conductors of current, and thus static electricity is easily accumulated on their surface.

10.13 Heat Conductivity

The heat conductivity of plastic is between 0.15 and 0.5 W/(m·K). This value is small compared to metals, whose conductivity is up to 2000 times higher.

Material	Heat Conductivity (W/m·K)
PE	0.32–0.4
PA	0.23–0.29
Steel	17–50
Aluminum	211
Air	0.05

10.14 Yellow Card

UL, Underwriters Laboratories, USA, carry long term temperature tests. These tests indicate the working limit in temperature and time for most thermoplastics.

The UL temperature of a thermoplastic (or relative temperature index, RTI) is the temperature at which a thermoplastic can hold at least 50% of its properties after 60,000 hours (about 7 years).

The RTI temperature can be given by three types of tests, in which the following properties are considered in each case:

- Mechanical without impact
- Mechanical with impact
- Electrical properties

QMF22 Component - Plastics			Friday, November 12, 1999					E6957B	
E I DUPONT DE NEMOURS & CO INC ENGINEERING POLYMERS CHESTNUT RUN PLAZA PO BOX 80713 WILMINGTON DE 19880									
Material Designation: FR515CS									
Product Description: Polyethylene Terephthalate (PET), flame retardant, glass reinforced, color stable, designated "Rynite" furnished as pellets.									
Color	Min. Thick. (mm)	Flame Class	HWI	HAI	RTI Elec	RTI Imp	RTI Str	IEC GWIT	IEC GWFI
ALL	1.5	V-0	-	-	140	140	140	-	-
	2.5	V-0, SVA	-	-	140	140	140	-	-
CTI: -			HVTR: -		D495: -		IEC BP: -		
NOTE	(1) Material designations may be followed by suffix letters and numbers (2) Material designations may be prefixed with "CRA" or "RYN".								
Report Date: 01/09/1996			Underwriters Laboratories Inc®					324299147	
UL94 small-scale test data does not pertain to building materials, furnishings and related contents. UL 94 small-scale test data is intended solely for determining the flammability of plastic materials used in components and parts of end-product devices and appliances, where the acceptability of the combination is determined by ULI.									

Figure 10.14 Example of Yellow Card;
source: DuPont

Part 2

Material Selection

Material Selection Checklist

In this chapter, an example of a checklist to choose a material is shown (source: Ascamm). When selecting a material for an application, one must consider a variety of information. To do this, several guides or checklists are used to consider all aspects that may affect the use of the material.

Part requirements
Type of load ■ Static ■ Dynamic ■ Cyclic ■ Simple impact ■ Repeated impact
Stress ratios ■ Static ■ Dynamic ■ Compression, tension, bending stress amplitude
Deformation load ■ Tension, compression, etc.
Apparent modules ■ Includes yield stress
Load direction
Safety factors
Size
Tolerance requirements ■ Dimensional stability ■ Coefficient of linear thermal expansion (CLTE)
Surface ■ Surface hardness ■ Coefficient of friction
Application environment – Product life
Ambient ■ Humidity ■ Water ■ Chemical compounds ■ Temperatures (minimum, maximum, and average) ■ UV radiation ■ Microwave radiation ■ Sterilization ■ Time
Safety factors

Aesthetic limitations
Shapes
Colors
Surface finishings: welding lines, parting lines, inlets
Decoration: printing, chroming, galvanizing, engraving
Costs
Current product cost
Amount of product considering the chosen manufacturing process
Mold cost
Removing finishing operations
Redesign of component to simplify the product
Component weight
Price of material
Warehousing and distribution
Sector regulations
Flame resistance
Food approval
Nontoxic additives
Electricity
Military
Recycling

11.1 Technical Specifications

Specifications	Safety regulations	Oxygen limit
		Flammability (UL 94 classification)
		Food contact
		Medical criteria
		Contact with drinking water
		RoHS
	Sector regulations	Automotive (PSA, VW)
		Electronics (UL, CTI, glow wire)
		Appliances (RAL, UL)
		Medicine, packaging (FDA, BGA)
Environment	Resistance to chemicals	Solvents
		Water/humidity; chlorinated water
		Acids
		Gasoline, oil, etc.
		Detergents
		Stress-cracking

	Temperatures	High-low time
		Continuous temperature resistance
		Expansion
		Vicat
		HDT
		RTI (with impact, without impact)
Structural properties	Resistance	Flexural modulus
		Traction modulus (stiffness/flexibility)
		Impact
		Traction resistance
		Bending resistance
		Fatigue creep resistance
	Others	UV
		Hydrolysis
	Hardness	Shore A, Shore D, Rockwell
	Rigidity	
Design considerations	Dimensions	Shrinkage
	Aesthetic	
	Wear	Abrasion
	Friction	
	Mounting	
	Color	
Physical	Density	
	Viscosity	Fluidity
Electrical	Insulation	Tracking, CTI
		Electrical conductivity
		Cross, surface resistivity
		Arc resistance
		Dielectric constant

11.2 Target Factor Values

			Indicator	Regulations	Magnitudes
Specifications	Safety regulations	Oxygen limit		ISO	Earth's atmosphere (21%)
		Flammability (UL 94 classification)	Combustibility index	UL 94	HB-V0-V1-V2-5V-5VB-5VA
		Food contact	European FDA, American FDA		
		Medical criteria	Pharmacopoeia, USP		
		Contact with drinking water	WRAS, NSF, KTW		
		RoHS			

			Indicator	Regulations	Magnitudes
	Sector regulations	Automotive (PSA, VW)	QK, TL		
		Electronics (UL, CTI, glow wire)			
		Appliances (RAL, UL)	RAL		
		Medicine, packaging (FDA, BGA)			
Environment Solvents	Resistance to chemicals				
		Water/humidity; chlorinated water			
		Acids			
		Gasoline, oil, etc.			
		Detergents			
		Stress-cracking			
	Temperatures	High-low time			
		Continuous temperature resistance			
		Expansion	Linear dilatation coefficient (CLTE)	ASTM D696	%
		Vicat	Vicat (10–50 N)	ISO 306	°C
		HDT	HDT (0.45–1.8 MPa)	ISO 75	°C
		RTI (with impact, without impact)	RTI: Relative temperature index	UL 7468	°C
Structural properties	Resistance	Flexural modulus	Flexural modulus	ISO 178	MPa
		Traction modulus (stiffness/flexibility)	Traction modulus, traction resistance	ISO 527	MPa
		Impact	Impact resistance (Charpy/Izod)	ISO 180-ISO 179	kJ/m ²
		Traction resistance	Traction resistance (break, yield)	ISO 527	MPa
		Bending resistance	Bending resistance	ISO 178	MPa
		Fatigue creep resistance	Creep graphics		
	Others	UV			
		Hydrolysis			
	Hardness	Shore A, Shore D, Rockwell	Shore A, Shore D, Rockwell	ISO 2039-ISO 868	
	Rigidity		Flexural modulus	ISO 178	MPa

			Indicator	Regulations	Magnitudes
Design considerations	Dimensions	Shrinkage	Shrinkage	ISO 2577	%
	Aesthetic				
	Wear	Abrasion	TABER	ASTM D1044	mg/1000 cycles
	Friction		Friction, wear coefficient		
	Mounting		Linear expansion coefficient (CLTE)	ASTM D696	
	Color				
Physical	Density			ISO 1183	g/cm ³
	Viscosity	Fluidity	MFI, MVI	ISO 1133	g/10 min, cm ³ /10 min
Electrical	Insulation	Tracking, CTI	CTI: comparative tracking index	ICE 60112	volts
		Electrical conductivity	Surface and volumetric conduction		kV/mm
		Cross, surface resistivity	ASTM D257		ohms/cm
		Arc resistance			
		Dielectric constant	ASTM D150		
Comments:					

Material Selection



Electrical



Flame Retardant



Flexible



High Temperature



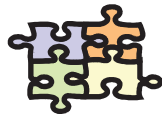
Metal Replacement



Tough-Strong



Transparent



Injection 2 K



Chemical Resistance

The information contained in the following pages has been obtained from several data sheets from various manufacturers of polymers. This information is for guidance only and does not represent the wide variety of manufacturers and materials available on the market.

If you decide to use some of the recommendations presented here, be careful. The author does not assume any responsibility for incidents or accidents, damages to equipment or injuries to people, or any unfavorable outcomes that may occur.

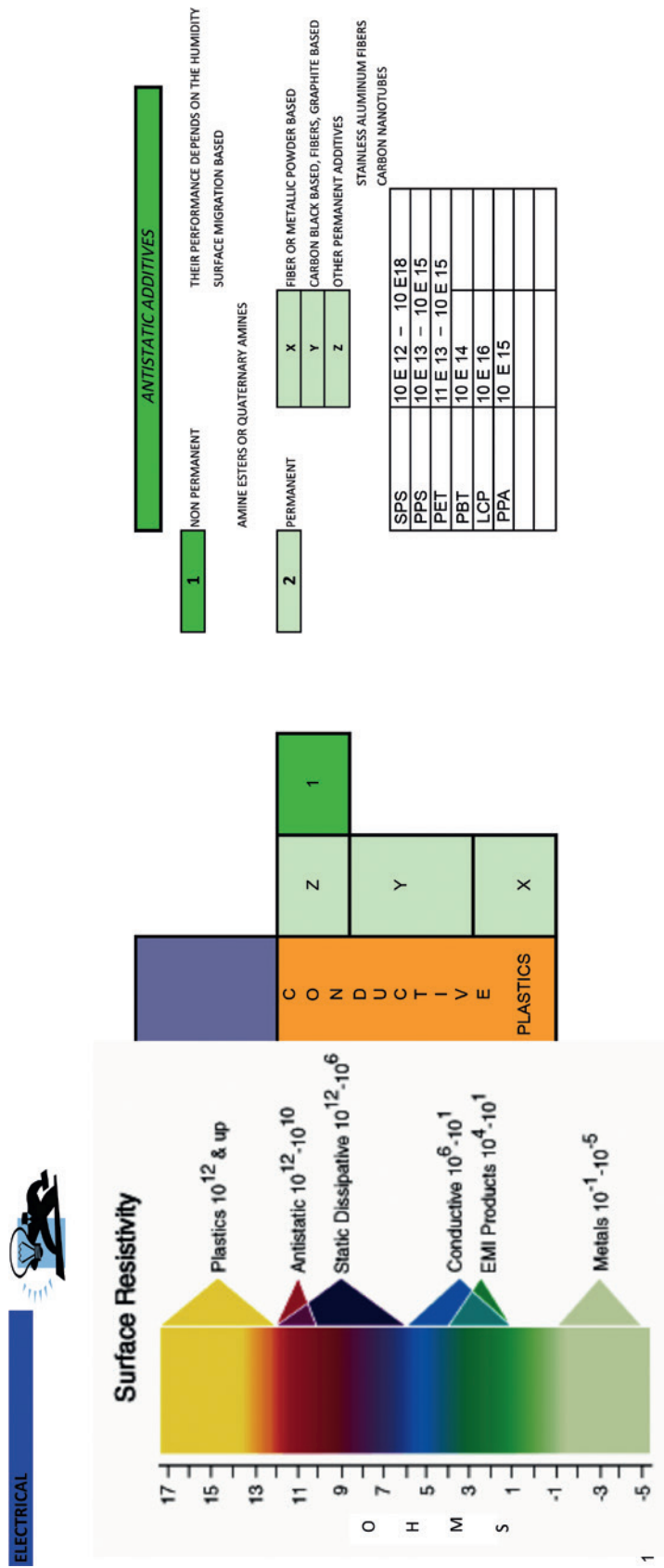


Figure 12.1 Surface resistivity: Most of the polymers on the market do not conduct electricity. (Plastics are electric insulators.) Their surface resistivity values are between 10^{15} and 10^{17} ohms

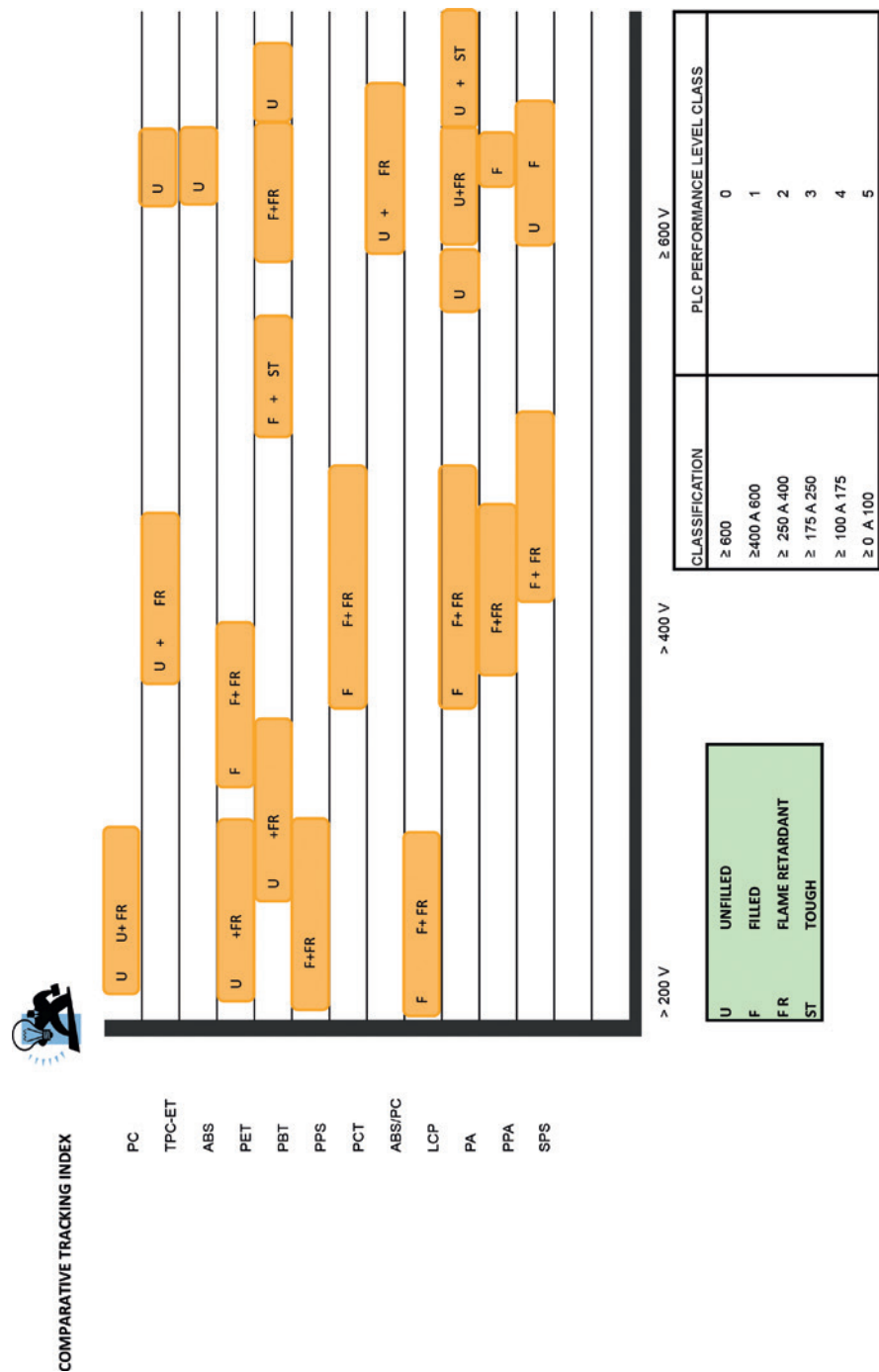


Figure 12.2 Comparative tracking index: voltage that causes tracking after applying 50 drops of ammonium sulfate

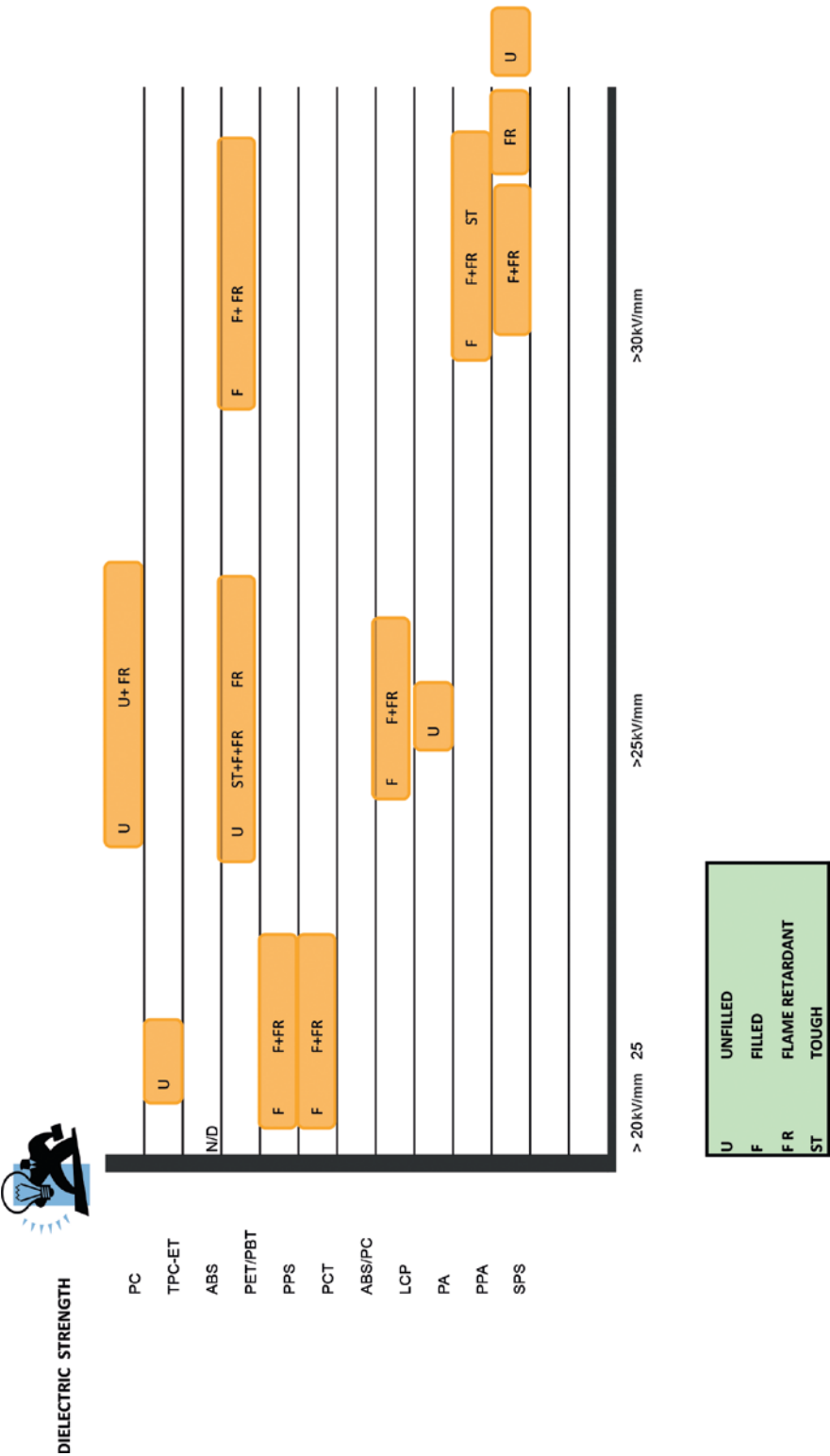


Figure 12.3 Dielectric strength: voltage at which insulating properties are lost

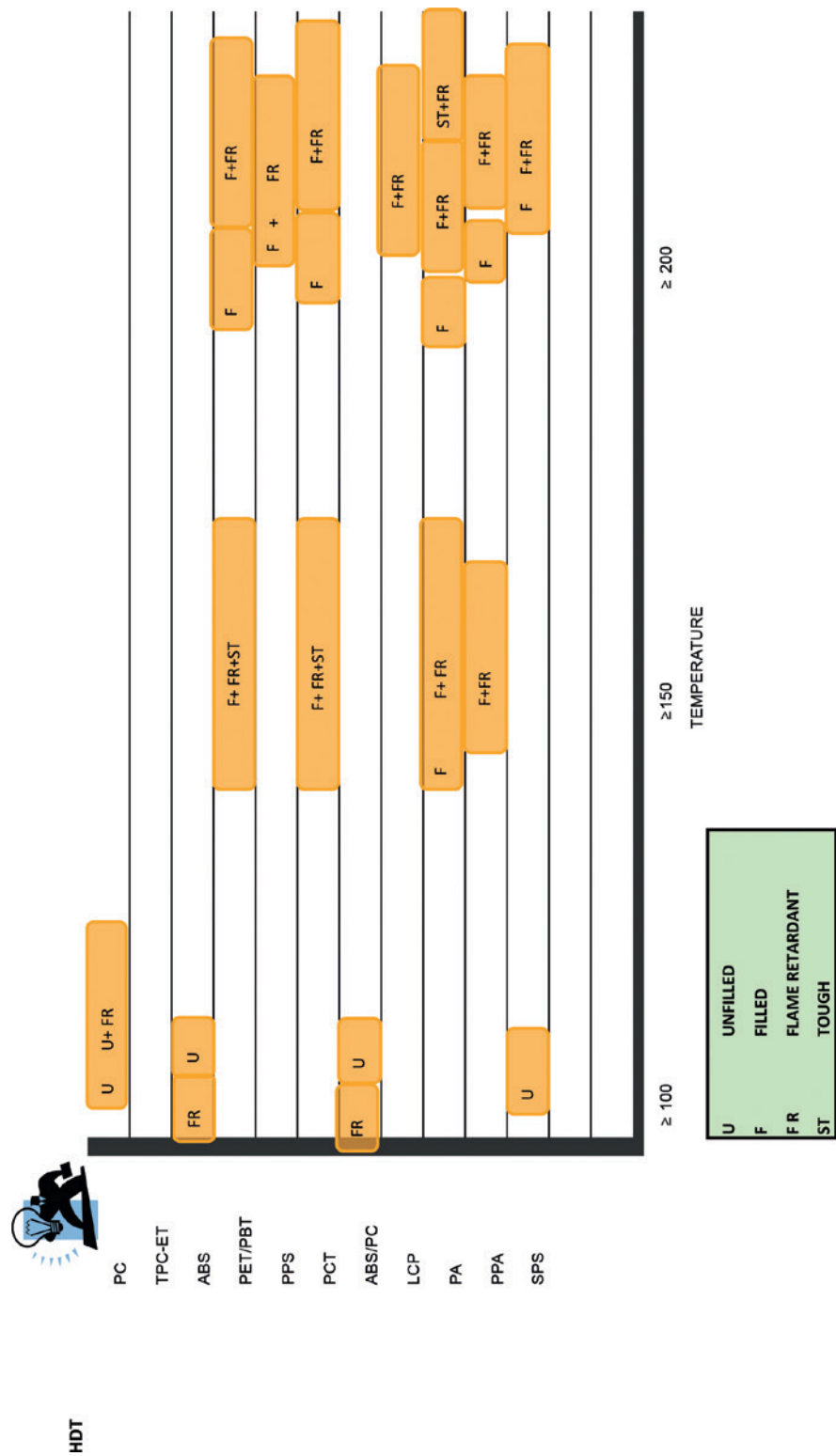


Figure 12.4 HDT

HOT WIRE IGNITION

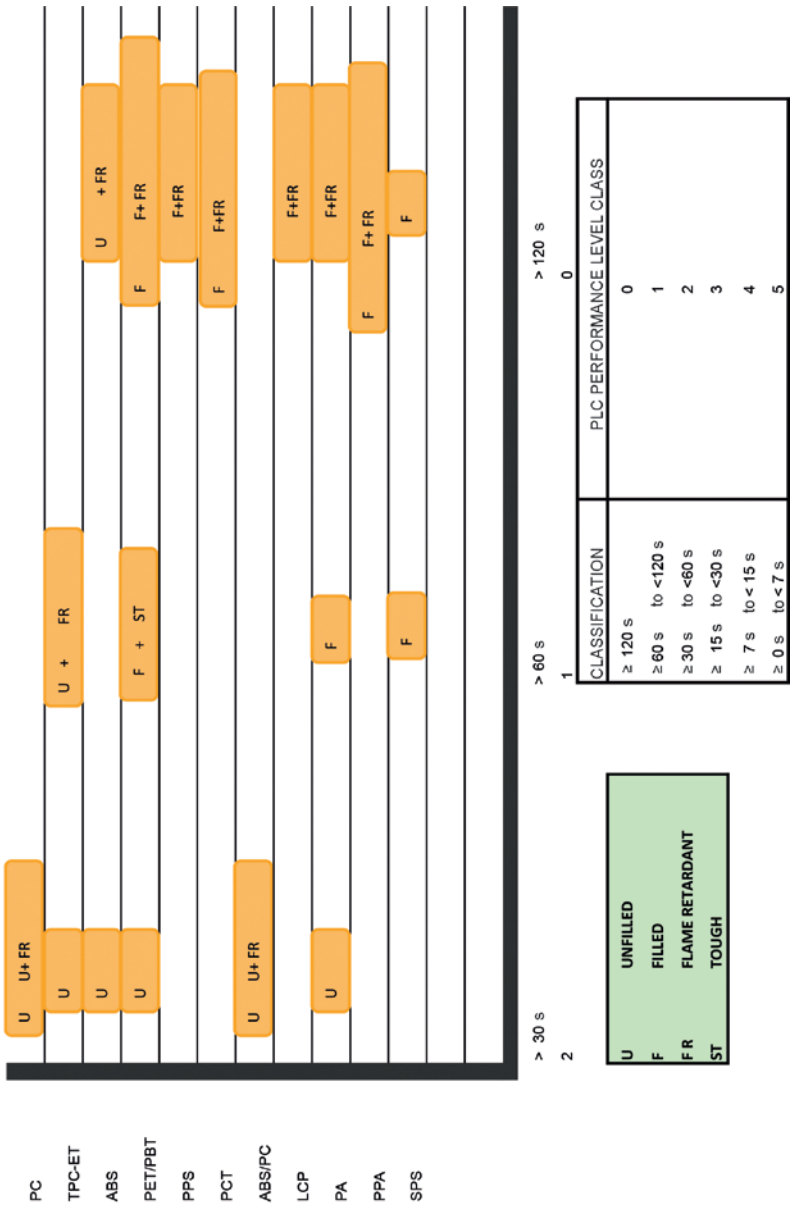


Figure 12.5 Hot wire ignition: Contact with hot wire through which an electrical intensity is applied. Time needed for ignition or burning

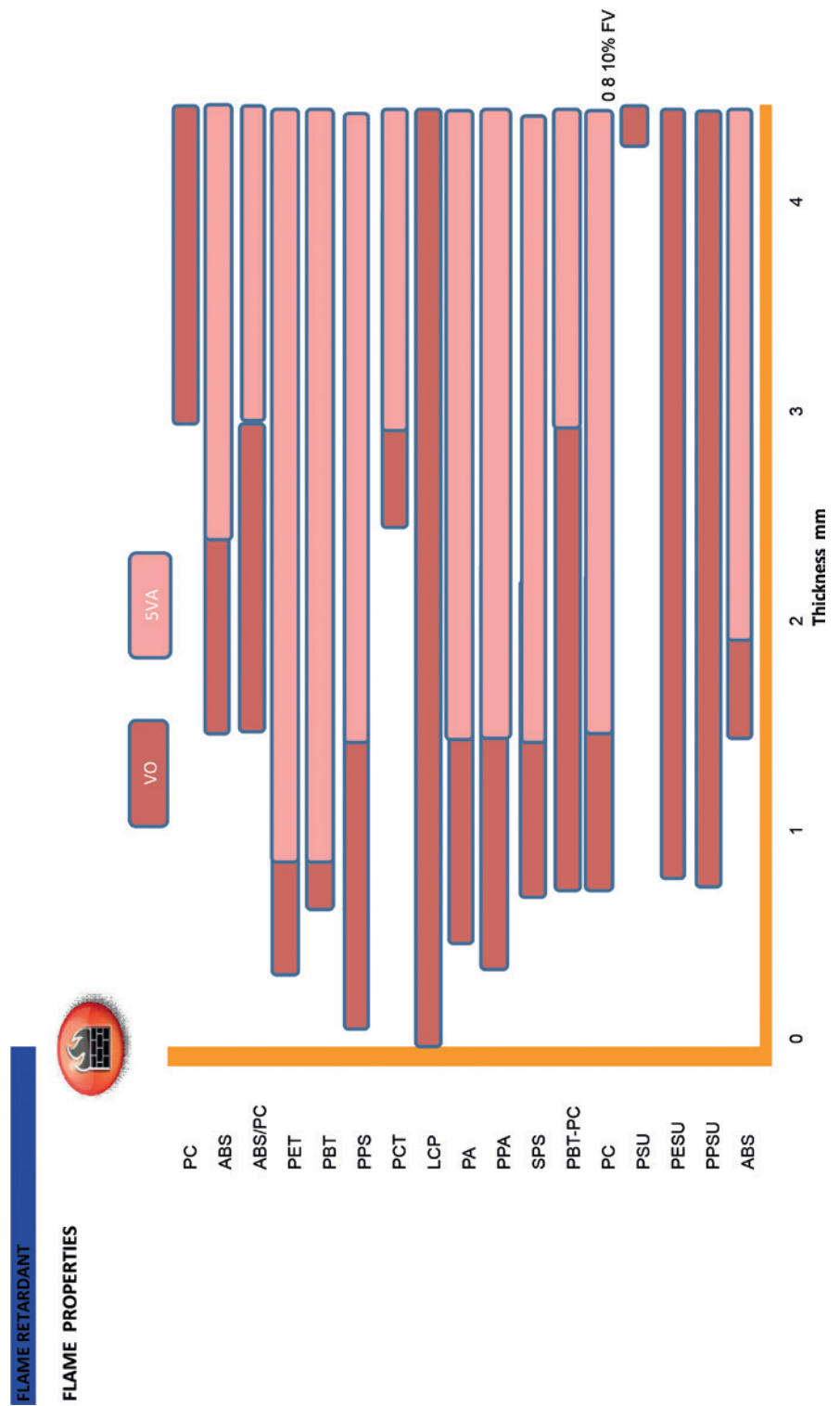


Figure 12.6 Flame properties

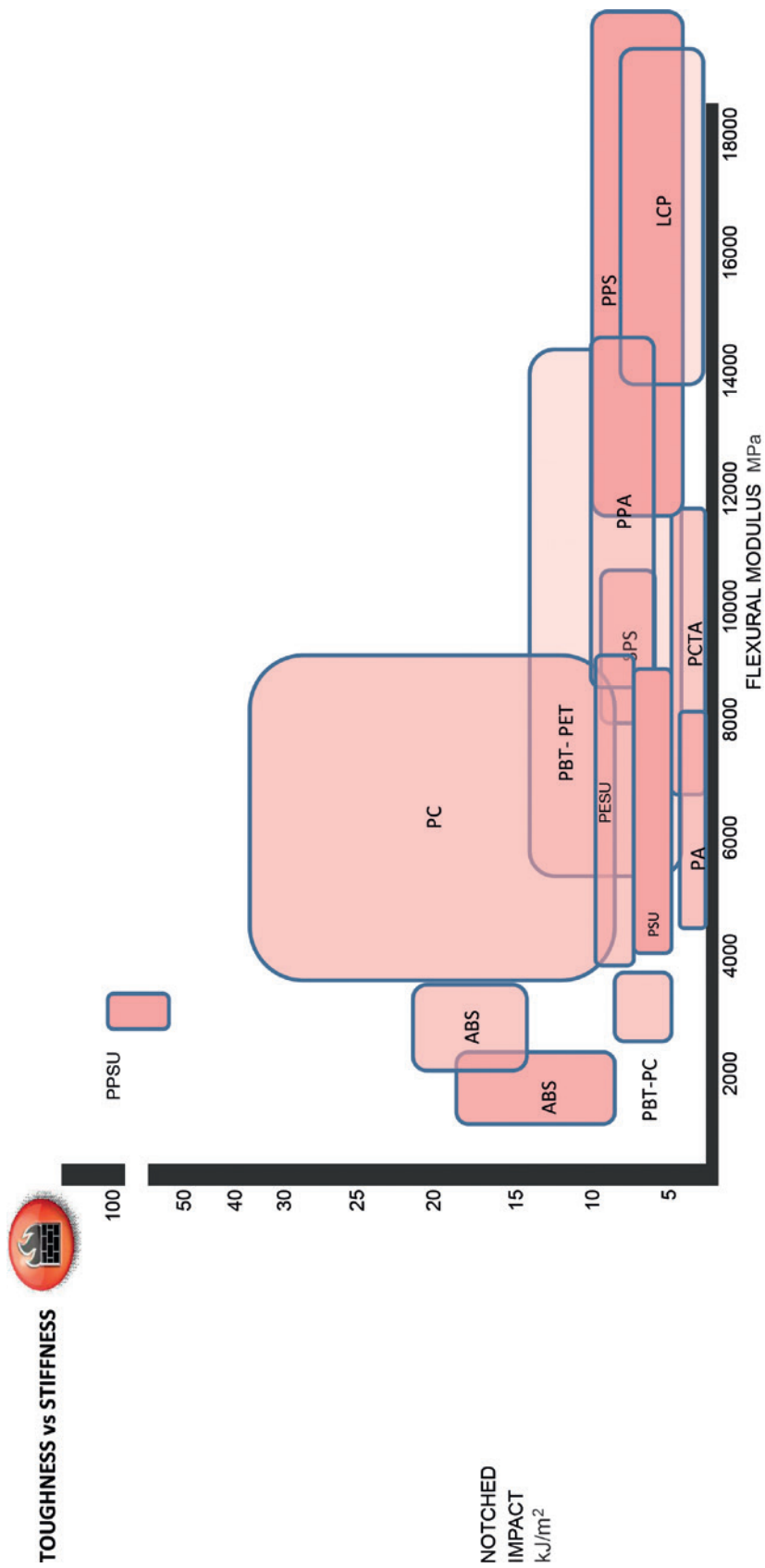
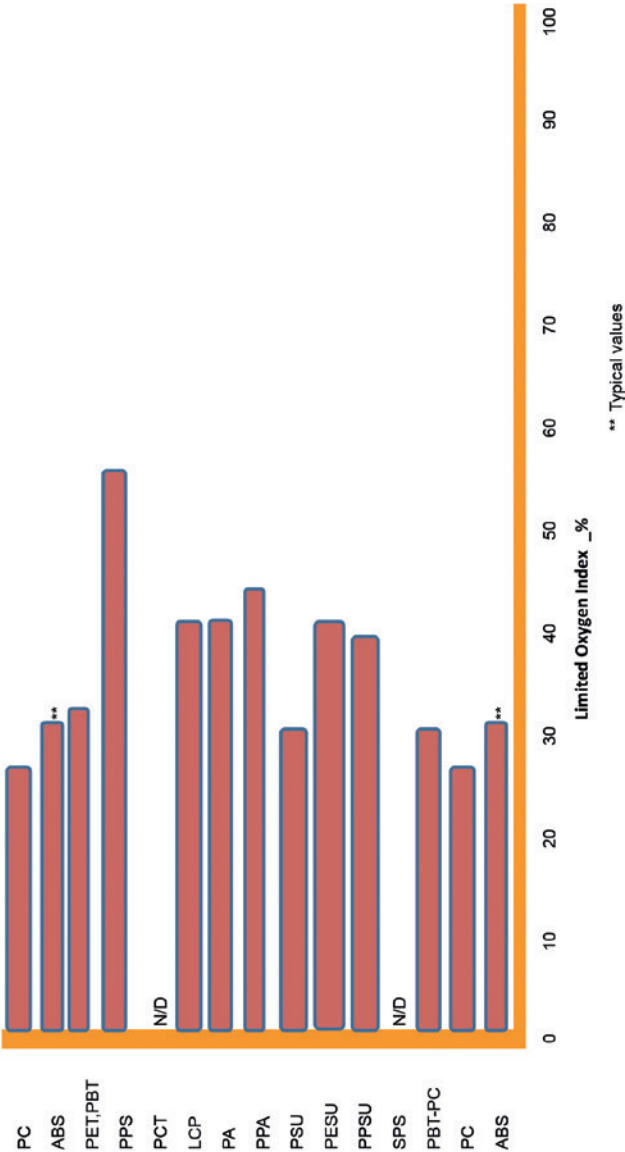


Figure 12.7 Toughness vs stiffness of flame retardant polymers



LIMITED OXYGEN INDEX

Figure 12.8 Limited oxygen index: Minimum level of oxygen with which the material can continue to burn. The higher the LOI, the lesser the combustion chances. ISO 4589 > 28 is considered self-extinguishing. The Earth’s atmosphere has 21% oxygen



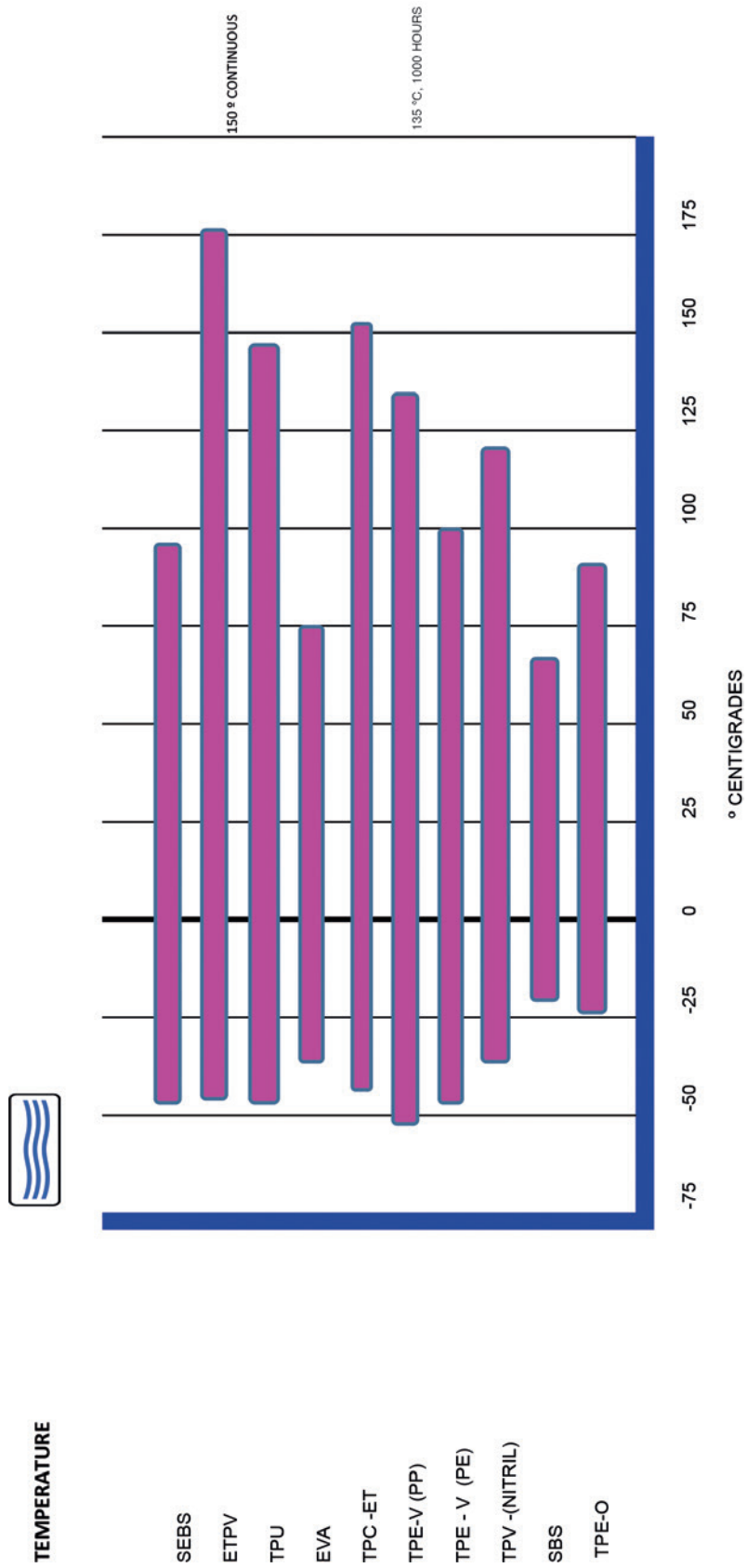


Figure 12.9 Temperature

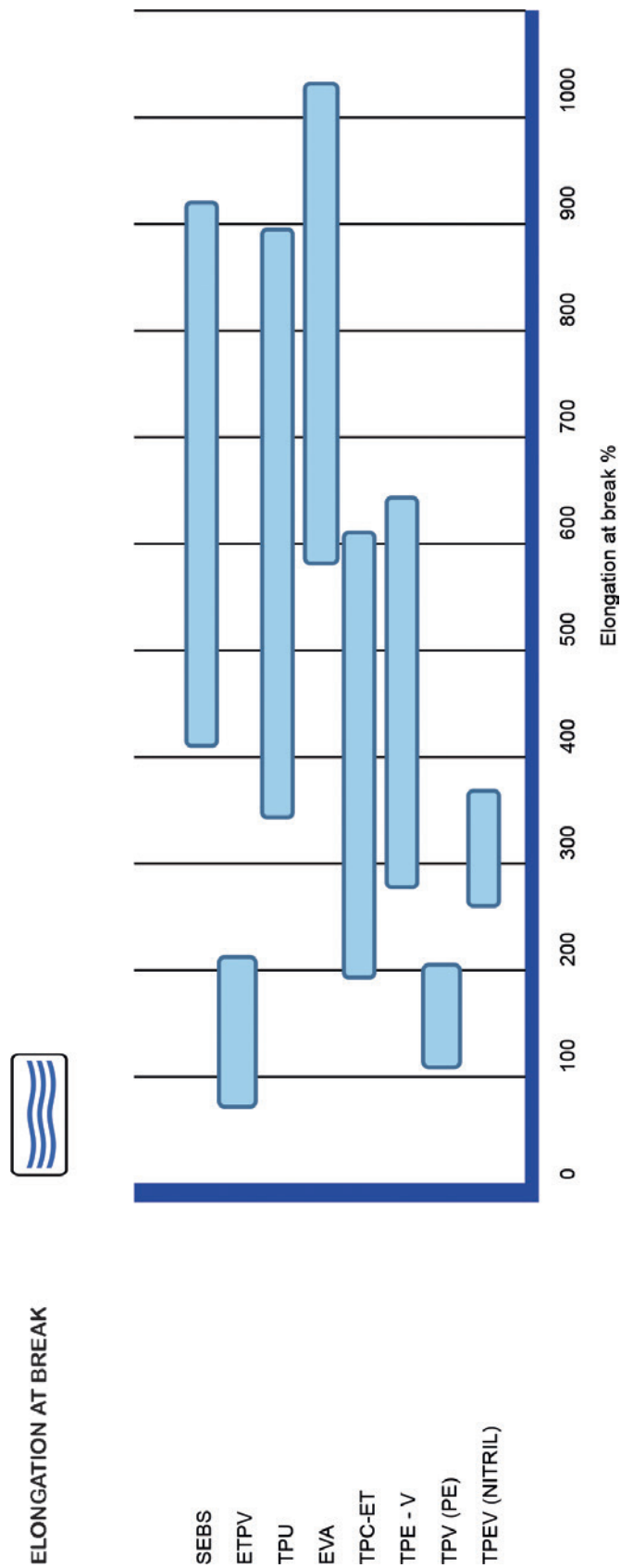


Figure 12.10 Elongation at break of some thermoplastics elastomers

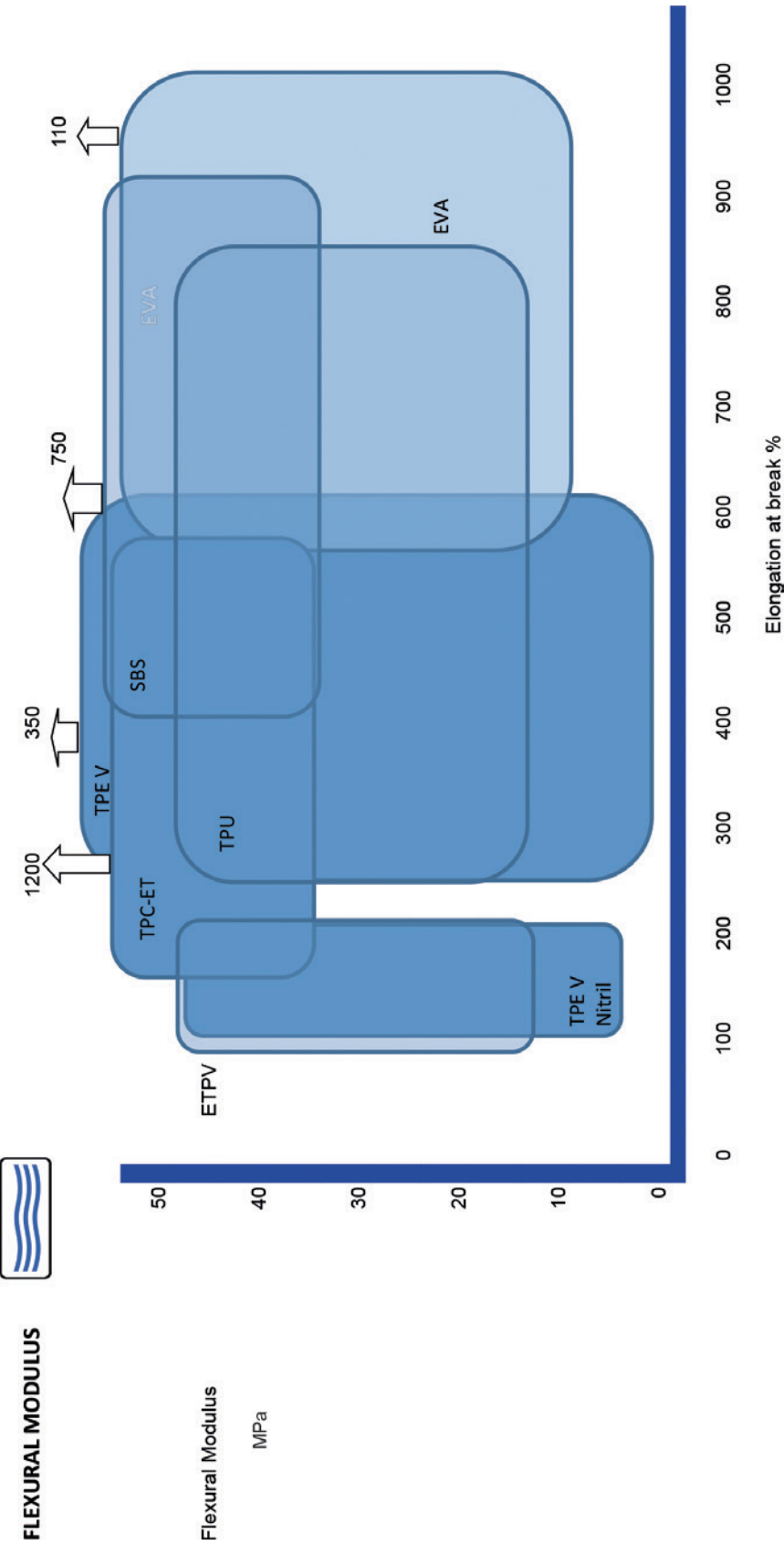


Figure 12.11 Flexural modulus vs elongation at break of some thermoplastics elastomers

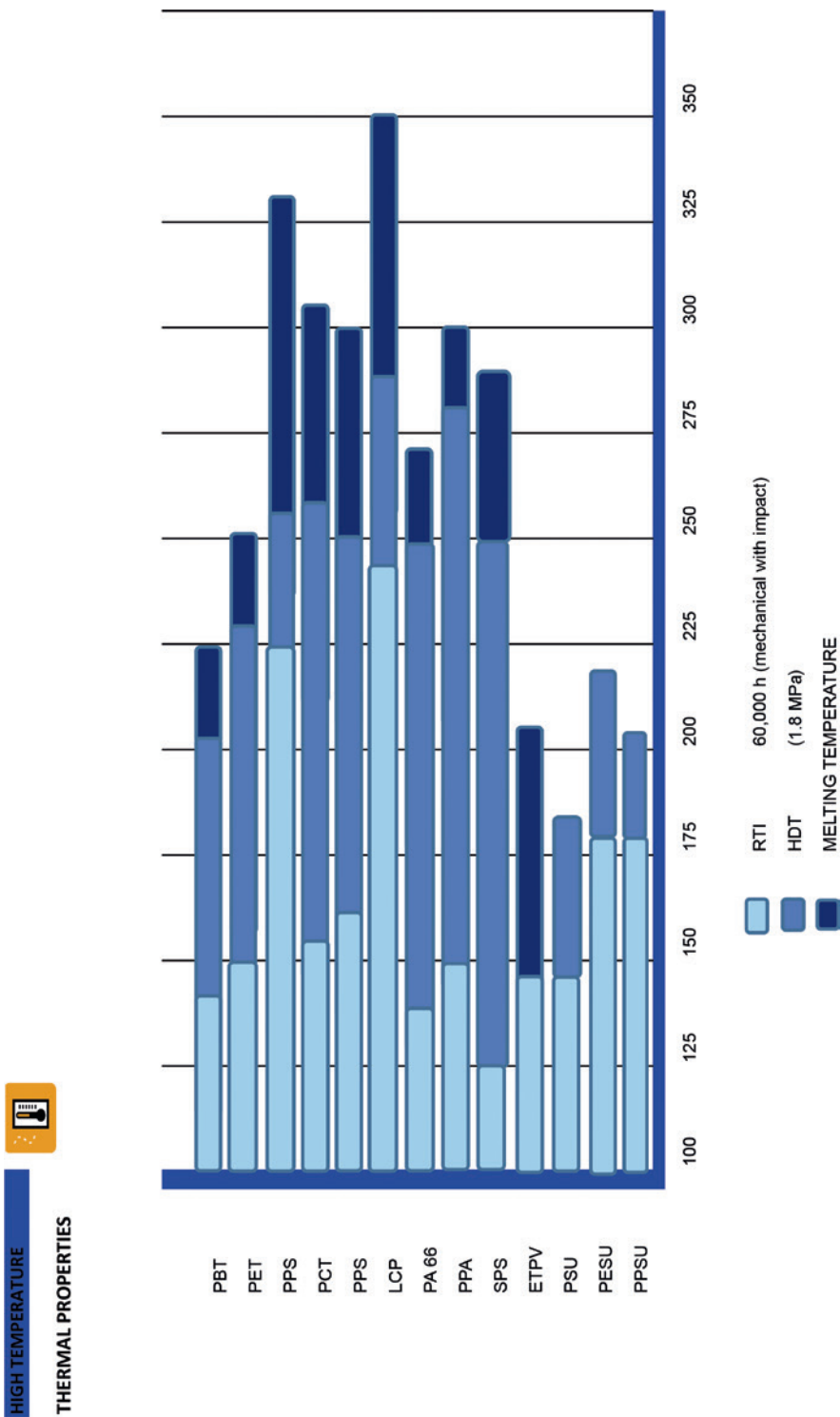


Figure 12.12 Thermal properties of high-temperature polymers

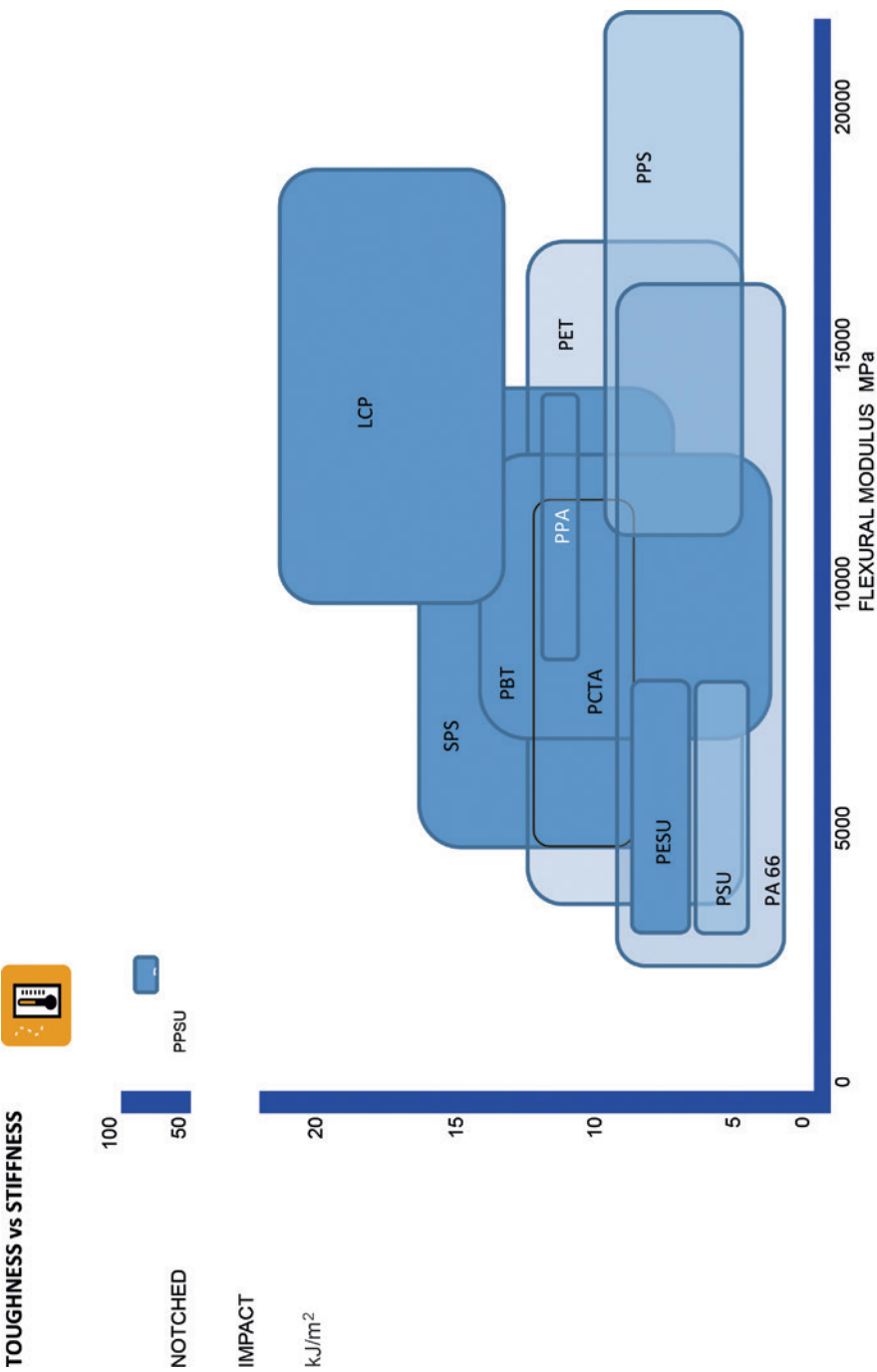


Figure 12.13 Toughness vs stiffness of some high-temperature polymers

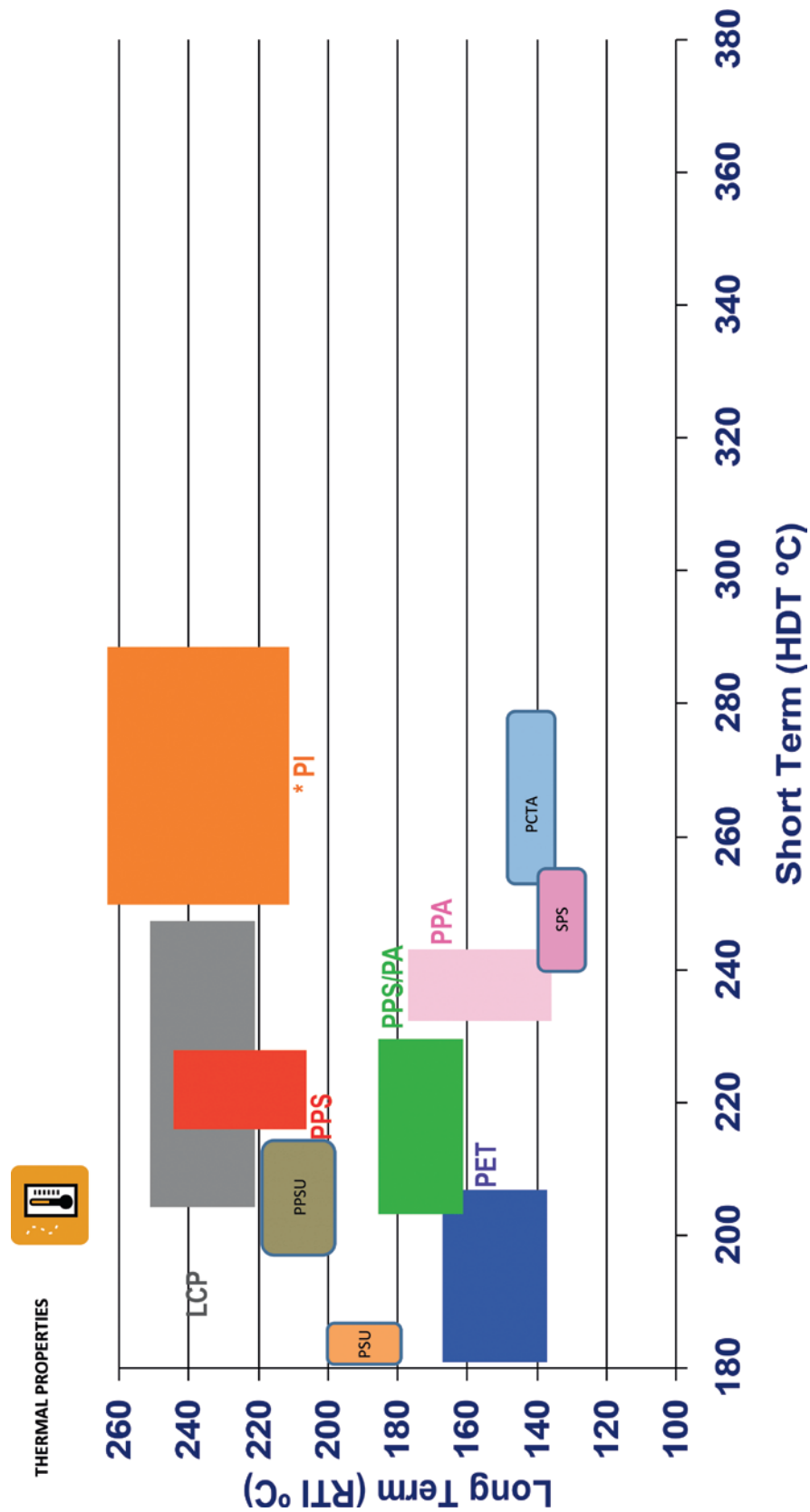


Figure 12.14 Thermal properties: comparative graph between high-temperature polymers



METAL REPLACEMENT

THERMAL PROPERTIES

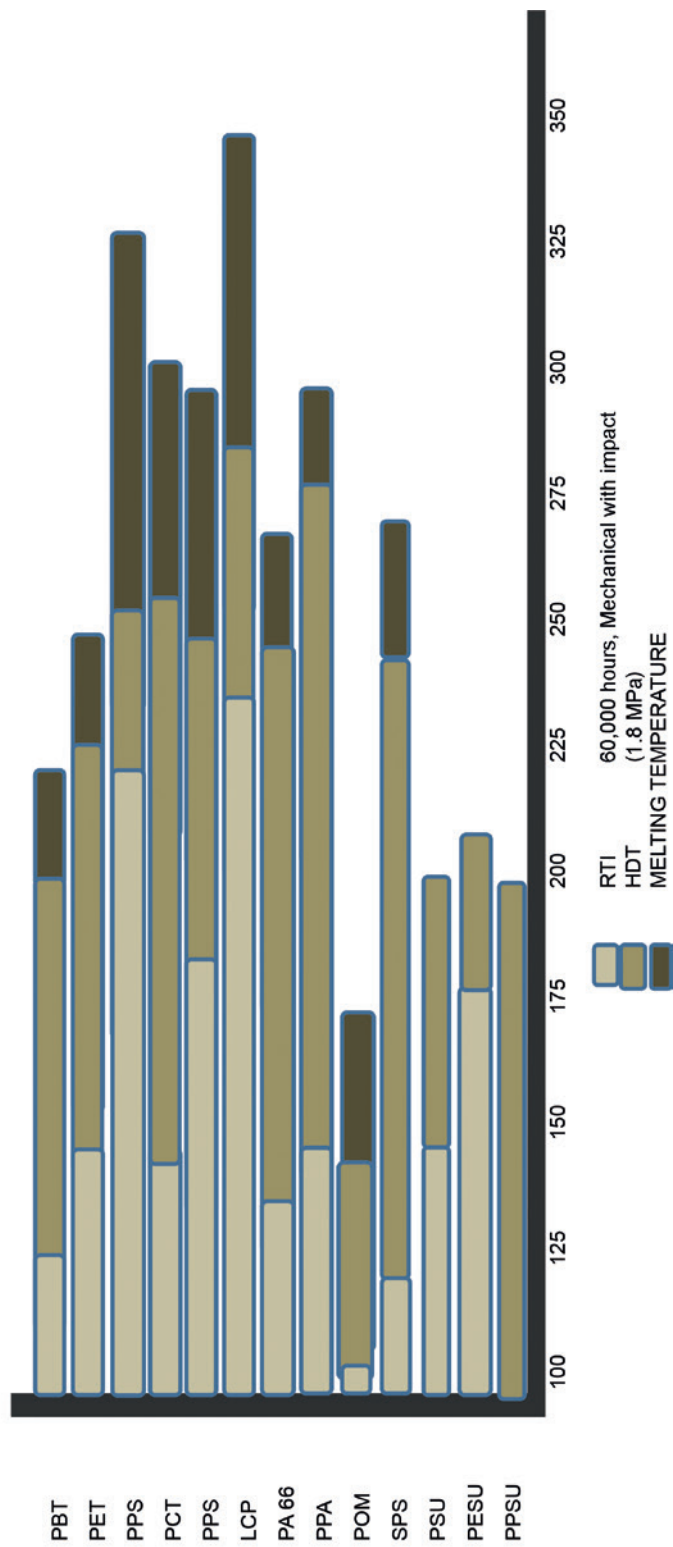


Figure 12.15 Thermal properties of high-performance polymers

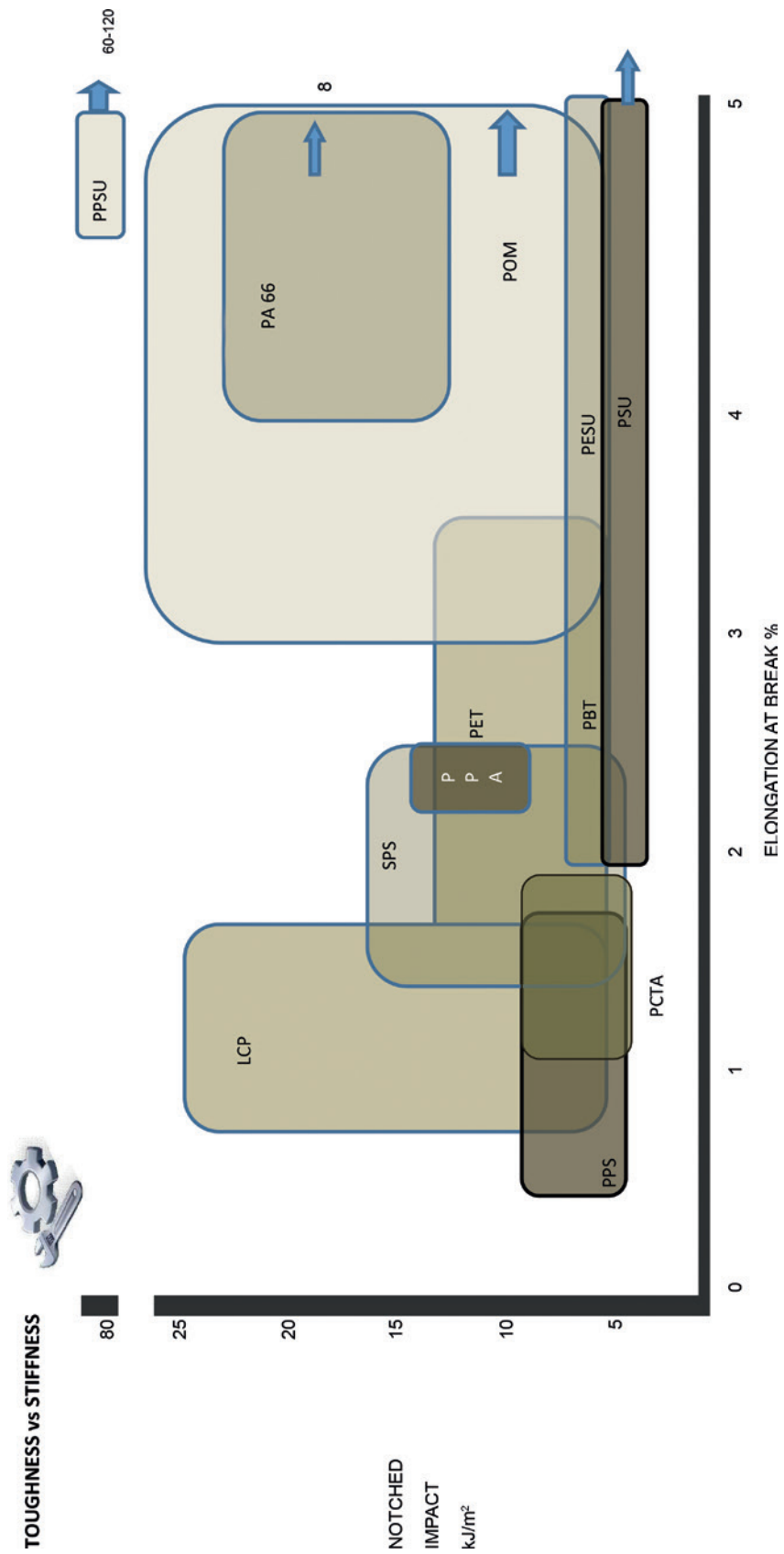


Figure 12.16 Toughness vs stiffness of high-performance polymers: impact vs elongation

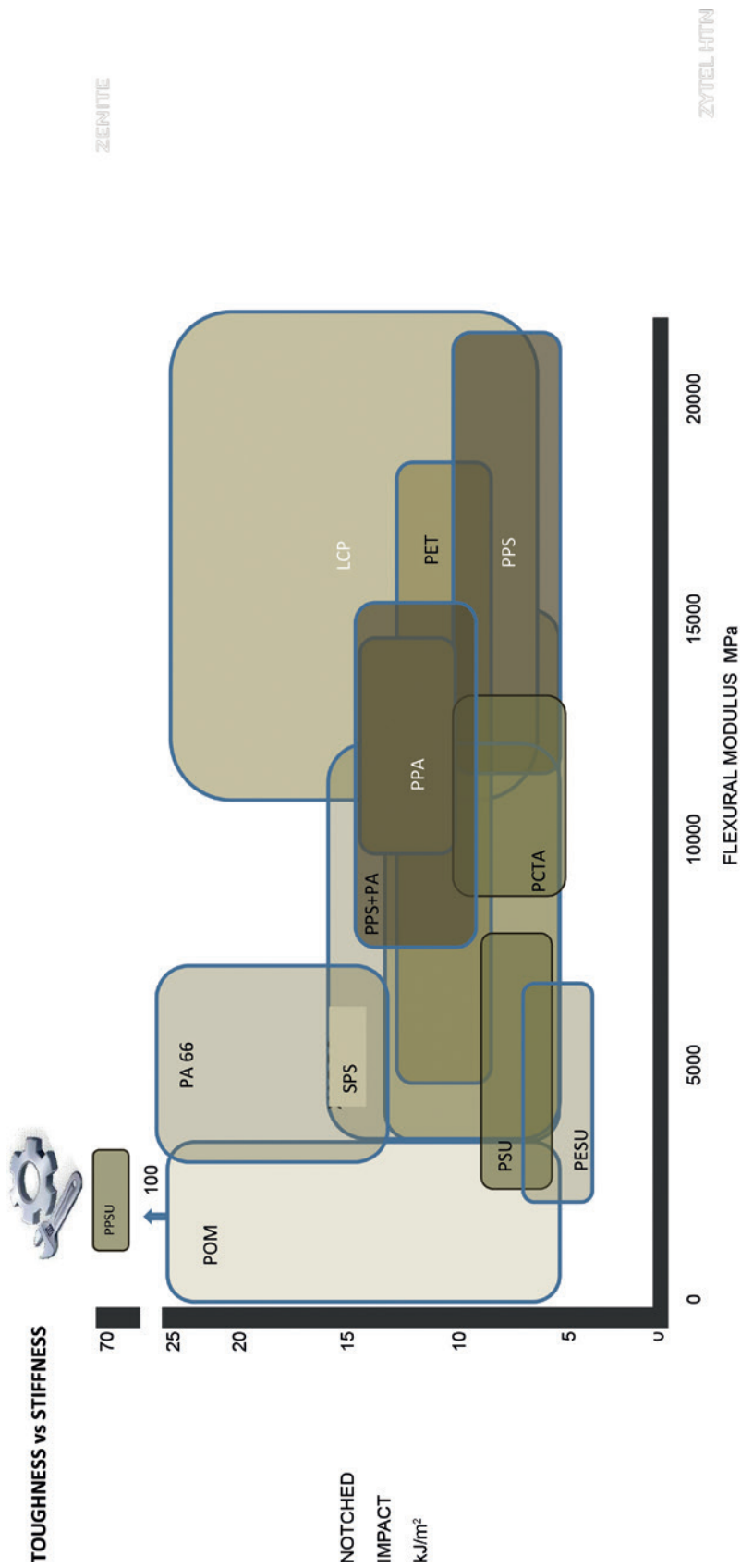
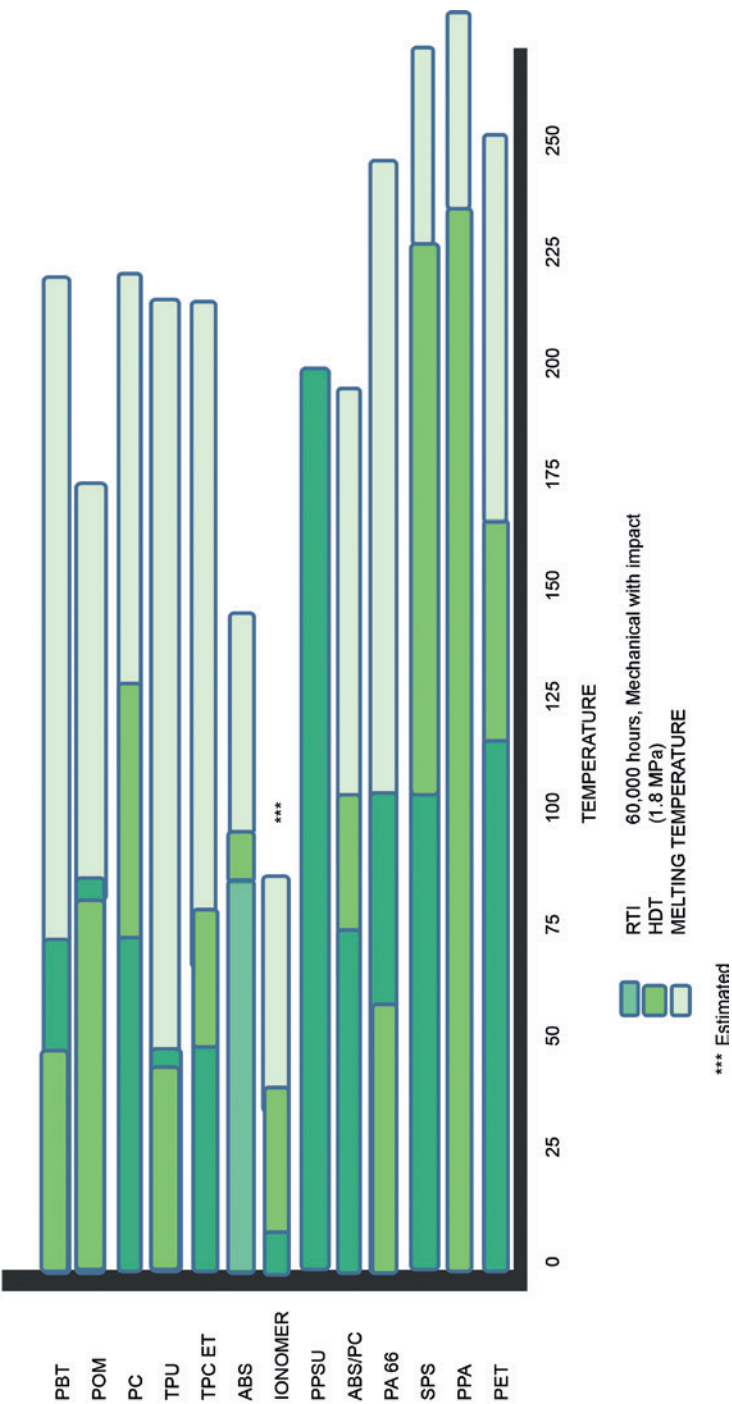


Figure 12.17 Toughness vs stiffness of high-performance polymers: impact vs flexural modulus

Figure 12.18 Thermal properties of good impact performance polymers

TOUGH AND STRONG

THERMAL PROPERTIES





TOUGHNESS vs STIFFNESS

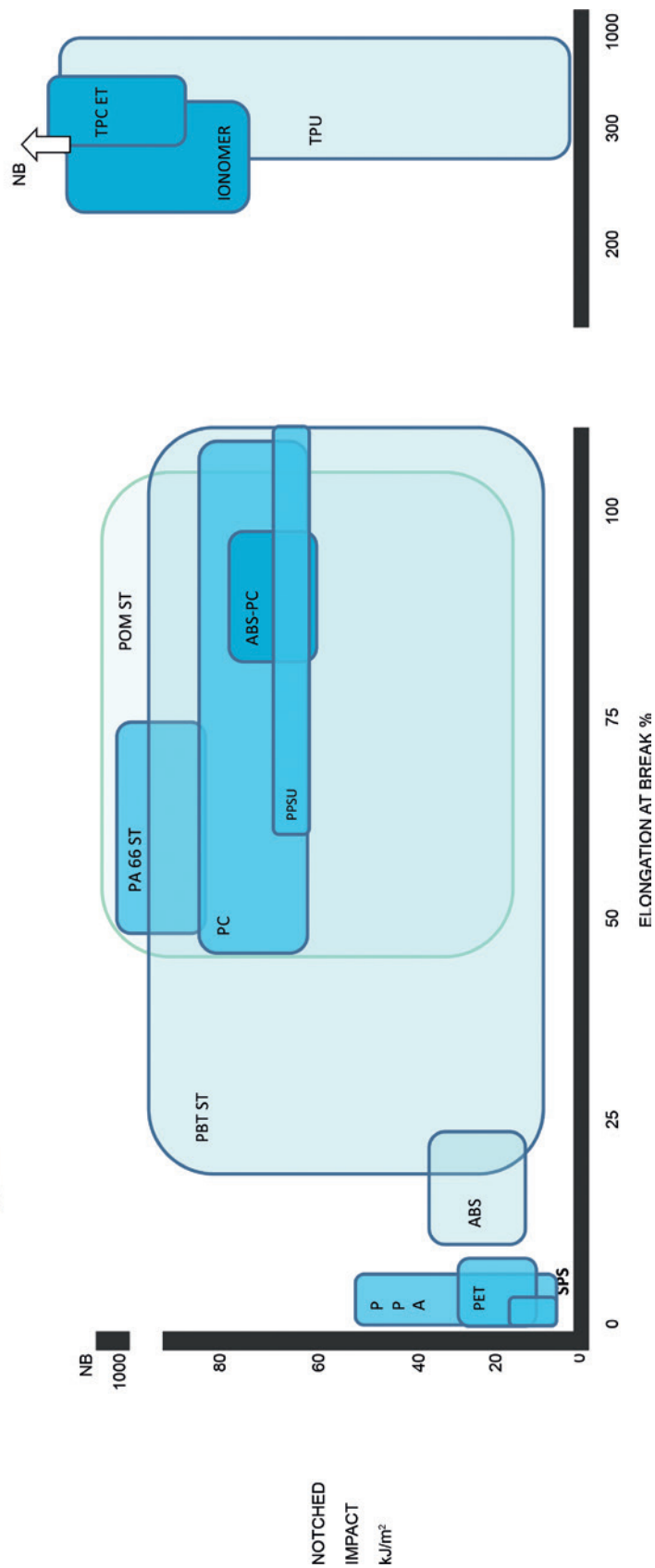


Figure 12.19 Toughness vs stiffness of good impact performance polymers: impact vs elongation

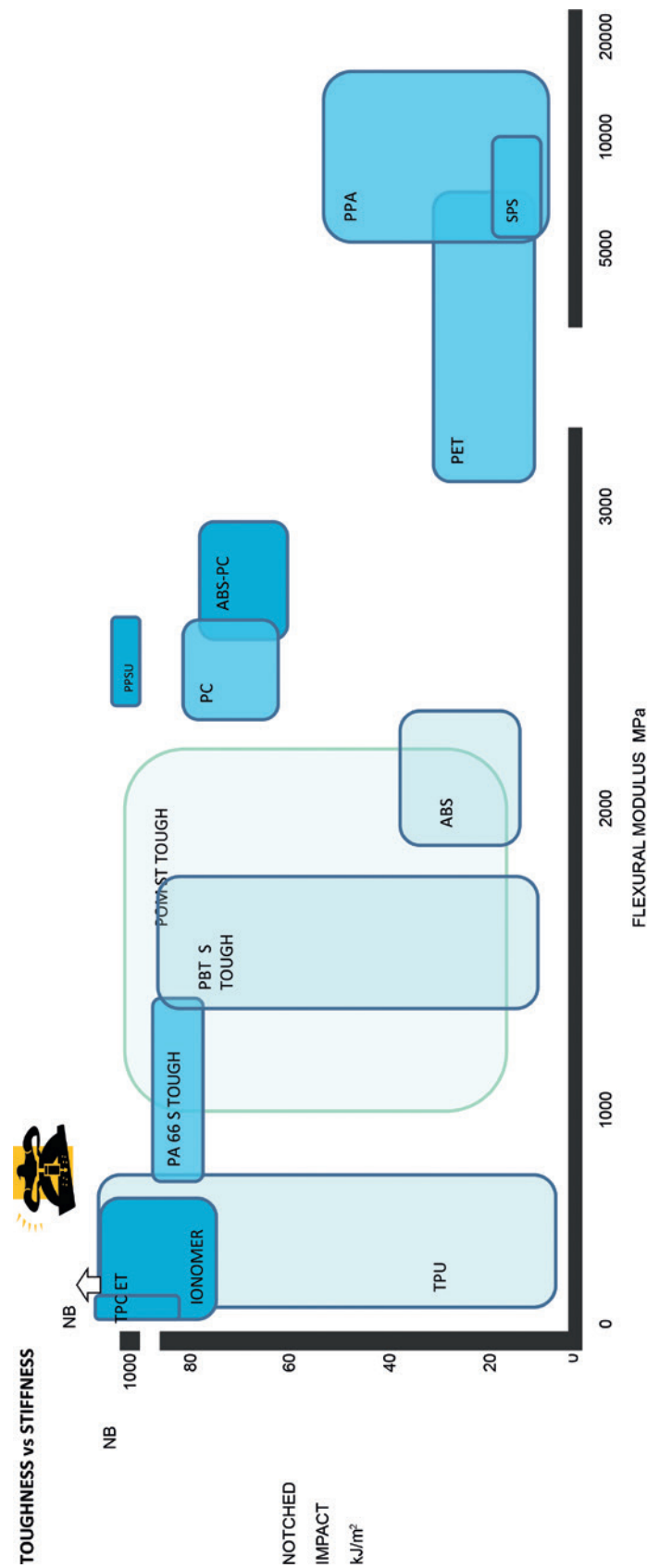


Figure 12.20 Toughness vs stiffness of good impact performance polymers: impact vs flexural modulus

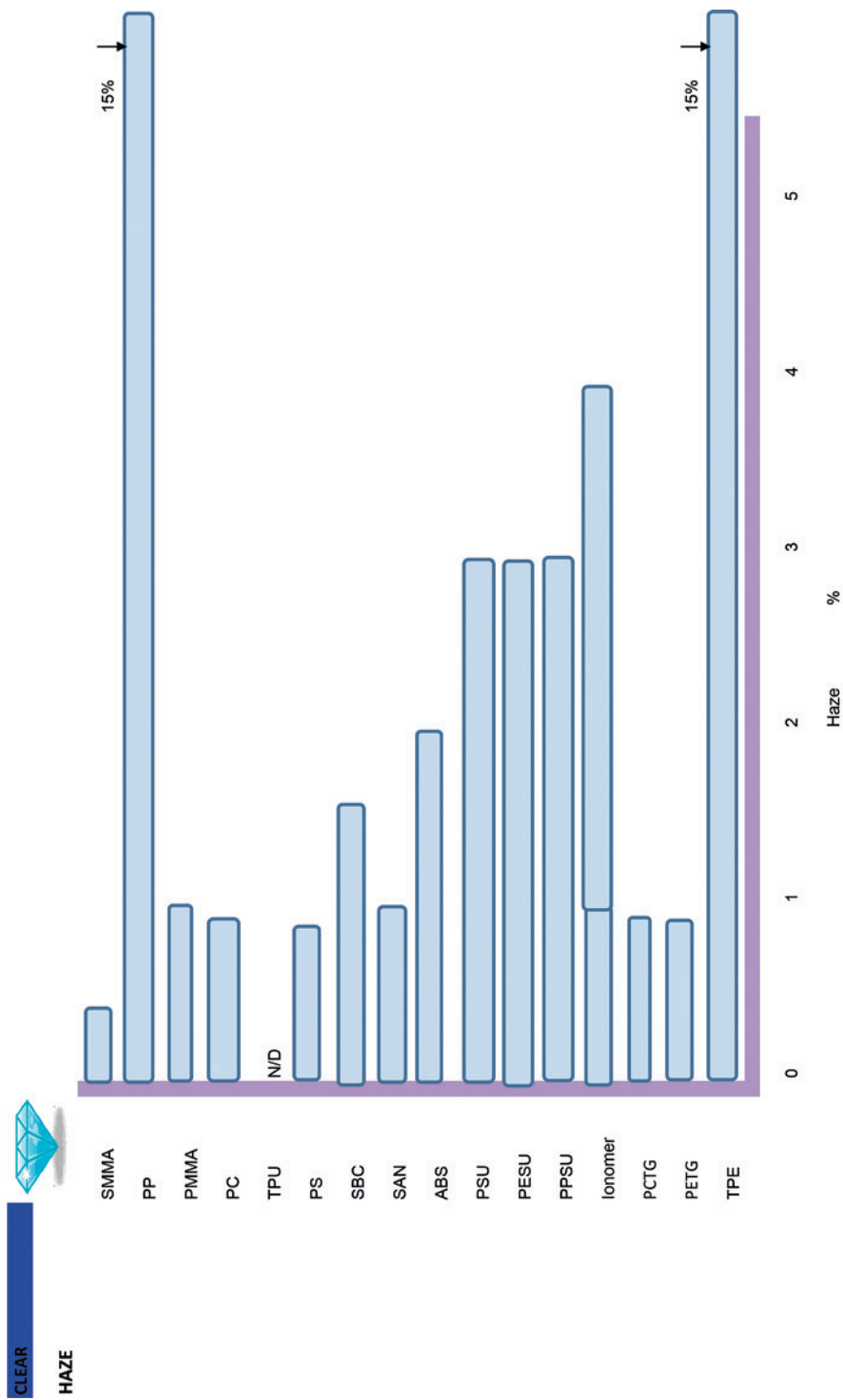


Figure 12.21 Haze in transparent polymers

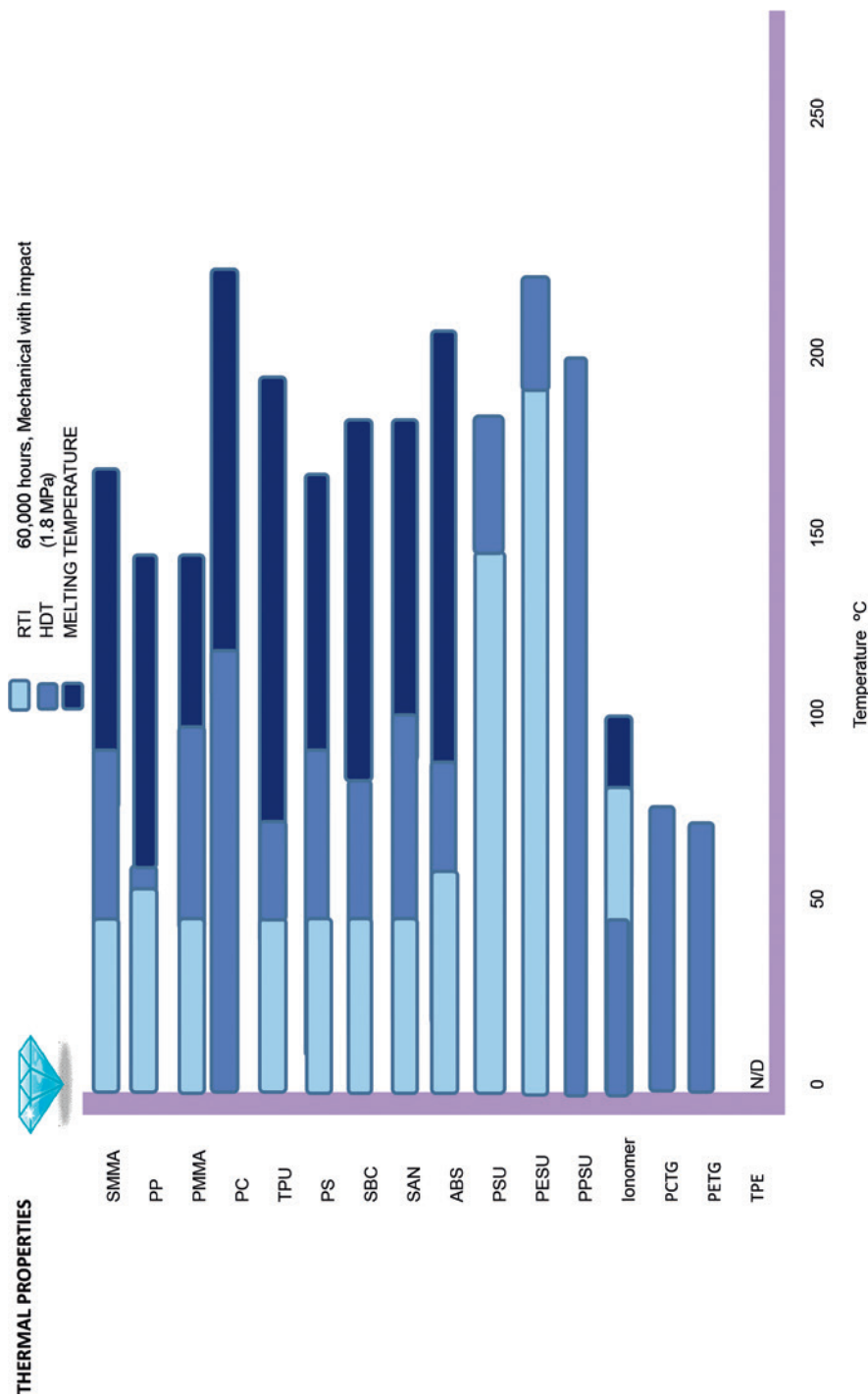


Figure 12.22 Thermal properties of transparent polymers

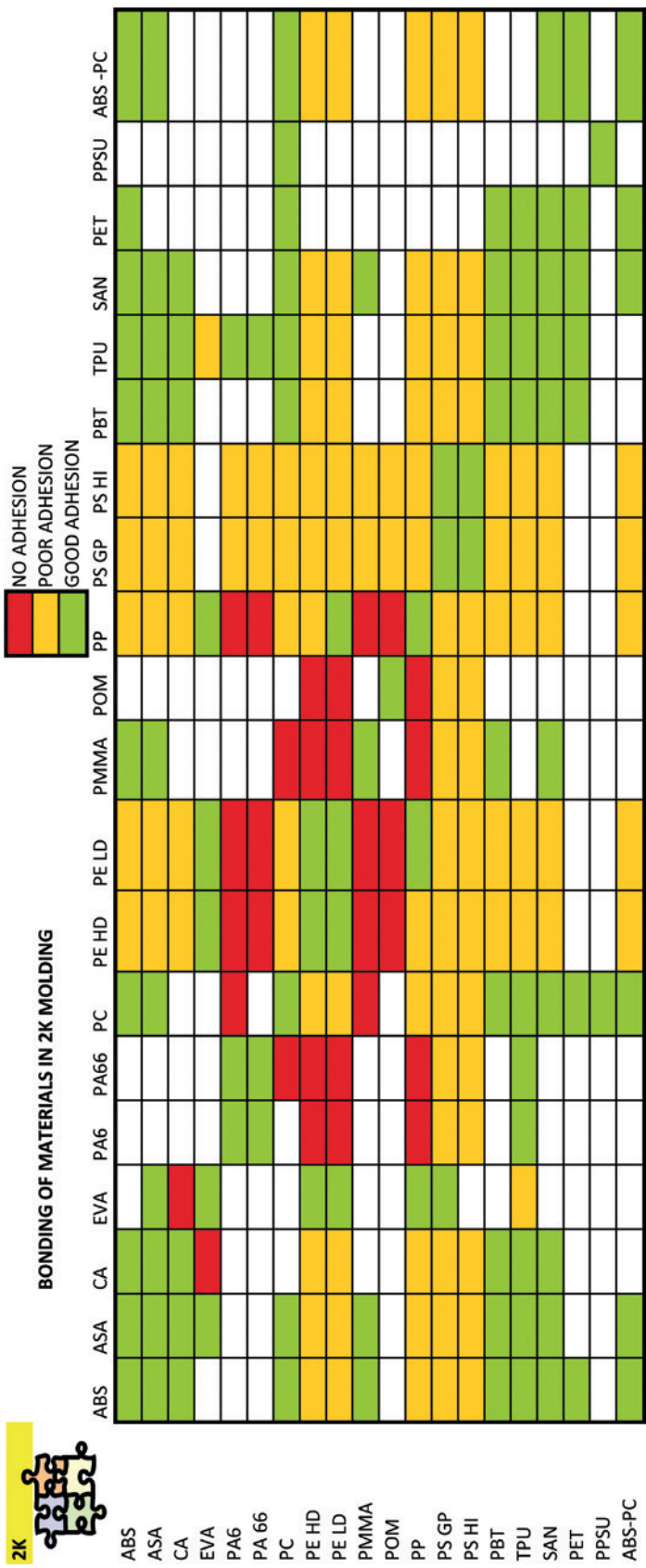


Figure 12.23 Bonding of materials in 2K molding

Figure 12.24 Chemical resistance



CHEMICAL

NOT
RESISTANT



NOT
RECOMMENDED



RESISTANT



	ABS	EVA	HDPE	LDPE	PA 6	ZYTEL PA 66	PA 12	PC	PMMA	DELRI POM	PP	RYTON	PS	SAI
WEAK ACIDS														
STRONG ACIDS														
OXIDANT ACIDS														
WEAK ALKALIS														
STRONG ALKALIS														
SALTS (SOLUTIONS)														
HALOGENS														
ALIPHATIC HYDROCARBONS														
CHLORINATED HYDROCARBONS														
ALCOHOLS														
ESTERS														
KETONES														
ETHERS														
ALDEHYDES														
AMINES														
ORGANIC ACIDS														
AROMATIC HYDROCARBONS														
OIL AND DERIVATIVES														
MINERAL OILS														
FATS AND OILS														
UNSATURATED CHLORINATED HYDROCARBONS														

Part 3

Injection: Machines and Processes

The Injection Molding Machine



Figure 13.1 Injection molding machine; source: Wittmann-Battenfeld

The characteristics and instructions included in catalogs and technical documentation brochures provided by injection machine manufacturers allow us to determine if a machine can be technically optimal for producing a particular project or part made by an injection molding process.

The injection machine can be divided into two main units: the clamping unit and the injection unit.

The clamping unit comprises, among others, the clamping force, the moving plate stroke, the tie bar free spacing, the mold minimum and maximum thicknesses, clamping and opening mold speed, etc.

The injection unit incorporates several characteristics, like the screw diameter, maximal pressure, L/D ratio, compression ratio, plasticizing capacity, maximal injection volume, heating power, maximal injection speed, etc.

13.1 Clamping Unit

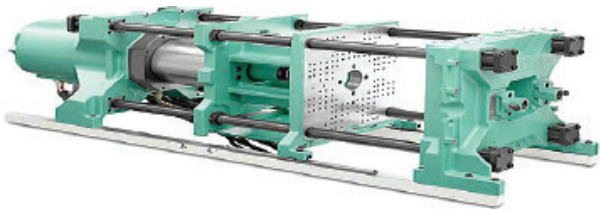


Figure 13.2 Clamping unit

Clamping unit determines:

Clamping force	Mold maximum and minimum thicknesses
Moving plate stroke	Plate thickness
Tie bar free spacing	Ejection stroke

13.1.1 Clamping Force

Function and characteristics

- Keeping the mold closed so it does not open due to the injection pressure thrust during the cavity filling and packing.
- When the product obtained by multiplying the projected part area in the mold by the injection pressure needed exceeds the closing force, the tie bars are overstressed and elongate even more. They can exceed the steel elastic tensile limit and break or deflect the clamping plates.
- The mechanical clamping systems are stiffer than hydraulic clamping systems.
- The hydraulic clamping system exerts pressure close to the center of the plate.
- The latest generation of mechanic toggle clamping systems also concentrate strength close to the center of the movable plate.

Movable platen stroke

A longer stroke will make the machine more versatile. In the hydraulic clamping systems, the total stroke of the piston is equal to the sum of the mold thickness and the maximum opening mold stroke.

Tie bars distance

The distance should be the widest possible, provided that the plate bending will be respected.

Stationary and movable platen

They should be parallel. The weight of the movable platen and mold must rest on the base of the bed and not on the tie bars.

Mold size regarding the platen size

According to the rule of thumb, the molds whose base area regarding the movable platen is less than $\frac{1}{4}$ of the area of the platen should not be placed.

The projected area of the molds used should not be **less than a quarter of the area delimited by the tie bars in the clamping platen**. If the mold area were smaller, the plates could be flexed more than recommended.

13.1.2 Clamping Unit Systems

According to their design, we can distinguish the following sealing systems:

- Mechanic toggle clamping system
- Hydraulic clamping system
- Hydraulic two-stage piston system
- Tie-barless system
- Electrical system

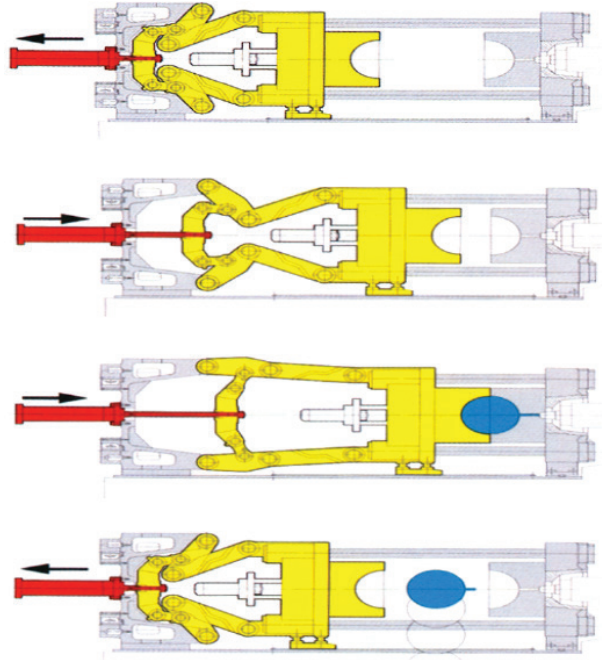


Figure 13.3 Toggle clamping system schema; source: Ascamm

13.1.2.1 Mechanical Toggle Clamping System

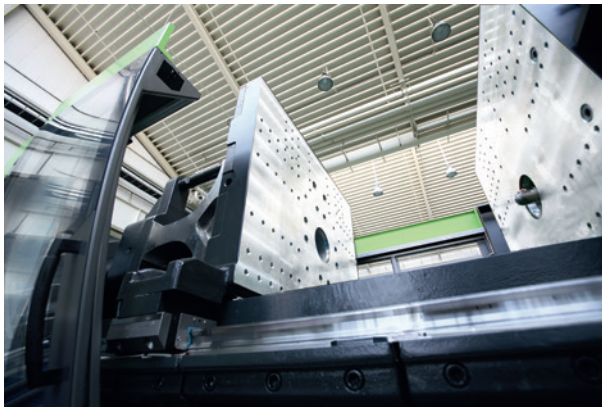


Figure 13.4 Tie-barless clamping unit detail; source: Helmut Roegele

13.1.2.2 Hydraulic Piston Clamping System

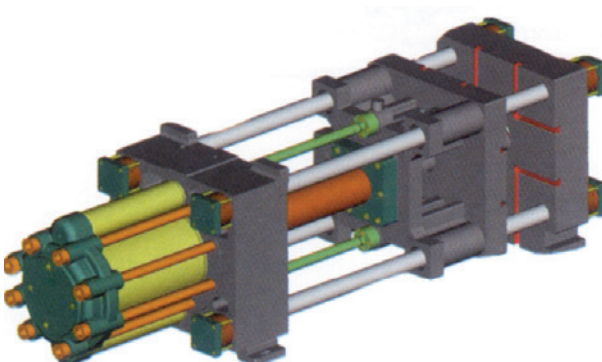


Figure 13.5 Hydraulic clamping system; source: Ascamm

There are several kinds of two-stage clamping systems that may be included within the hydraulic clamping systems. The most common system is a mechanical lock in the machine made by two very small hydraulic cylinders, driving two locking parts which act over the central axis. Once the central axis is locked, the high pressure enters through a larger cylinder (pressure cylinder), moving it only a few millimeters, to provide the necessary and programmed clamping force.

13.1.2.3 Hydraulic Closure System for Large Tonnages

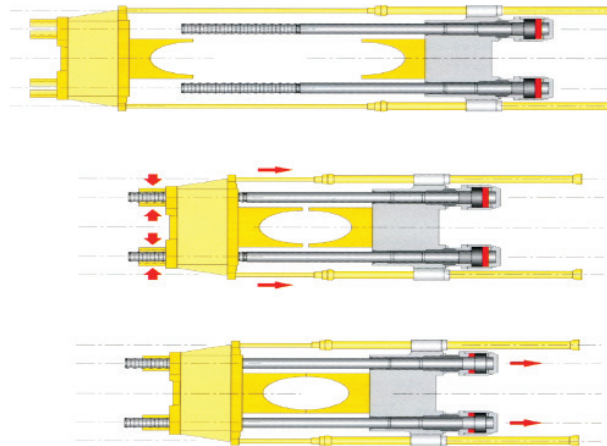


Figure 13.6 Hydraulic clamping system scheme; source: Ascamm

There are as many hydraulic clamping systems as there are machine manufacturers. All of them have tried to develop more versatile, fast, accurate, and low-maintenance systems.

In general, these devices have a system of small-section and low-volume piston to effect a fast closing movement. Thus, this movement requires little volume of oil and, therefore, has a low energy cost and is performed very rapidly. The system is complemented with a large piston. This piston performs the final locking of clamping force by a short stroke.

13.1.2.4 Servoelectric Clamping: Movements Made by Servomotors, Bearings, and High-Precision Screws

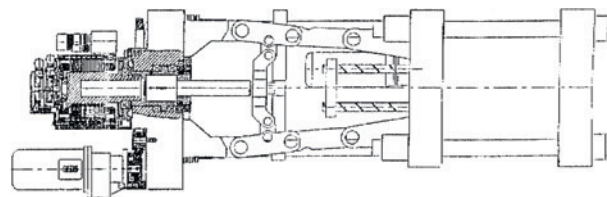


Figure 13.7 Servoelectric motor clamping

Mechanical Toggle Clamping System Versus Hydraulic Clamping System

Mechanical toggle clamping system		Hydraulic clamping system	
Advantages	Disadvantages	Advantages	Disadvantages
High movement speed	More maintenance	Long opening strokes	Slower movements
Low oil flow	Shorter opening stroke	Cleanroom application	Higher energetic costs
Low sensibility to hydraulic leaks	Tendency to overload	No breakage stress of tie bars	
Favorable kinematics in opening and closing movements	Less precision of movements	Less mechanical wear and friction	
		Less maintenance needed	

13.1.3 Theoretical Clamping Force Required

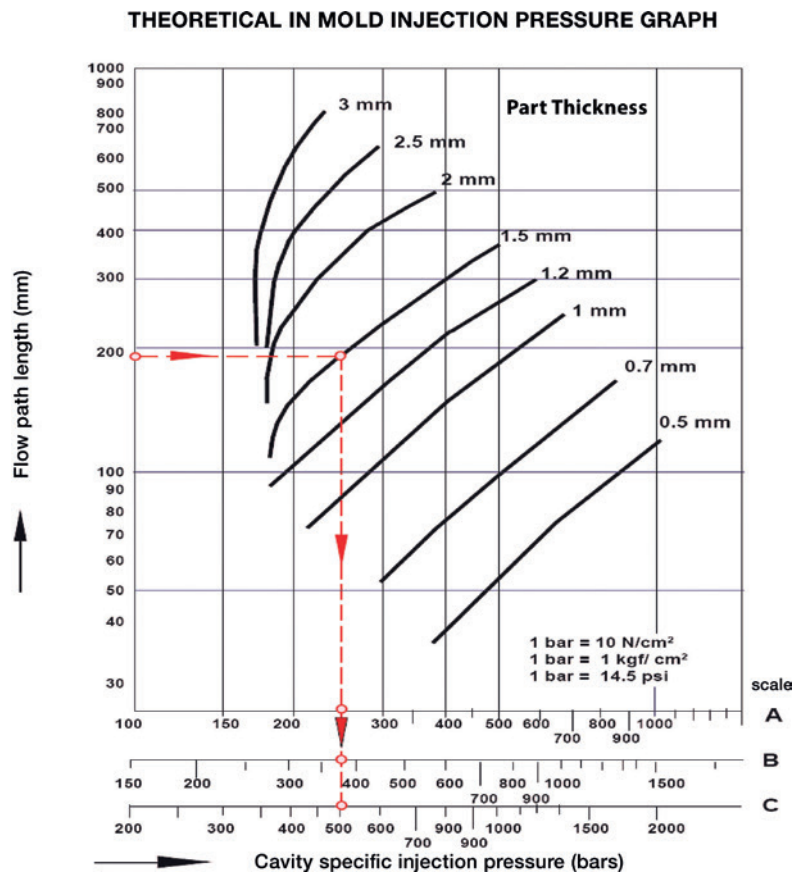


Figure 13.8 A scale: low viscosity material, PA-PE-PP-PS; B scale: medium viscosity material, ABS-CA-POM-SB; C scale: high viscosity material, PC-PMMA-PPO-PVC; source: Ascamm

To use the graph in Figure 13.8 to aid in the calculation of the estimated clamping force, we need to know the flow path, the thickness of the part, and the material used. In the graph, considering the example shown in red, for a flow path of 180 mm and a wall thickness of 1.5 mm, we can see the specific pressure depending on the different materials classified on the scales A, B, and C. This pressure

obtained in the graph has to be multiplied by the projected area of the parts to be injected. Thus, we can know the total clamping force required. The necessary clamping force is the result of multiplying the projected area of the parts by the maximum pressure in the cavities.

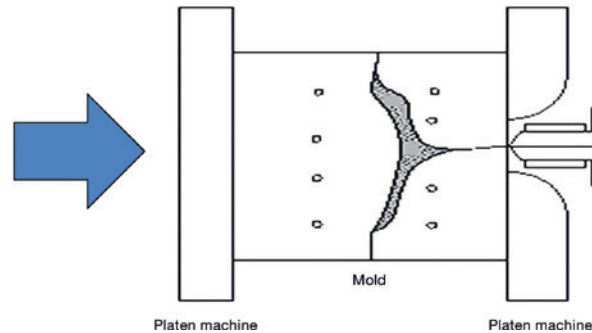


Figure 13.9 Clamping force applied to the mobile plate

13.2 Injection Unit

The injection unit consists of the following main elements:

- Hopper
- Plasticizing cylinder
- Screw
- Non-return valve
- Screw tip
- Nozzle

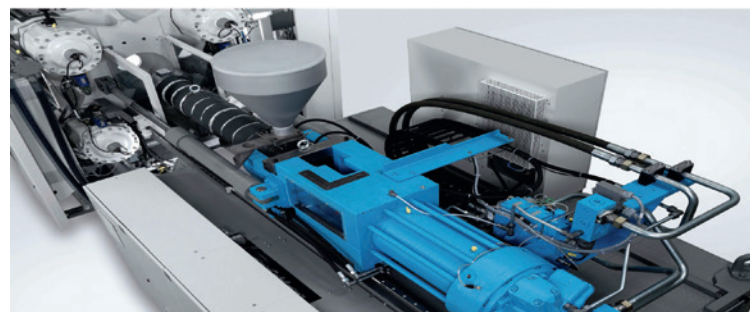
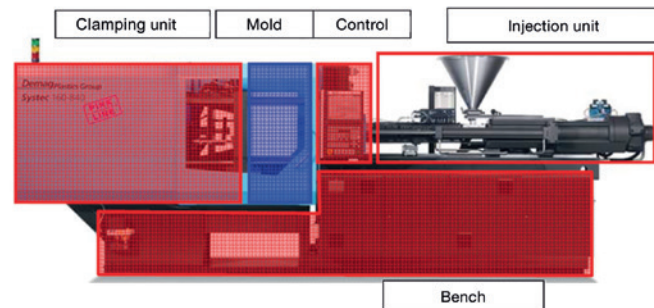


Figure 13.10 Injection unit;
source: Coscollola

13.2.1 Injection Unit Characteristics

13.2.1.1 L/D Ratio

- L/D : ratio of length to diameter of the screw
- Usual L/D ratio: 18 to 20
- For ratios higher than 20: too long material path, more homogeneity, but also longer residence time, degradation, etc.
- For ratios lower than 20: possible lack of homogeneity in the melt

13.2.1.2 Compression Ratio (K -Ratio)

- K -ratio: ratio of the volume of a fillet in the screw in the feeding area near the hopper to the volume of another fillet in the dosage zone near the valve ring
- Higher K -ratio = higher compression
- Low compression ratios are recommended for amorphous materials or those which are sensitive to temperature
- Higher compression ratios are recommended for semi-crystalline materials
- PVC: $K = 1.6 : 1$; POM: $K = 2.6 : 1$

13.2.1.3 Plasticizing Capacity

- Plasticizing capacity: It is the machine capacity if it acted as an extruder. It makes possible to calculate how much time it takes the machine to plasticize a kilo of material.
- Unit: kg/h
- This capacity serves as a comparison between machines

13.2.2 Screw

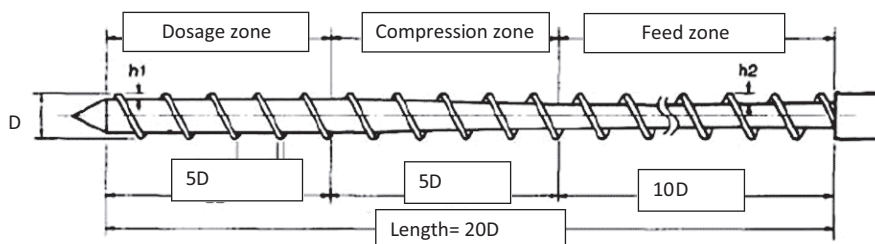


Figure 13.11 D = outer diameter; compression ratio: h_2/h_1

Feed zone: It is placed at the rear end of screw, near the hopper. The material, in pellet form, is fed into the injection unit. Good transport properties of solids to the front parts of the screw are required. The coefficient of friction between the pellets and the screw is important in this area.

Compression zone: A decrease in available volume inside the fillet causes a progressive compression of the material and heats it by friction and shear. This heat aids to melt the material and therefore also causes an increase in the specific volume. In this area, through compression, the air between the pellets is moved to the feeding zone and does not pass to the metering zone.

Dosage and metering zone: The melt is mixed and homogenized here.

The ideal size of each of these areas varies depending on the type of thermoplastic used, especially in the compression zone. For semi-crystalline materials, the length of this area will be shorter than for amorphous materials.

13.2.3 Barrels

The barrel is a cylinder of treated steel, coated externally by electric heaters and their corresponding thermocouples, with independently adjustable zones. The screw is placed inside of it.

The plasticizing capacity of the injection unit is determined by its length and its L/D ratio.

The injection unit is subject to heavy wear by thermoplastic processing. This wear is the result of different causes or variables, for example:

- The material of which the screw/barrel is made
- The design of the screw
- Injection parameters
- Types of processed materials (flame retardant, reinforcement, etc.)

The most used barrels and screws are made of nitrided steel with a hard surface layer with a thickness from 0.4 to 0.5 mm.

Bimetallic hard treatment is one of the best solutions to reduce the wear in barrel and screws.

13.2.4 Screw Mechanism

13.2.4.1 Screw Feeding Zone, Initial Zone

In this zone takes place the filling of the screw helical channel with solid or pellets. While the machine screws, the fillet pushes and catches the pellets dropped into the slot in every turn. The performance depends on the screw geometry, the thread angle, the channel width, and the screw speed.

13.2.4.2 Compression Zone, Solids Conveying Zone

Pellets are compressed, filling the channel volume. The performance depends on the coefficient of friction between polymer, screw, and barrel. For an optimum performance, the pellets must “stick” to the barrel and slide on the screw.

In the area of $2/3$ of the fillet height, the internal speed is zero. Above $2/3$ of the fillet height, a movement toward the active flank of the screw is produced. Below $2/3$ of the fillet height, a movement toward the passive flank of the screw is produced.

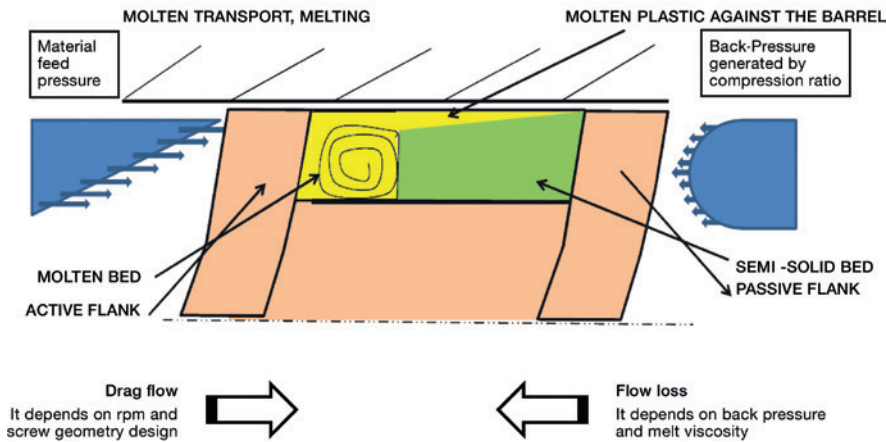


Figure 13.12 Screw mechanism scheme

The friction between the pellets and the screw must be lower than the friction against the barrel chamber. Let us imagine a nut screwed onto the center of the screw. If we turn the screw, this will move but the nut will not shift along the screw. In this case the nut is the pellets compressed against the fillet and the screw is the spindle. If we put something to hinder the rotation of the nut, the friction will be increased and transmitted, and the nut will shift along the screw.

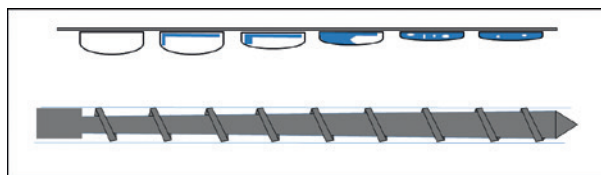


Figure 13.13 Polymer melting evolution scheme

13.2.4.3 Nitrided Screw vs Bimetal Screw

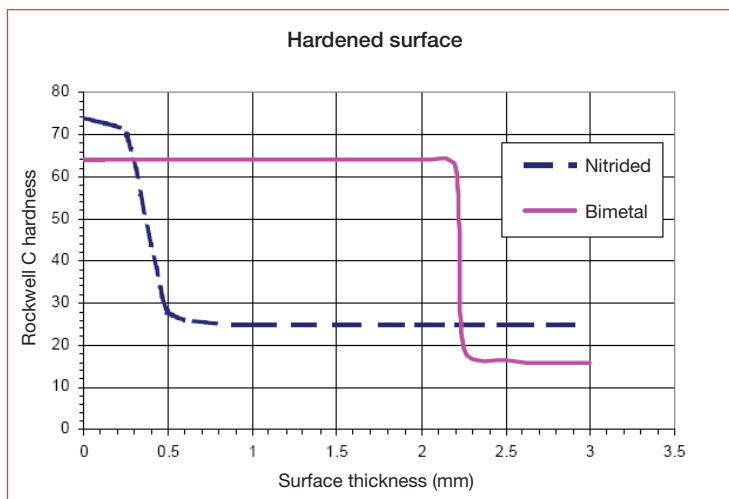


Figure 13.14 According to the chart, the nitrided screw has a hard layer of 0.5 mm and the bimetal screw a layer of 2 mm (i.e., four times that of the nitride screw); source: Ascamm

13.2.5 Check Valve Non-Return Tip

This mechanical element prevents return of the material toward the rear of the injection unit during the injection phase and allows the advance of material toward the front of the screw during the dosing phase.

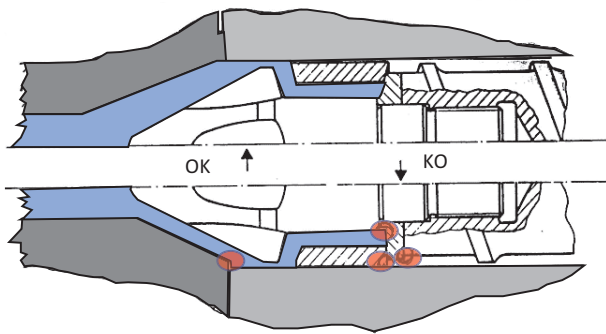


Figure 13.15 Non-return valve design



Figure 13.16 Non-return valve parts: ring closure, seat ring, and screw tip

The check valve should be “aerodynamic” and have no sharp edges or dead angles that might retain the material.

The non-return valve is a critical element of the injection unit. There are different types:

- Bushing valve or seal ring (see Figure 13.17)
 - The most commonly used
 - Good performance in purges and color changes
 - Optimal flow passage and hermeticity or sealing characteristics
- Ball valve
 - Narrow weights range of the injected parts
 - Especially recommended for low-speed injection rates
 - Durability
- Internal ball valve
 - Low wear
 - Recommended for large screw diameters



Figure 13.17 Non-return valve

Possible problems

- Difficulty in maintaining the stability of the cushion material
- Long and irregular dosing times
- Excessive shrinkage in parts
- Burned black spots on the parts
- Streaks on the part surface
- Low dimensional stability of the parts

This element must be carefully controlled during the scheduled maintenance service in order to detect wear or lack of hermeticity.

13.2.6 Nozzle

The nozzle's main mission is to drive the molten plastic material from the plasticizing barrel to the mold. So it is the connection between machine and mold.

The nozzles are attached to the machine head and they can be changed easily. In each production, we must choose the most appropriate nozzle. We have to consider the following items:

- Outlet diameter according to the mold sprue diameter
- Outer geometry and length
- Inner design suitable to the material to be processed

The nozzle is a critical element, given the operational pressures and temperatures. Nozzles are usually heated by electrical heaters. The regulation of their temperature must be very accurate to prevent the plastic from solidifying or being thermally degraded during the time it remains inside.

The outlet must be perfectly smooth and have a diameter slightly smaller than the diameter of the mold sprue (10% less), which is in relation to the volume and type of material used in the process. The right rule is “the more viscous the material to be injected and the greater the volume of the piece, the bigger the outlet diameter”.

Types

Flat nozzle: by having a large surface in contact with the mold, high heat losses by transmission are produced. No self-centering.

Taper nozzle: its shape allows self-centering, but it also makes it less resistant. In fact, if the machine is decentered, the nozzle can be deformed. Compared to the flat nozzle, the contact surface with the mold is smaller.

Spherical nozzle: with less than 10 mm radius, the problems are the same as with the taper nozzle. A radius greater than 10 mm is a good solution, since it has good self-centering and the contact surface with the mold is minimal, given that the radius of the mold sprue must be 1 mm larger.

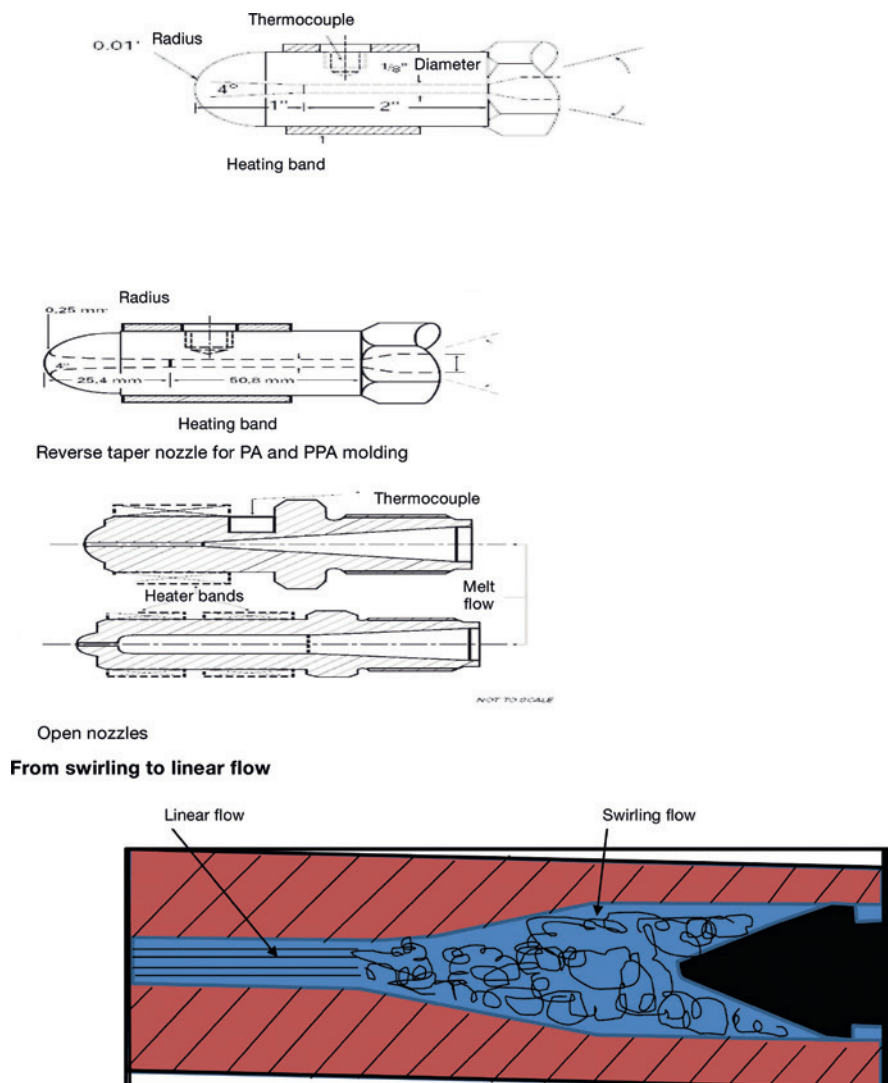


Figure 13.18 Reverse taper nozzle and open nozzle examples; source: DuPont

There are different models of shut-off nozzles systems:

- Valve nozzles driven by material pressure
- Needle nozzles
- Spring nozzles
- Hydraulic shut-off nozzles

The bottom image in Figure 13.18 shows the internal polymer flow differences in the barrel. Along the screw and through the non-return valve the flow is swirling, but just in the nozzle holder the flow system changes to laminar flow. This means that, in case of some kind of polymer retention or degradation issues in the laminar flow zone, the defect in the part always will be in the same part position.

13.3 Which is the Right Machine?



Figure 13.19 Source: Wittmann-Battenfeld (top); Krauss-Maffei (middle); AGI, FANUC (bottom)

13.3.1 Factors to Consider for Choosing the Right Machine

- Raw material manufacturer's recommendations (they have the greater material knowledge, on its behavior and performance)
- Temperatures required
- Screw L/D ratio
- Compression ratio (K -ratio)
- Clamping tons per unit area recommended
- Residence time, dose/screw ratio
- Maximum injection pressure required

13.3.2 Clamping Force

Table 13.1 Clamping Force per Unit Area Required for Different Materials

Material	Estimated clamping (ton/cm ²)
ABS	0.45–0.65
LCP	0.75–0.8
PA	0.65–0.75
PBT	0.65–0.75
PC	0.5–0.8
PE	0.15–0.55
PET	0.65–0.75
PMMA	0.45–0.75
POM	0.85–1
PP	0.15–0.55
PPS	0.3–0.6
PS	0.3–0.5

Estimate the clamping force according to these variables:

- Type of material, viscosity
- Part wall thickness
- Material flow path

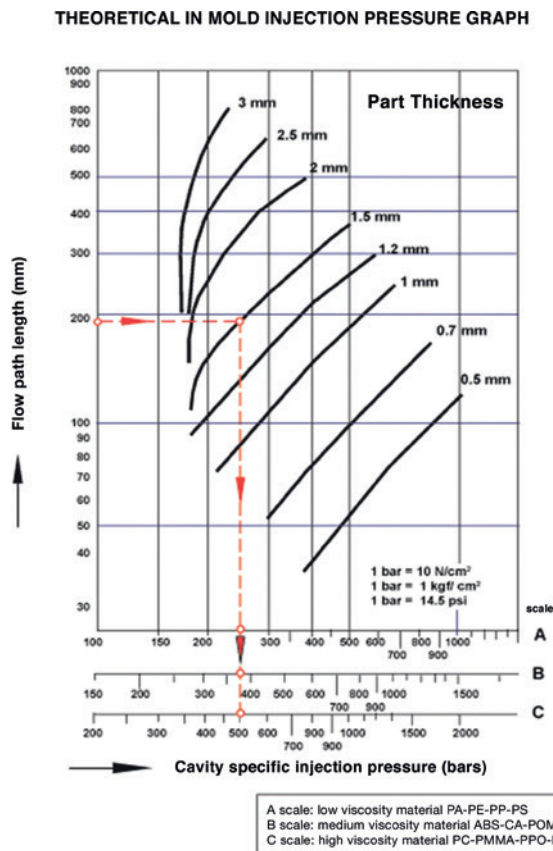


Figure 13.20 Source: Ascamm

13.3.3 Residence Time of Material

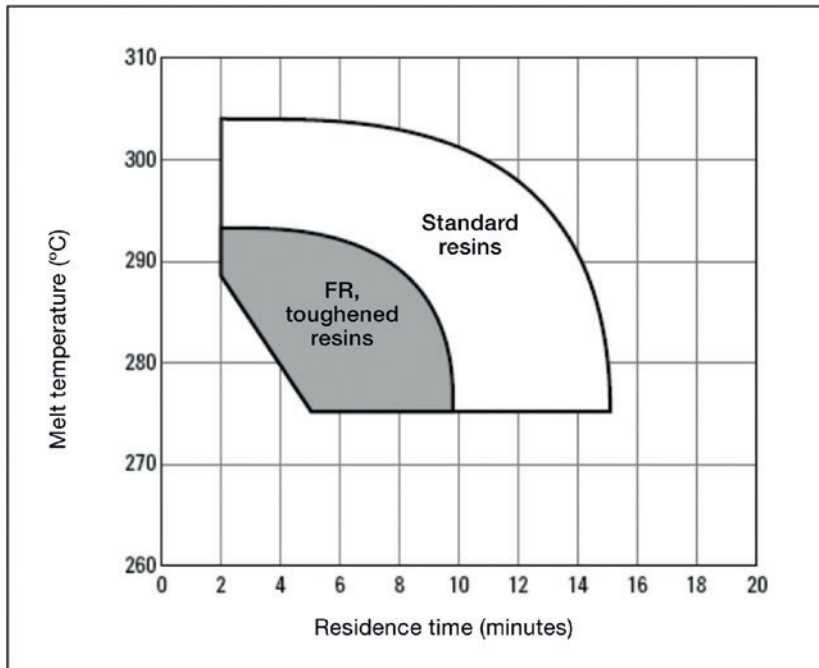


Figure 13.21 Example of degradation area as a function of time and temperature for a PBT polymer, standard and flame retardant; source: DuPont

Rule of thumb: the longer the residence time, the lower the injection unit temperature required in order to avoid thermal degradations.

13.3.4 Injection Unit Size

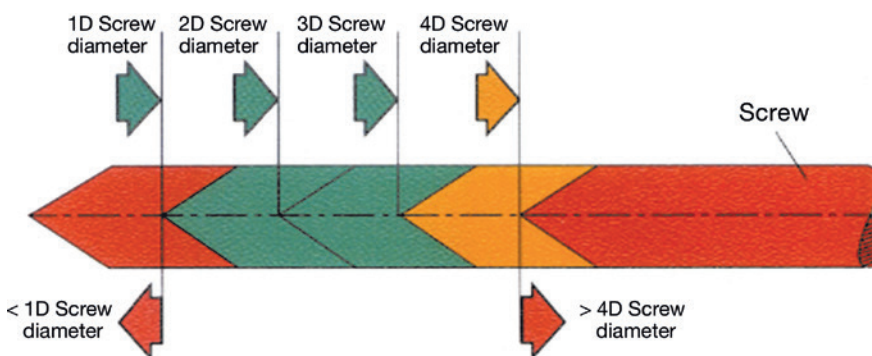


Figure 13.22 Optimal range of use of the injection unit capacity: dosage stroke from 1D to 3D (D = screw diameter); 3D–4D, exceptionally; not recommended: less than 1D or more than 4D

- Choose the machine whose injection unit has the better ratio dosage/screw diameter
- Do not exceed the recommended maximum residence time
- Do not exceed the optimum diameter range of 1D to 3D

13.3.5 Screw

See Sections 13.2.1.1, 13.2.1.2, 13.2.1.3, and 13.2.2.

It is recommended, if possible, to choose for some materials such as PMMA, PC, PPSU, PVC, etc. special screw designs for each material. If not, a universal screw design usually works fine.

13.4 Hardening Treatments for Injection Unit

Bimetallic Screw

Hardening treatments affect the life duration of the barrel and screw due to wear. With bimetallic treatment the operative life can be until four times more than with nitrided treatment. See Figure 13.14.

Barrels, screws, screw tip, non-return check valves and nozzles with hardening treatment are highly recommended for materials with fillers or reinforcements or chemical aggressive additives and flame retardants materials. For this kind of polymers, the most recommended is bimetallic treatment.

13.5 The Pressure Multiplier

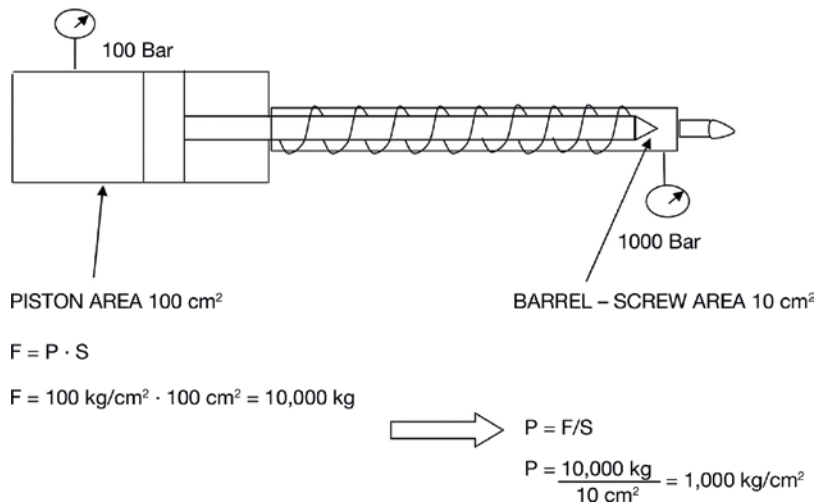


Figure 13.23 Pressure multiplier scheme

The injection unit acts as a pressure multiplier. The hydraulic pressure that the hydraulic pump provides is multiplied by the intensification ratio (IR) and the specific injection pressure over the material is obtained.

For example: 100 bar hydraulic pressure becomes 1,000 bar specific injection pressure over the material. The intensification ratio in this example is IR = 1 : 10.

According to the hydraulic and specific pressures chart (Figure 13.24), if we divide the specific injection pressure by the hydraulic pressure, we will know the relationship between the hydraulic piston and the screw.

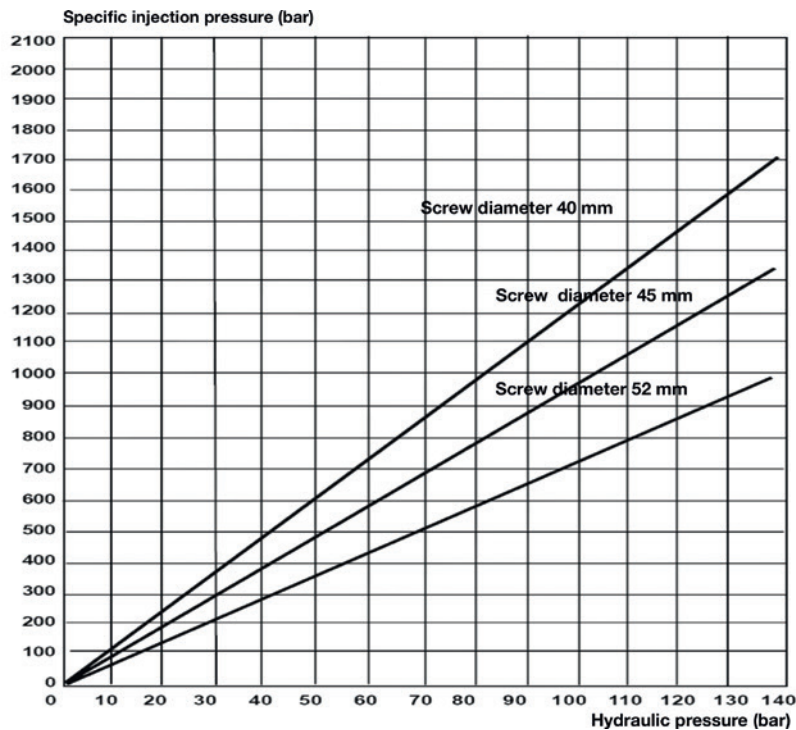


Figure 13.24 Hydraulic and specific pressures chart; source: Ascamm



Figure 13.25 Source: AGI, FANUC

Specific Injection Pressure

In the graph in Figure 13.24 it can be observed how in the same injection unit different specific injection pressures can be obtained, depending on the screw diameter. This multiplier is called the intensification ratio IR or multiplier ratio.

- When choosing the right machine, we have to take into account the pressures required to fill cavities
- Viscous materials or with small thicknesses may require high injection pressures
- High or explosive injection speeds need very high injection pressure

Key Parameters for Setting the Injection Molding Process

14.1 Injection Speed

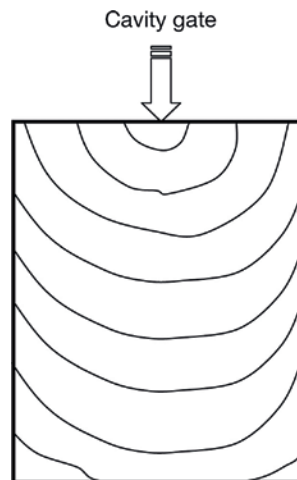


Figure 14.1 Isochronous lines show the progress of the flow front. These lines should be as equidistant as possible

Injection speed is the only critical speed in the injection process. Depending on the part geometry and the regulation of this speed, a faster or a slower cavity filling will be obtained.

It is clear that a higher speed shortens the injection time and a lower speed will lengthen the injection or filling time.

High injection speeds cause a fast increase of the injection pressure. Rather low injection speeds involve pressure drops in the nozzle and channels due to the rapid growth of the solid layer. In this case “we lose liquid vein” and therefore we cannot transmit the pressure far and optimally.

Screw speed should control the progress of the material into the cavity. The filling should be as steady and fast as possible, so that the slope of injection pressure will also be constant.

14.2 Ideal Filling Situation

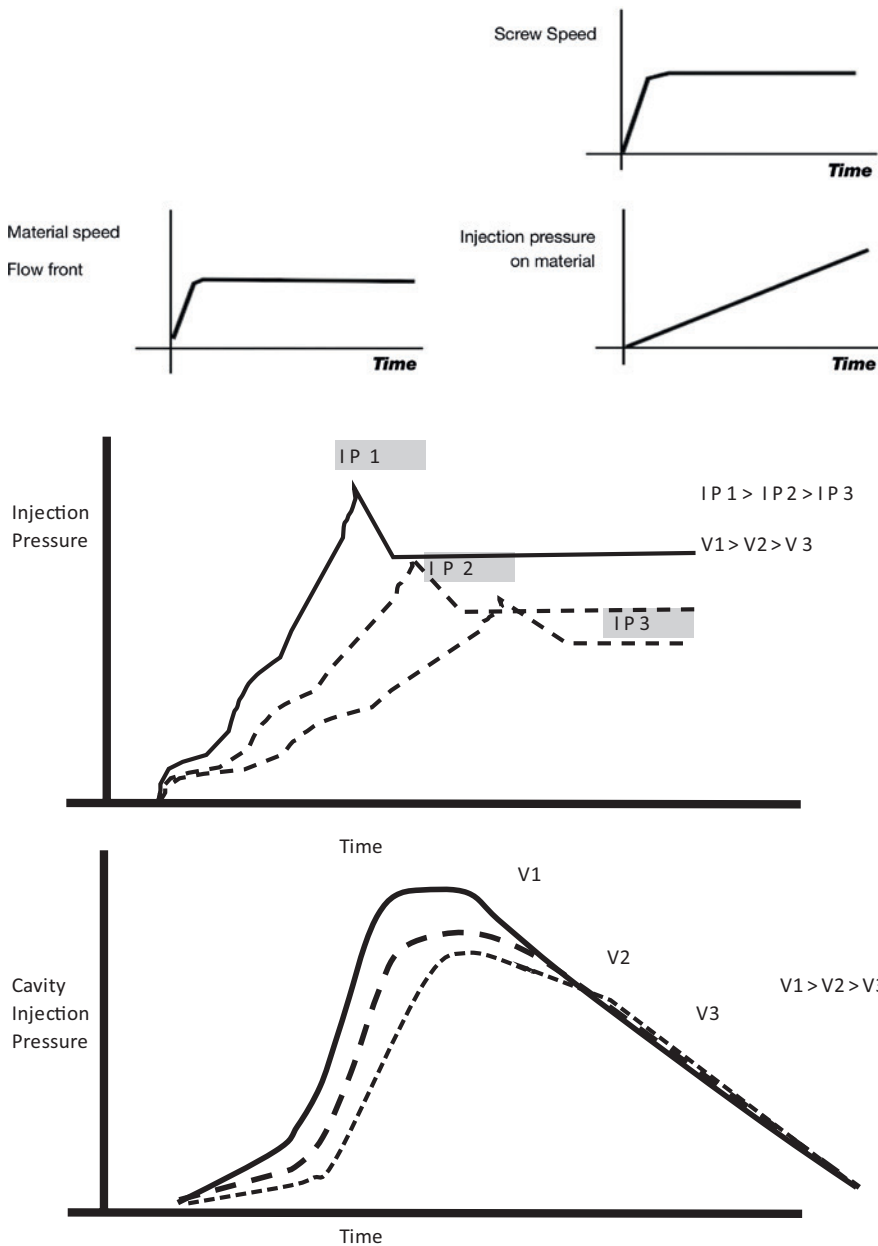
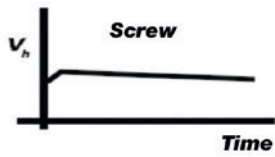


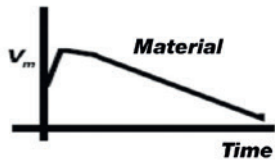
Figure 14.2 The higher the injection speed, the higher the required injection pressure (both the hydraulic and the cavity pressure)



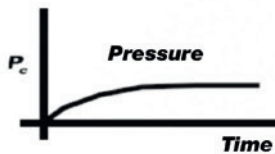
Let us imagine a part with a small thickness near the gate, and thick at the end of the filling: **thin to thick flow path**.



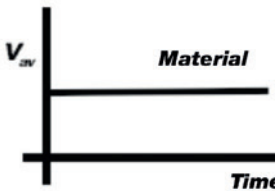
If our screw speed profile is flat.



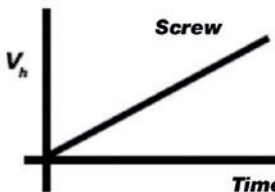
The true speed of the flow front inside the cavity will decrease.



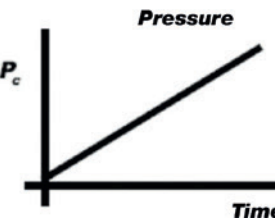
The hydraulic pressure will be flat because there is no increasing effort requested to meet the speed profile set in the machine control.



The flow front must advance into the cavity at a constant speed.



To achieve this, the speed profile set in the machine control must be increasing. Thus, we request a higher screw speed in the filling area, which has a greater thickness.



The hydraulic pressure will proportionately increase because the hydraulic system of the machine will require a greater pressure to meet the speed profile set.



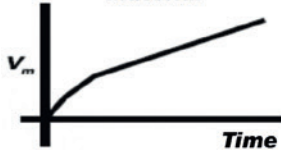
Now let us imagine a part with a great thickness near the gate, and thin at the end of the flow path: **thick to thin flow path**.

Screw



If our screw speed profile is flat.

Material



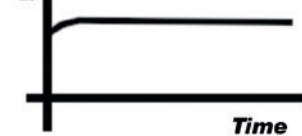
The true speed of the flow front inside the cavity will increase.

Pressure



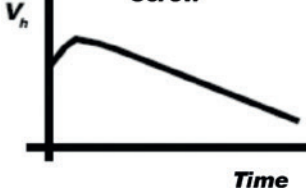
The hydraulic pressure will grow quickly and not proportionally because there is a big effort requested to the hydraulic machine system to meet the speed profile set in the machine control.

Material



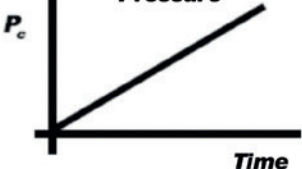
In order to have a right cavity filling, the flow front must advance into the cavity at a constant speed.

Screw



To achieve this, the speed profile set for the screw must be decreasing. Thus, the screw speed will be lower for the filling of the thin part area.

Pressure



The hydraulic pressure will grow proportionately because the hydraulic system of the machine will require proportionately more injection pressure to meet the speed profile set in the machine control.

The decreasing speed profile scheduled avoids pressure peaks at the end of filling.

The key point is that we must establish a screw forward speed profile that allows us to obtain a constant advance of flow front during the cavity filling.

14.2.1 Filling Speed Rate

As a general rule we must fill the cavity in the shortest time possible, not only to reduce the total work cycle but to prevent premature growth of the solid layer that renders the proper pressurization of the cavity more difficult. However, we must take into account the following aspects:

14.2.1.1 Very High Speeds

- They may cause overheating and thermally degrade the material.
- They may cause maximum shear stress of the material, causing breakage of molecular chains and the consequent loss of properties.
- They may cause stretching and displacement of the solidified layer cold. The inner molten layer will emerge outward creating aesthetic defects and exfoliations.

14.2.1.2 Very Low Speeds

They may cause reductions in material passage area due to the increase of cold layer in contact with the steel of the mold. This situation causes an increase in the injection pressure needed to move the flow.

14.2.1.3 What Affects the Filling Speed?

The filling speed rate is mainly influenced by the following elements:

- | | |
|----------------------|--|
| ■ Material | Flow rate, viscosity
Melt temperature |
| ■ Design of the part | Wall thickness
Thickness changes
Sharp corners, radii
Mold and part surface finish |
| ■ Mold design | Gate sections
Runners passage sections
Mold heating and cooling system
Injection gate position
Venting, efficiency, and location |

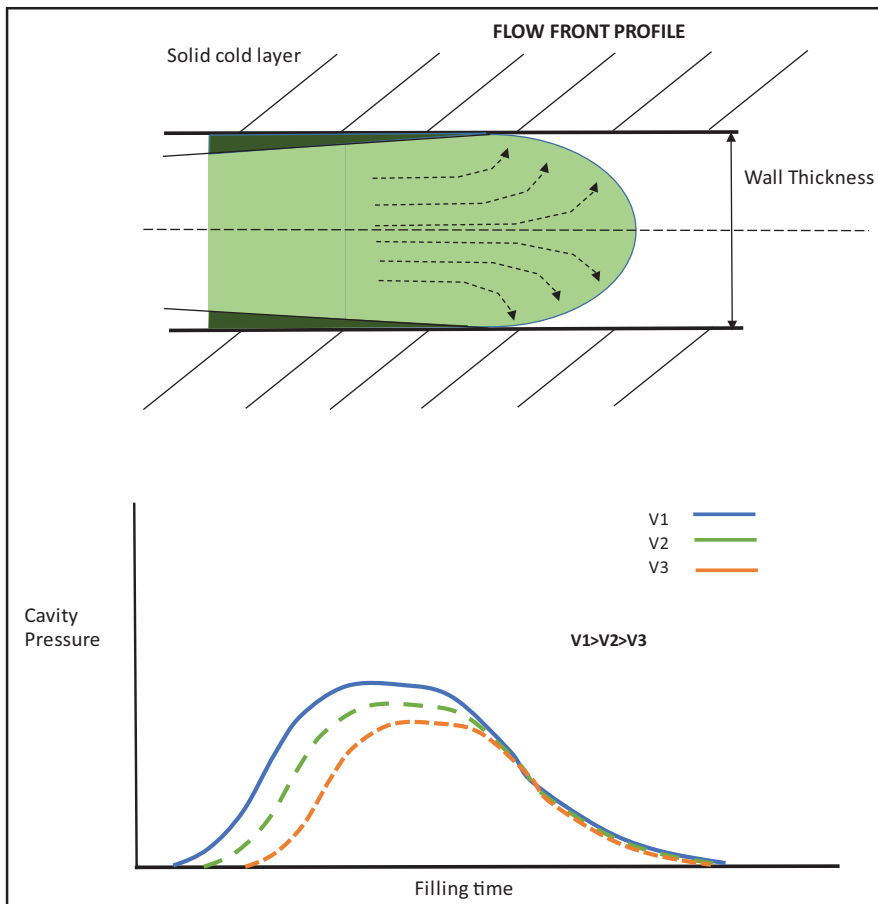


Figure 14.3 Flow front and cavity pressure as a function of injection speed

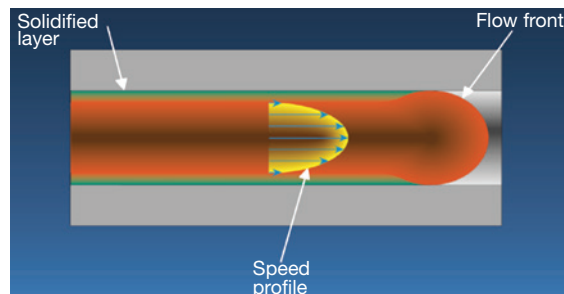


Figure 14.4 Flow front different speeds and orientation

Increasing the filling speed, we get:

- A reduction in the visibility of weld lines
- A greater mechanical strength of the weld lines
- An increase in the surface gloss of the piece
- An increase in the crystallinity
- An increase in the melt temperature during the filling
- An increase in the clamping force required
- A higher degree of balance of the cavity pressures
- A higher degree of surface orientation

14.3 Melt Temperature

This parameter is the result of the following elements:

- Screw rotation speed
- Back pressure
- Injection unit temperature

The value obtained must be in the processing range recommended by the manufacturer of the polymer. The melt temperature chosen will also depend on the following elements:

- Material melt flow
- Mold design (gate, hot runner, runners section, cooling system)
- Part design (flow path length, thickness ratio, etc.)

Influence of the mass temperature

If we increase the mass temperature, we will get:

- A lower material viscosity and an increasing melt flow
- A reduction in orientation
- A reduction in internal stresses
- A reduction and an improvement in the resistance of the weld lines
- A smaller pressure drop in the mold
- An increase in the shrinkage
- An increase in the gas generation
- An increase in the cooling time
- An increase in the crystallinity
- An increase in the surface brightness
- An increase in the tendency to burrs and flashes

BARREL TEMPERATURE PROFILE FOR A CONSTANT AND HOMOGENEOUS MELT TEMPERATURE

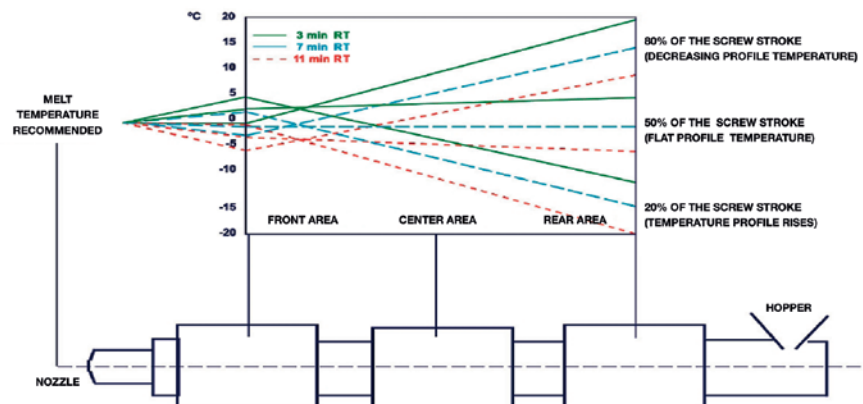


Figure 14.5 Source: DuPont

$$\text{RESIDENCE TIME (min)} \quad RT = \frac{\text{Resin weight into the barrel}}{\text{Shoot weight}} \times \frac{\text{Cycle (s)}}{60}$$

Material	Melt temperature (°C)	Ejection part temperature (°C)	Material	Melt temperature (°C)	Ejection part temperature (°C)
Amorphous			Semi-crystalline		
PS	170–200	60	LDPE	190–200	80
SB	180–280	90	HDPE	210–300	110
SAN	200–260	110	PP	200–290	110
ABS	200–270	100	PA66	270–320	230
PPO	250–290	200	PA6	230–280	200
Rigid PVC	170–210	50	PA6 10	230–280	200
Flexible PVC	140–200	60	PA11	200–250	170
PMMA	180–260	140	PA12	200–260	160
PC	280–320	140	POM	190–220	150
			PET	260–280	210
			PBT	240–260	200

14.4 Screw Peripheral Speed

The melt temperature depends not only on the heat supplied by the barrel electrical heaters but also on heat generated by friction and shear within the screw during the melting and plasticization.

The units used to determine the tangential screw speed are meters per second.

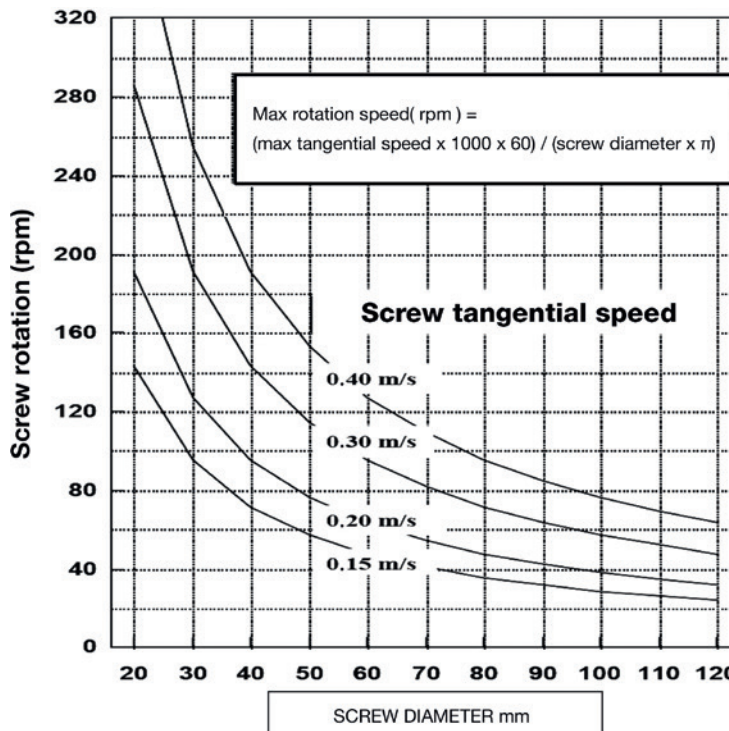


Figure 14.6 Tangential speed as a function of screw diameter and rotation speed; source: Ascamm

Table 14.1 Maximum Rotation Speed Recommended

Material	Tangential speed (m/s)
PE	0.8
PP	0.7
PS	0.7
PA	0.5
POM	0.1 to 0.25
PET	0.3
PBT	0.35
ABS, ASA	0.5
SAN	0.55
PC	0.35
CA	0.45
PPE/PA, PPO	0.4
HYTREL	0.4
ABS/PC	0.2
PA 66	0.8
TPU	0.2

14.5 Back Pressure

Back pressure is the effective pressure value in the front tip of the screw during metering and dosage. It is equal to the pressure over the melt material supplied by the screw rotation movement and the screw design in the front area when material is being pumped to the screw front area, and that moves the screw backward to the dosage position. This parameter is adjustable by the machine operator and can reach values from 5 to 25 or 30 bar of hydraulic pressure.

This parameter may help in the right dispersion and homogenization of the material, melting unmelted material, and better plasticizing the melt.

The back pressure is very important in the mixture of pigments and additives and we must take care when processing reinforced materials (i.e., with glass fibers, mineral, steel fibers, carbon, etc.) to minimize wear of the screw and prevent damage of the reinforcing fibers.

Back pressure influence

By increasing the back pressure we get:

- A more homogeneous melted material
- More heat caused by friction
- A displacement of air trapped in the pellets to the feed zone
- A reduction in the dosage fluctuations and material cushion

Likewise, we must take into account these drawbacks:

- An increase in the time cycle due to a longer dosing time
- Sensitive materials can be thermally degraded

- The reinforcing fibers incorporated may be damaged
- The abrasion and wear between the screw and the barrel increases

14.6 Injection Pressure

The injection pressure during the filling stage should be sufficient to achieve the injection speed profile programmed in the machine control and to obtain the desired fill time. Factors influencing the injection pressure are the same as those affecting the filling rate:

- Resistance to material flow
- Filling speed
- Hydraulic oil temperature
- Material temperature
- Mold temperature

The resulting value of the filling pressure can be used to determine the correct setting of the parameters that influence it.

See Figure 13.24 in Chapter 3.

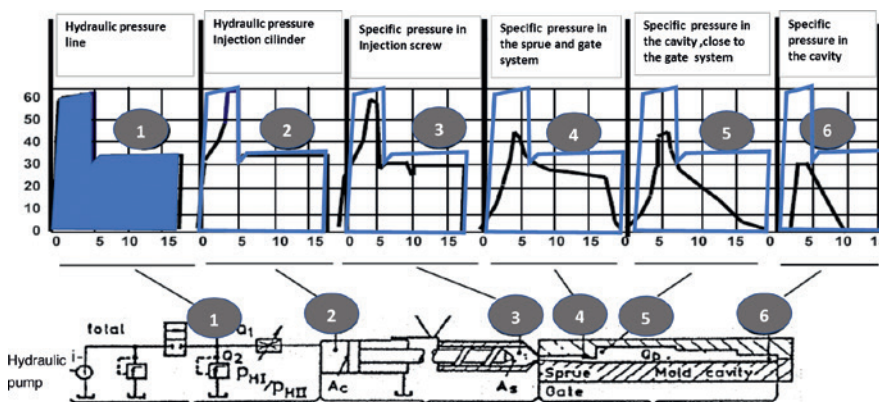


Figure 14.7 Pressure evolution along the hydraulic path (from the hydraulic oil tank to the melt). Pressure drops occur for various reasons

The injection pressure should be sufficient to achieve the set speed and, therefore, the desired filling time. It is influenced by the same factors as the injection speed.

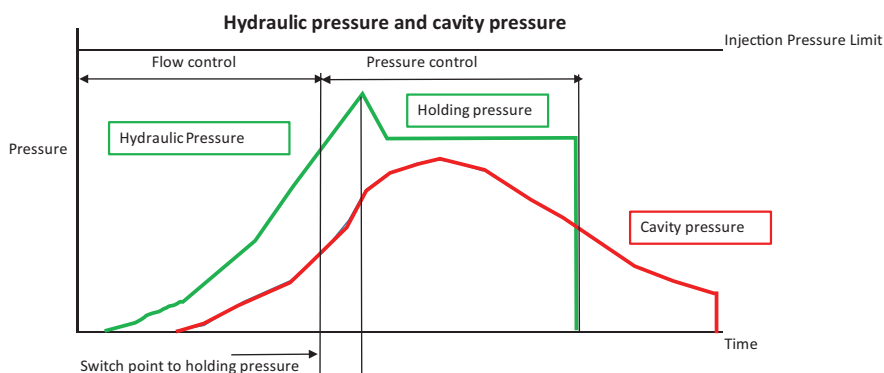


Figure 14.8 Injection pressure and cavity pressure evolution

14.6.1 Holding Pressure Switching Systems

- Switching by time
 - The worst of all systems
 - It ignores variations in viscosity
 - It ignores variations in melt temperature
 - Possible loss of precision when molding with high injection speeds
- Switching by stroke
 - The most commonly used system
 - It ignores possible material drop in the nozzle
 - It ignores transducers inaccuracies
 - Not recommendable with high dose/capacity ratios
- Switching by injection pressure
 - Reliable
 - It does not envisage variations in viscosity
- Switching by cavity pressure
 - Most reliable and expensive
 - It ignores mass and mold temperature variations
 - It compensates variations in speed, viscosity, material dripping, etc.

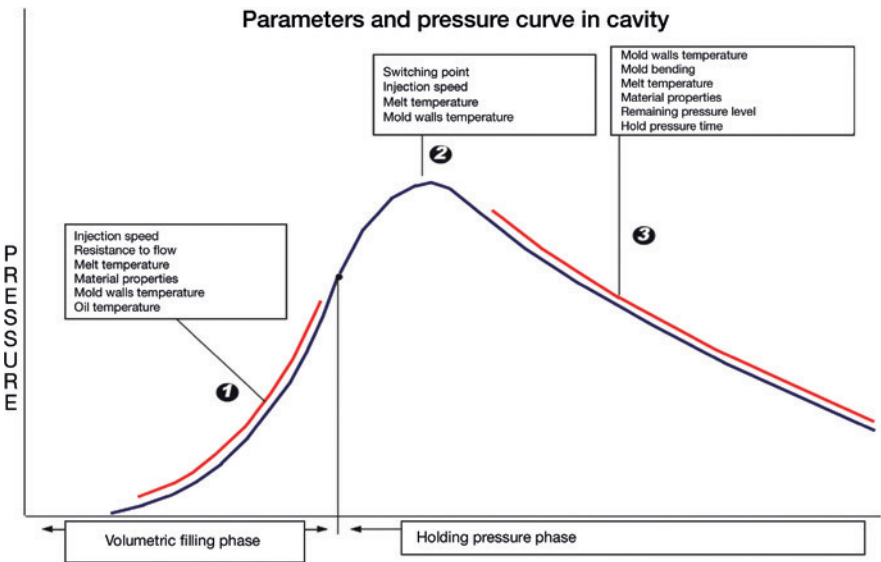


Figure 14.9 Cavity pressure chart (with affected parameters in each phase of filling and pressurization); source: Ascamm

14.7 Holding Pressure

Table 14.2 Related Features

Flashes formation	Sink marks
General shrinkage of the part	Vacuoles
Difficult part ejection	Weld lines resistance
Stresses in the gate area	Part weight

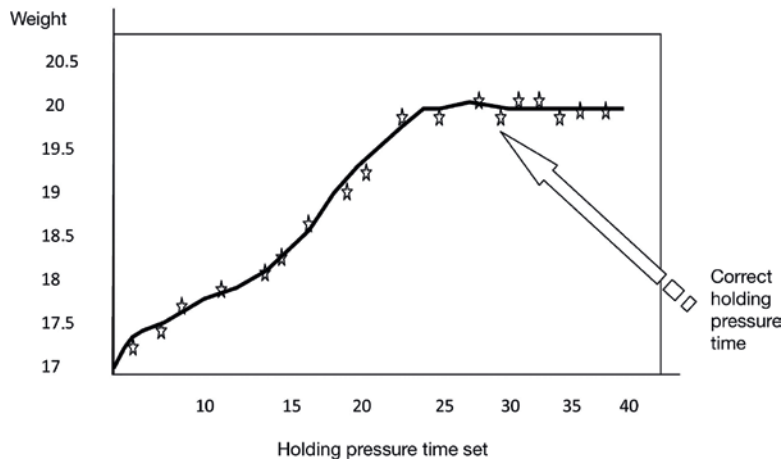


Figure 14.10 Evolution of injected mass weights to determine the optimum holding pressure time

14.8 Holding Pressure Time

The holding pressure time can be determined or defined by:

- Cavity pressure drop (a sensor cavity is needed)
- Injected mass weight control

14.8.1 Cavity Pressure Drop

When determining the optimal holding pressure time with this system, we must bear in mind that, if time is shorter than the optimal, the pressure in the cavity will drop sharply when the hydraulic pressure ceases. But if the time is long enough, the cavity pressure will remain and slowly fall when the hydraulic pressure ceases. This indicates that the gate has been sealed.

14.8.2 Injected Mass Weight Control

The optimal time gets the maximum weight of the piece. By increasing the holding pressure time we obtain weight gains. However, there is a moment in which the weight stops growing although the time is increased.

When controlling by weight, runners must be disregarded.

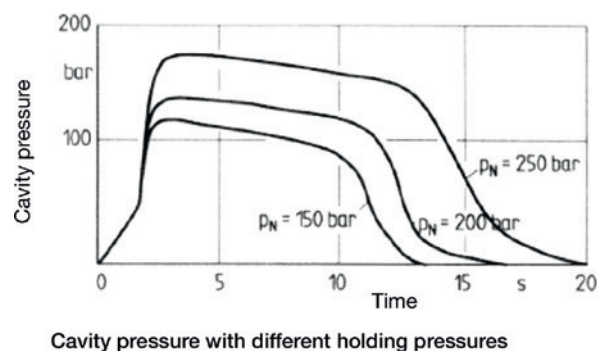


Figure 14.11 Cavity pressure; source: Ascamm

14.9 Mold Temperature

The mold and cavity temperatures determine the cycle time and the quality of the structure of the injected part.

Low mold temperatures cause shorter cooling times and high cooling speeds that can adversely affect the quality of the part.

In the case of semi-crystalline thermoplastics, the properties of molded parts depend on the cooling speed. A fast cooling makes an amorphous outer layer and a low level of crystallinity. In contrast, a slow cooling results in a high degree of crystallinity, stable lamellae and crystals, and better mechanical properties.

The ideal situation is a homogeneous cooling obtained from a homogeneous temperature distribution in the mold and in the melt. To achieve this, a correct thermal conditioning of the mold is necessary.

Depending on the material we are transforming, we must act differently in order to achieve an appropriate mold temperature:

- Cooling with water
- Tempering with pressurized water to temperatures up to 140–150 °C
- Tempering with oil to temperatures over 150 degrees
- For higher temperatures, heating with electrical heaters

Increasing Mold Temperature

Increasing the mold temperature means:

- Increased surface brightness, gloss
- Reduced internal tensions
- Increased impact resistance
- Improved weld lines resistance and aspect

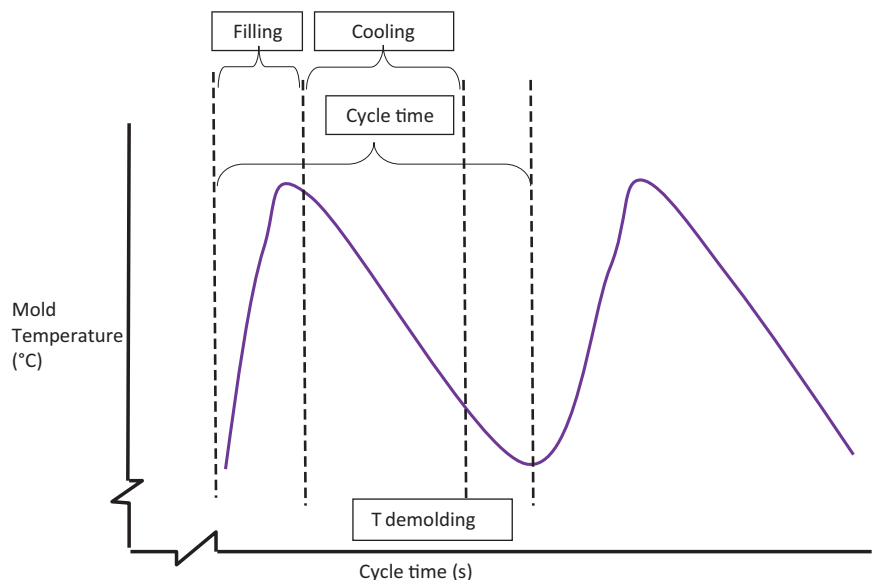


Figure 14.12 Temperature behavior in the mold wall at each injection cycle

- Increased molding shrinkage
- Increased formation of flashes
- Increased injection cycle time

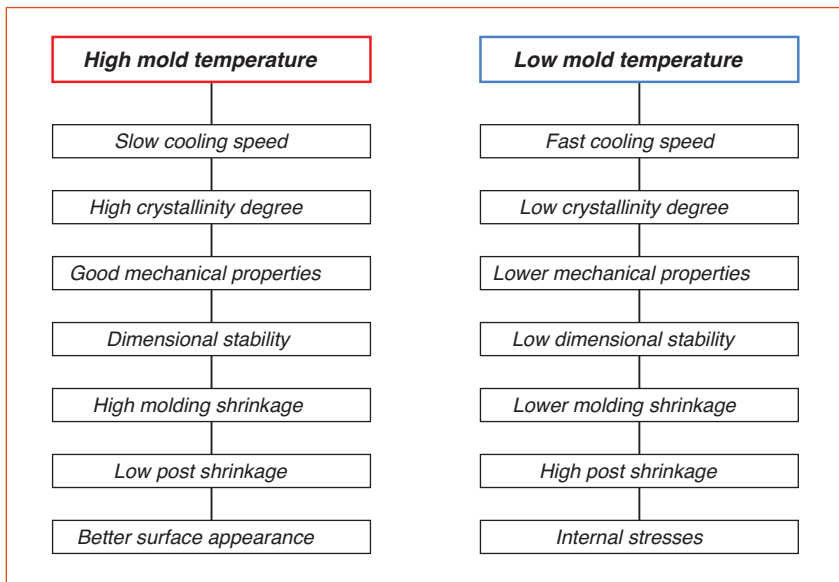


Figure 14.13 Comparison between hot and cold mold



The mold temperature influences:

- Mold shrinkage and post-shrinkage
- Surface gloss
- Internal stresses
- Impact resistance
- Weld lines
- Flashes
- Injection time

Table 14.3 Mold Temperatures Recommended for Some Materials

Amorphous	Mold (°C)		Semi-crystalline	Mold (°C)
PS	20–80		LDPE	20–60
SB	10–60		HDPE	20–60
SAN	40–80		PA6	80–90
ABS	60–80		PA66	80–90
PVC	80–90		PA610	40–90
CA	50–80		PA12	40–80
CAB	50–80		POM	40–120
PMMA	40–80		PAT	90–160
PC	80–120		PBT	40–100
PPO	80–120		PPS	130–150
PA	70–100			

14.10 Dosage

Experimentally, it has been determined that the optimal screw stroke is between 1–3 screw diameters. Dosages lower than one diameter and greater than four diameters should be avoided.

The volume used in an injection unit is approximately 70 to 80 % of its maximum capacity and a minimum of around 20 to 30 %.

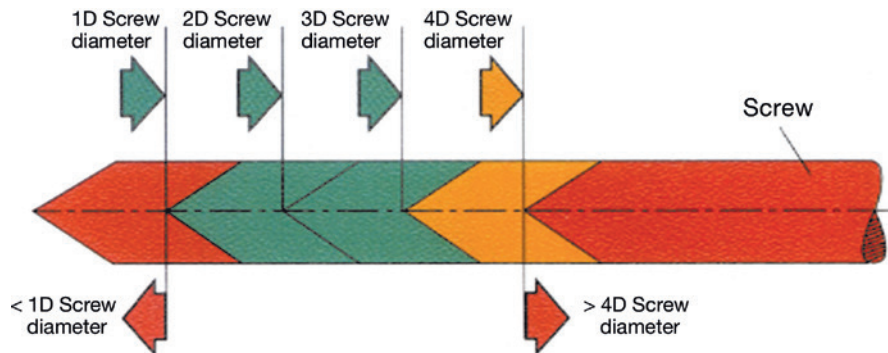


Figure 14.14 Optimal range of injection unit use: 1 to 3 diameters (exceptionally, from 3 to 4); not recommended: < 1 or > 4

14.11 Cushion

Cushion is the residual volume remaining at the front zone of screw at the end of the holding pressure stage. It is essential to have some cushion level to ensure the correct application and “upstream” transmission of the injection pressure. It also absorbs volume differences between cycles, providing stability in the weights and volumes injected.

This parameter provides very good information about the stability, consistence, and precision of the defined process.

In general, and depending on the screw diameter, the cushion should have a volume equivalent to 5–10 % of the injected volume.

Table 14.4 Parameters’ Deviations Percentage by Type of Parts Injected

Parameter	Precision parts	Technical parts	Commodity parts
Dosing time	1	2	5
Injection time	0.5	1	2
Switch point to holding pressure	1	1.5	2
Cushion	2	3	4
Melt temperature	1	2	3
Clamping force	2	3	4
Back pressure	5	8	10
Dosage stroke	0.1	0.2	0.3

Correct and Optimized Methodology for the Process Start-up

15.1 Requirements: Information Required

15.1.1 Material

- Molding recommendations given by the manufacturer of the raw material
- Technical data (viscosity, MFI, Vicat, etc.): data sheet

15.1.2 Part

- Design tolerance
- Standard reference part sample
- Weight and volume of the part
- Thickness

15.1.3 Mold

- Drawing design of the mold
- Cooling system scheme
- Mold flow and simulations
- Scheme of electrical connections, hydraulic cores, slits, etc.
- Kinematics of movement

15.1.4 Machine

- Technical data of the machine
- Screw diameter and type
- Screw compression ratio
- L/D ratio
- Tons of clamping force
- Maximum injection volume
- Maximum injection pressure
- Intensification ratio
- Equipment and peripherals

15.2 Possible Previous Calculations

Injection pressure required Depends on:

- Material type
- Part thickness
- Flow path

According to the graph in Figure 15.1, we can estimate the injection pressure required depending on the material, thickness, and the flow path; it is recommended to add 10% to the result. (A: high fluidity; B: medium fluidity; C: low fluidity.)

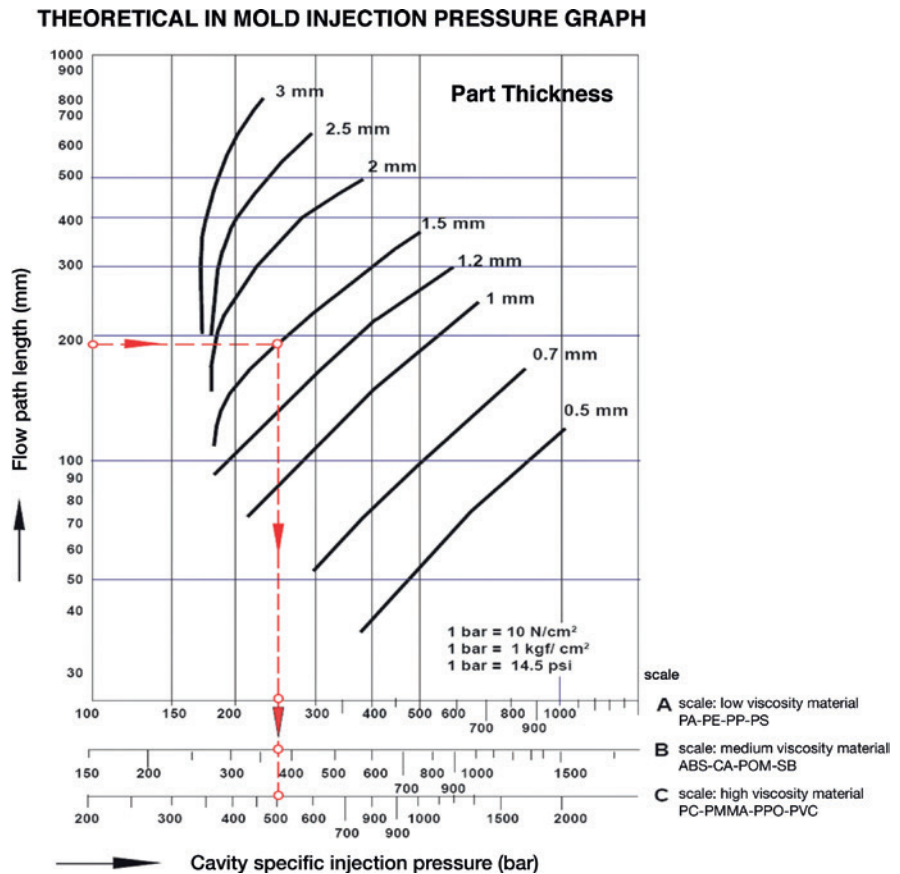


Figure 15.1 Theoretical in-mold injection pressure graph; source: Ascamm

Clamping force T_n required Depends on:

- Injection pressure [kg/cm²]
- Projected area [cm²]

$$CLAMPING\ FORCE = \frac{(INJECTION\ PRESSURE \cdot AREA)}{1000} = T_n$$

Maximum peripheral screw speed (rpm) Depends on:

- Material
- Screw diameter

$$MAX\ rpm = \frac{MAX\ SPEED\ (m/s) \cdot 60,000}{2\pi r}$$

Cooling time (initial and theoretical)	Depends on:	■ Material
		■ Part thickness
		■ Hot or cold mold

$$T = E_2 \times K + (\text{if mold} > 60^\circ\text{C}) 30\%$$

Note: part temperature must be 10 or 15 °C below the Vicat to be unmolded.

K depends on the material, for example:

Semi-crystalline (POM, PA, PBT)	$K = 0.4 - 0.6$
Amorphous (ABS, ASA, SAN)	$K = 1.2$
Other amorphous	$K = 2.5$
TPU	$K = 2.5$

Estimated dosage stroke	Depends on:	■ Screw diameter
		■ Part weight
		■ Material (melting density)

$$D = \frac{(\text{weight} \cdot 1273.2)}{(\text{screw diameter}^2 \cdot \text{melting density})} + (\text{screw diameter} \cdot 0.3)$$

Note: ideal dosage: from 1 to 3 screw diameter; ideal cushion: from 5 to 10% of dosage.

Residence time of material	Depends on:	■ Cycle time
		■ Dosage stroke
		■ Maximum dosage stroke
		■ Screw diameter

$$RESIDENCE\ TIME\ (min) = \frac{MAXIMUM\ DOSAGE\ STROKE\ OF\ MACHINE}{DOSAGE\ STROKE} \times (CYCLE / 60)$$

Note: compare the result with maximum residence time recommended tables.

However, the following formula is preferable:

$$RESIDENCE\ TIME = \frac{(8 \cdot SCREW\ DIAMETER)}{MAXIMUM\ DOSAGE\ SCREW} \times (CYCLE / 60)$$

Dosage/diameter ratio	Depends on:	■ Dosage stroke
		■ Screw diameter

$$R = \frac{DOSAGE\ STROKE}{SCREW\ DIAMETER}$$

Note:

Ideal ratio: from 1 to 3 screw diameter.

If ratio < 1 diameter → air on melt (less homogeneous).

If ratio > 3 diameters → excessive permanence.

Ideal L/D ratio: 20.

15.3 Injection Machines Tune-up

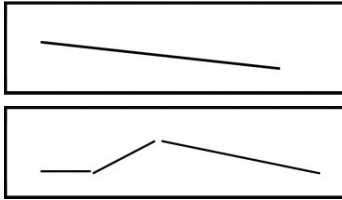
Temperatures

We must program drying temperatures according to the manufacturer's recommendations.

Key points

- Dehumidified better than conventional forced air-dried
- Dew point: -30 or -40 °C

Melt temperatures setting



- Manufacturer's instructions
- Amorphous materials profile
- Semi-crystalline materials profile
- Profile according to residence time
- Increasing or decreasing depending on the residence time

Key points

- Programming +/- temperature deviation regulation tolerances
- Screw stop when temperature set point is not reached
- Decreasing temperature when process stops
- An increase in melt temperature reduces viscosity, increases fluidity, and can cause problems with gases
- A decrease in melt temperature can difficult the mold filling

Mold temperatures setting

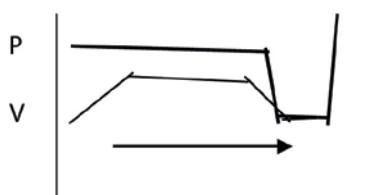
- According to material and work-piece
- Excessive bridges connected are not recommended
- If we double the passage section of the tube, the flow will be quadrupled
- Turbulent flow drags more heat (up to four times) than laminar flow
- No less than 3/8 of diameter water flow
- Input/output thermal difference: no more than 3-5 degrees
- Less means an excessive cooling
- More means an excessive path in the system

Key points

- Semi-crystalline materials: it defines structure and crystallinity
- It affects shrinkage and surface gloss
- It minimizes internal stress
- It affects the filling speed and pressure

15.3.1 Motion Setting

Closing Profile

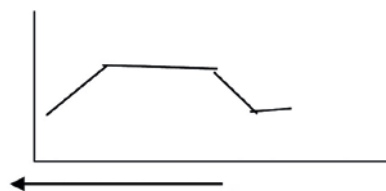


Key points

- Slow-fast-slow motion
- Favorable toggle kinematics
- Fine adjustment of the toggle by cross-head position at end of movement
- Switch point to mold closing security stroke, critical dimension
- Pressure and speed in closing security mold zone is critical
- High closing pressure—critical switch point

Opening Profile

Profile



Key points

- Slow-fast-slow closing movement speed profile
- Mold protected by first opening stage slow
- Natural movement, without shock
- Set opening stroke position for starting the ejection movement

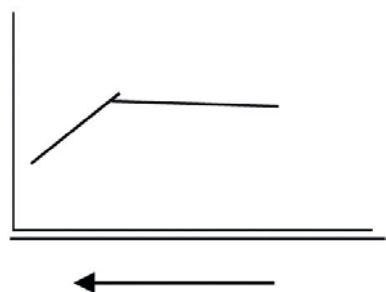
Ejector

Key points

- No fluid hammers
- Different pressures and speeds for optimizing this movement
- Ejection plate should not knock the mold during the ejection movements

Injection unit movement

Profile

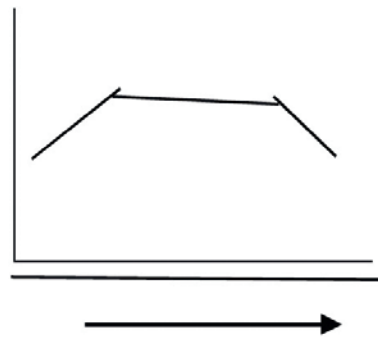


Key points

- Hot channels: carriage always in contact with mold
- Soft movements (without fluid hammers)
- Return after dosage is finished
- Beware of drooling material in open nozzles, nozzle temperature, and suction

Dosage

Profile



Key points

- Screw peripheral speed does not exceed the maximum recommended
- Slow-fast-slow speed profile
- High energy consumption movement
- Dosage time should be shorter than cooling time

Back pressure

Key points

- Back pressure, profile ascent ramp, descent
- Back pressure homogenizes melt
- Back pressure eliminates air in the melt material
- Back pressure improves dose accuracy

Suction

Key points

- It can generate air streaks
- The nozzle-sprue contact is not hermetic
- We must do the suction movement slowly and make it as short as possible

15.3.2 Injection Machine Start-up

15.3.2.1 Injection Fine-Tuning

15.3.2.1.1 Injection Speed

It should be the highest possible without damaging the material or generating excessive shear rate or entrapment of air (Diesel effect).

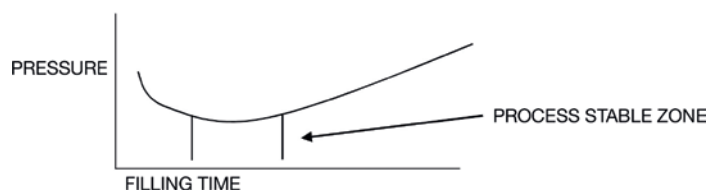


Figure 15.2 Evolution of the injection pressure needed according to the programmed injection speed rate

Injection speed affects:

Incomplete parts	Surface gloss
Parts with flashes	Melt temperature increased by shear rate
Parts with burns	Increases in the needed clamping force

15.3.2.1.2 Holding Pressure

Setting as initial holding pressure:

- Amorphous materials: 50% of the pressure required to fill cavities
- Semi-crystalline materials: 75% of the pressure required to fill cavities

Modify these values depending on the injected parts.

Holding pressure affects:

- Shrinking cavities, sink marks Vacuoles
- Flashes Ejection marks
- Deformations, warpage Stress near the gate

Holding pressure controls:

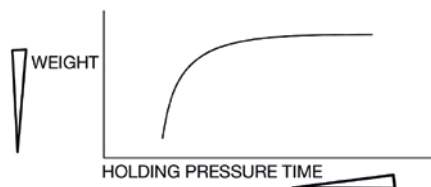
- Part weight
- Part dimensions

A combination of high pressure during short times causes lower levels of stress than the opposite (low pressure levels during long hold pressure times).

15.3.2.1.3 Holding Pressure (Time)

Initially use 2–3 times the filling time.
Then we must do a gate seal study.

Modify according to the part injected.



15.3.2.1.4 Switching to Hold Pressure Stage: Systems

Before switching to hold pressure stage, we must have filled the cavity up to 95–98%.

Switch system	Advantages	Disadvantages
Stroke position	Easy programming Good for small thicknesses	Affected by variations in melt temperature Affected by the different viscosities between batches of material When the dose-screw diameter ratio is small, a small mistake in the switch change position involves a big mistake on material volume and results in low accuracy

Switch system	Advantages	Disadvantages
Time	Easy programming	Unreliable, inconsistent Affected by changes in injection speed Affected by temperature variations of melt Affected by variations in mold temperature Affected by changes in viscosity between batches High injection speed can cause high variations of injected volume and result in low accuracy Worst system
Hydraulic or specific injection pressure	More stable and consistent More accuracy	More complicated programming Not available on all machines
Cavity pressure	More stable and consistent Process variables are absorbed	Machine and mold are more expensive

The switchover by hydraulic or specific injection pressure system of changing to hold pressure stage absorbs slight viscosity differences between batches of material and mold and melt temperatures. When the switching pressure is reached and the programmed switching window too, the machine will switch over to holding pressure. This change will be made regardless of the time taken to reach the pressure or the stroke position displacement of the screw in which the change to holding pressure will be made.

It is the most precise and consistent switching system except for the in-cavity pressure change system.

It is not recommended when the injection pressure rises quickly at the start of injection stroke due to restrictions of flow passage.

Hydraulic Pressure vs Specific Pressure on the Material

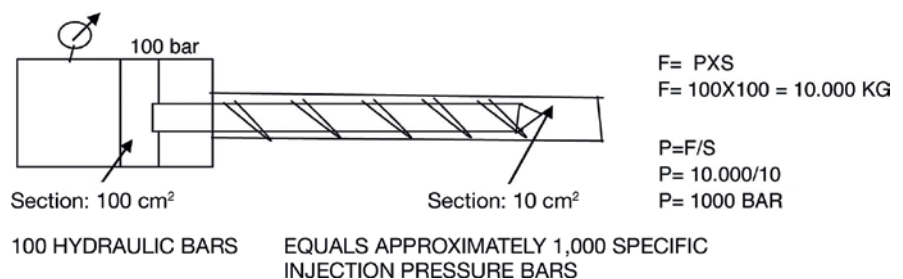


Figure 15.3 Schema of multiplication from hydraulic to specific pressure

15.3.3 Operative Method

Start-up and Fine-Tuning of Injection Machines: Methodology

We have to set the temperature profiles of the injection unit and the hot runners as recommended by the manufacturer of raw material.

1. Set mold temperatures according to the material and the part to be injected following the plastic material manufacturer's recommendations.

Place and fix the mold into the clamping unit

2. Set the thickness of the mold in the clamping unit.
3. Set the clamp force T_n (according to previous calculations).
4. Set opening stroke, opening speed profile, different speeds change points, and switch point of the ejection start.
5. Set closing stroke, speed profile, safe mold stroke points, pressure and speed in the safe mold stage, switch point to high pressure clamping force, setting time control surveillance for closing mold.
6. Set ejector stroke, forward and return speeds and pressures, ejection repetitions or number of ejection movements.
7. Set injection unit forward movement stroke, damping positions, speeds, contact pressure, with open mold. Repeat this process with the injection unit return stroke.
8. Set dosage stroke (according to previous calculations), rpm, and peripheral speed profiles without exceeding the maximum calculated for the material used, set back pressure level and, if necessary, a profile for the back pressure during dosing stage.
9. Set injection speed rate, high or medium speed level profile at the beginning (flat initial profile). Later retouch depending on the filling of the part.
10. Set cooling time (according to initial calculations).
11. Set maximum injection pressure available near the maximum peak of the machine. A limited by pressure injection process should not be programmed.
12. Set holding pressure to zero.
13. Set holding pressure time to zero.
14. Set switching point to holding pressure stage to a value close to the stroke level of dosage for a gradual and progressive filling. The goal here is to inject a little material volume with no pressure limit.

Progressive mold filling setting

15. Make a progressive mold filling, watching how the filling of the cavity occurs. Reduce gradually the switch point to hold pressure stage or switching point. The goal here is to increase gradually the injected volume step by step.
16. Pay special attention to the points where the flow accelerates, characterized by an increase of flow front, and where the flow slows down and sometimes stands. Observe at which levels of the injection stroke the movements of acceleration and deceleration of flow occur.

- 17. Modify the velocity profile at the points where the flow front of the material undergoes accelerations and decelerations. The objective is to obtain a uniform advance of the flow front.
- 18. Determine the optimum switching point or change point to hold pressure stage. Fill the cavity to 95–98%. (Under normal conditions, the material will have reached every corner of the cavity.)
- 19. At this point the machine provides the following information:

Filling time:

Use these data for setting if we want to switch by time.

Injection pressure at switching point:

Use these data for setting if we want to switch by injection pressure switch.

Real switch point position:

Use this setting if we want to switch by stroke.

Setting the holding pressure

- 20. Initial setting of the holding pressure depending of the material morphology:

Amorphous:

50% of the injection pressure required to fill.

Semi-crystalline:

75% of the injection pressure required to fill.
- 21. Set the limit injection pressure 200–300 bar above the pressure needed to fill (whenever this does not decrease by hydraulic effect; see “Determining Delta P” section in Chapter 21–Section 21.6.2).
- 22. Set an excessively long holding pressure time to ensure that the gates are sealed.
- 23. Set a holding pressure to provide injected parts with accurate dimensions and appearance.
- 24. Weigh the parts.
- 25. Reduce holding pressure time and control the weight of the injected parts. When the weight of the parts begins to decrease (as the gates are open), slightly increase preceding time. This is the minimum holding pressure time to ensure that the gates are well sealed.
- 26. Set tolerances in process control for the following parameters:

Injection unit

Filling time

Dosage time

Cushion level

heaters tempera-
tures

Cycle time

Melt index

Control charts

Etc.

15.3.4 Progressive Mold Filling

For the correct setting of a mold it is advisable to perform a filling study through a progressive filling of the cavities. Thus we can see how the cavities are filled and detect the critical filling points.

Setting of the injection machine for a filling study:

- Melt temperature as recommended
- Mold temperature as recommended
- Set a high injection pressure limit so that the process cannot be pressure-limited
- Set holding pressure values at zero
- Set holding pressure time at zero
- Switching system selected by the screw stroke
- Set a switching point to holding pressure near to the dosage stroke position

With this setup we can start to inject in semi-automatic mode.

The injection should be performed gradually, changing the point of switching level. Thus, each injection will increase the volume of material introduced into the mold.

The pressures will evolve in this way:

15.3.4.1 Progressive Filling Pressure Graphs

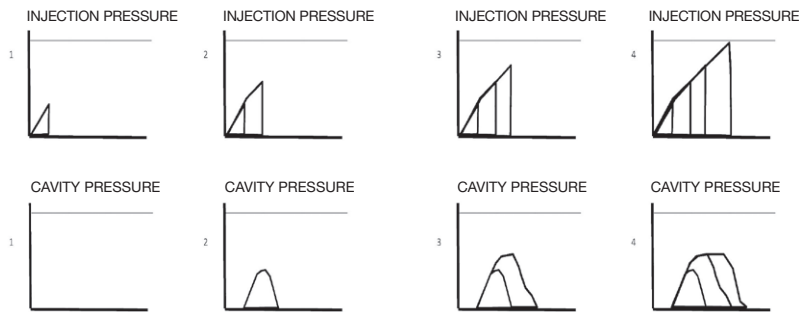


Figure 15.4 Injection pressure evolution during progressive filling

In this phase of progressive filling with partial shots, we can see where the material flow accelerates, slows down, or stops. Thus we can set up a profile of injection speeds adapted to true flow advance.

15.3.4.2 Hold Pressure Stage

At this stage, we apply holding pressure to compensate the loss of volume when the polymer cools and shrinks.

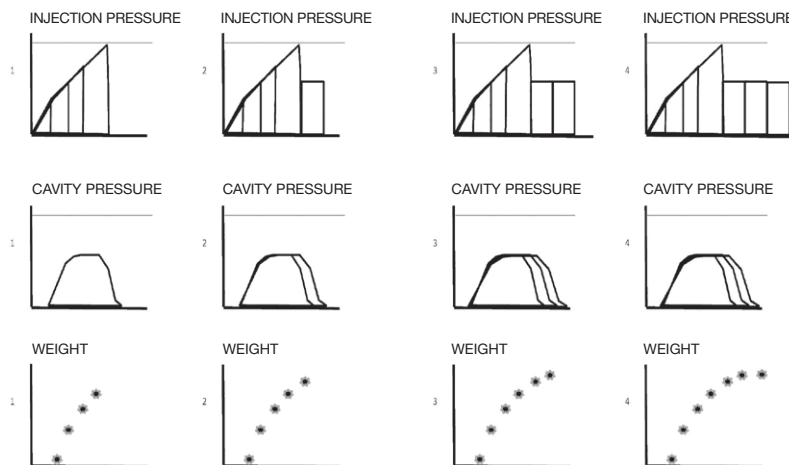


Figure 15.5 Injection pressure and cavity pressure evolution during hold pressure time definition stage

Applying holding pressure progressively and weighing the parts without the runners, we can determine the optimal compaction time. When the weight is not increased, it means that the gate is sealed and it does not make sense to apply more pressure and time.

15.3.5 Key Parameters of Process Control

These key parameters are a result of the process, called process outputs. Directly programmed setting parameters are useless for an accurate process control.

- Real melt temperature ■ Real mold and cavities temperatures, etc. ■ Filling time
- Real speed filling ■ Cushion ■ Dosage time
- Injection pressure at switch point to holding pressure ■ Cycle time ■ Filling pressure-speed curves
- Real back pressure ■ Real switching point position ■ Weight of parts

Table 15.1 Key Parameters and Units for Various Machines

Parameter	Units
Injection volume	Cubic centimeters
Filling rate (or speed)	Cubic centimeters per second
Filling time	Seconds
Specific injection pressure	Bars
Specific holding pressure	Bars
Cushion	Cubic centimeters
Switch to holding stage point	Cubic centimeters
Switching pressure	Bars
Peripheral speed of screw	Meters per second
Back pressure	Bars
Cycle time	Seconds
Holding pressure time	Seconds
Cooling time	Seconds
Melt temperature	Celsius degrees
Mold temperature	Celsius degrees

15.3.6 Start-up and Fine-Tuning of Injection Machines—Interpreting Graphs

Source: Ascamm

15.3.6.1 Injection and Cavity Pressures

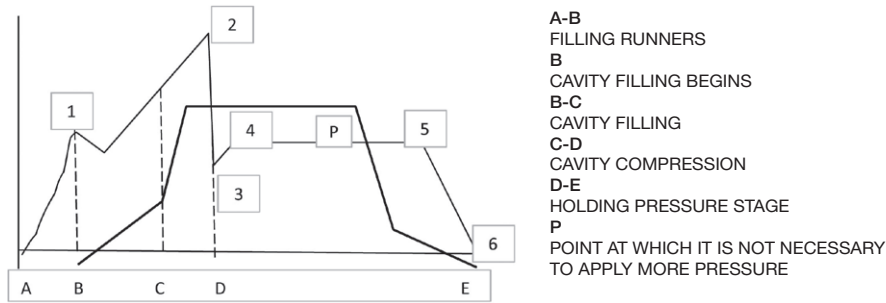
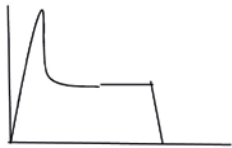
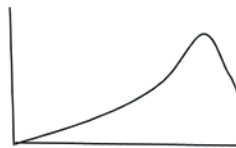


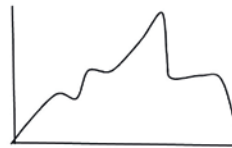
Figure 15.6 Injection pressure and cavity pressure graphs



High resistance to flow



Low resistance to flow



Variable resistance in runners, thin sections, etc.

15.3.6.2 Effect of Parameters

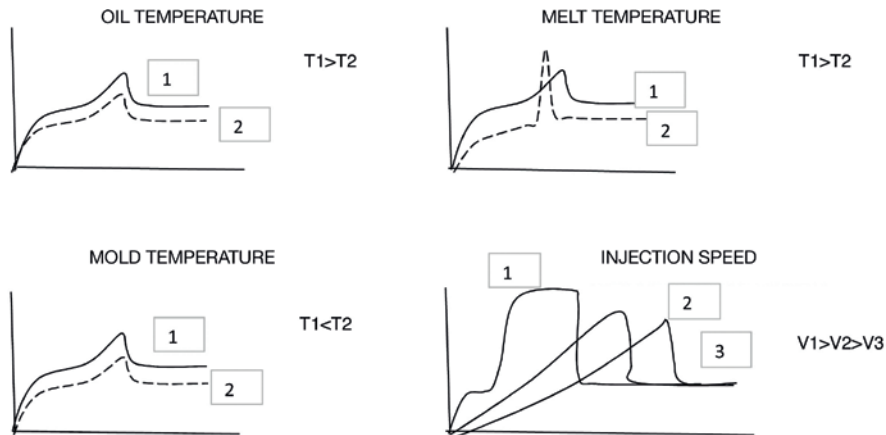


Figure 15.7 Injection pressure graph affected by several parameters

15.3.6.3 Cavity Pressure

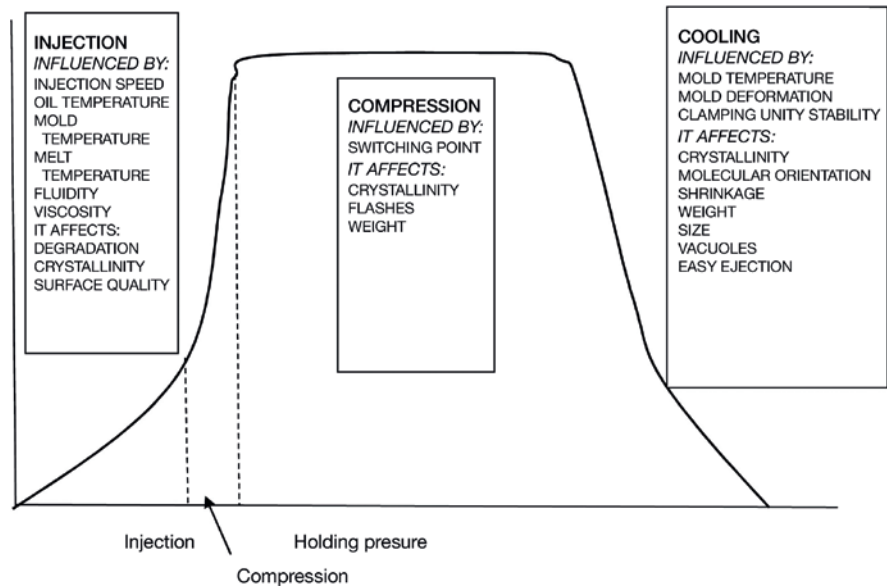


Figure 15.8 Injection cavity pressure curve characteristics

15.3.7 Effects of the Different Parameters

15.3.7.1 Mold Temperature

Effects

- Increases the crystallinity and improves the structure in semi-crystalline materials
- Decreases post-shrinkage and increases mold shrinkage
- Increases the molding thermal stability
- Reduces the internal stresses
- Decreases orientations
- Increases the reproducibility of the cavity surface
- Reduces flow resistance
- Increases the cycle time
- Increases the crystallinity
- Reduces the viscosity
- Reduces the weld lines
- Reduces the pressure loss in molds

15.3.7.2 Melt Temperature

- Increases shrinkage
- Reduces flow resistance
- Reduces weld lines

- Increases the flashes
- Increases gas formation
- Increases thermal degradation
- Increases cooling time

15.3.7.3 Part Temperature

Temperature of the parts should normally be 10 or 15 degrees below the Vicat temperature of the material before being ejected.

15.3.7.4 Dosage Stroke

- Optimal between 1 and 3 times the screw diameter
- If dosage stroke < 1 diameter → residence time excessive and low accuracy of the seal ring movement in the non-return valve
- If dosage stroke > 3 diameters → streaks of air entrapments, thermally inhomogeneous mass

15.3.7.5 Back Pressure

Its function is to homogenize the mass thermally.

Effects

- Expels the air in the pellets and compensates the differences of temperature in the screw
- Avoids fluctuations in the cushion

15.3.7.6 Injection Speed

Effects

- Burns
- Incomplete parts
- Flashes
- Streaks air occlusions
- Diesel effect
- Corona effect
- When high, gloss of parts are increased
- Melt temperature increased by shear rate
- Increase of clamping force required

15.3.7.7 Holding Pressure

Effects

- Sink marks
- Air occlusions

- Flashes
- Cracks and stress
- Weight and size of parts
- **Short hold pressure time** = Shrinking cavities – Vacuoles – Reduced weight – Small size – Bursts by backflow – Size variations
- **Excessive hold pressure time** = Deformations due to hard demolding – Stresses close the gates – Excessive time cycle – Flashes

15.3.7.8 Material Viscosity

Effects

High viscosity provides greater resistance to filling but facilitates the transmission of pressure in far areas.

Delayed switching to holding stage

Effects

- Pressure peaks
- Over-pressure parts and flashes
- Greater weight
- High stresses
- Inner flow lines
- Damages in mold
- High efforts in the injection unit

Premature switching to holding stage

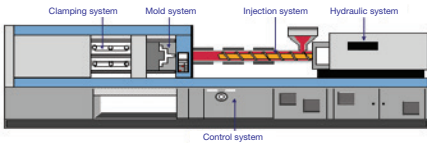
Effects

- Descent of cavity pressure
- Less weight
- Subsequent filling in uncontrolled holding pressure
- Flow lines
- Weak weld lines
- Weight variations
- High shrinking

Generic Recommendations for Injection Molding Conditions

Attention: follow carefully the recommendations in this chapter. The author assumes no responsibility for incidents, accidents, damage to equipment or people, or adverse outcomes that may occur.

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
FEP	FLUORINATED ETHYLENE POLYPROPYLENE	200-240°C	345-370°C	330-350°C	335-350°C	390°C	5 min

DRYING			PERIPH SPEED m/s
TEMPERATURE	TIME		0.5
150°C	2-4 hours		BACK PRESSURE bar
			< 60
			INJECTION PRESSURE bar
			1050
			HOLD PRESSURE bar
			600

VENTING DEEP	SHRINKAGE

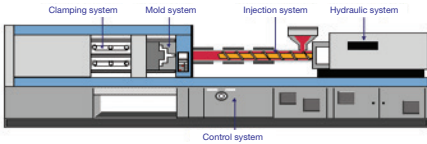
GATES	

COMMENTS	
FILTERS, CAPS, AND GASKETS	

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PEI	POLYETHERIMIDE	175°C	325-410°C	320-400°C	310-375°C	415°C	5 min

DRYING

TEMPERATURE	TIME
150°C	4 hours



Clamping system Mold system Injection system Hydraulic system Control system

VENTING DEEP	SHRINKAGE

GATES	

PERIPH SPEED m/s
0.5
BACK PRESSURE bar
< 5
INJECTION PRESSURE bar
2000
HOLD PRESSURE bar
1800

COMMENTS
ELECTRICAL COMPONENTS INTEGRATED CIRCUITS' HOLDERS f/e 150:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PEEK	POLYETHER ETHER KETONE	150-160 °C	370-380 °C	350-370 °C	340-350 °C		

DRYING

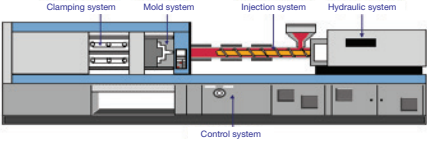
TEMPERATURE	TIME
150°C	4 hours

VENTING

DEEP

GATES

SHRINKAGE



PERIPH SPEED m/s
BACK PRESSURE bar
INJECTION PRESSURE bar
HOLD PRESSURE bar

COMMENTS

CLUTCH PLATES
GEARS
RT1 260
TF 343
f/e 200:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PSU/PPSU/PESU	POLYSULFONES	150°C	315-380°C	310-370°C	295-365°C	380°C	30 min

DRYING

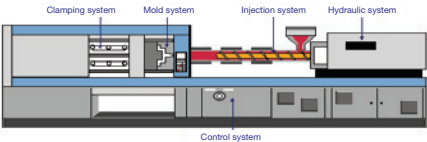
TEMPERATURE	TIME
150°C	3 hours

VENTING

DEEP

GATES

SHRINKAGE



PERIPH SPEED m/s
BACK PRESSURE bar
INJECTION PRESSURE bar
HOLD PRESSURE bar

COMMENTS

MEDICAL PRODUCTS
AIRCRAFT INDOORS
f/e 60-120:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PC	POLYCARBONATE	80-120°C	295-315°C	285-315°C	275-300°C	320°C	7 min

DRYING

TEMPERATURE	TIME
120°C	4 hours

VENTING

DEEP

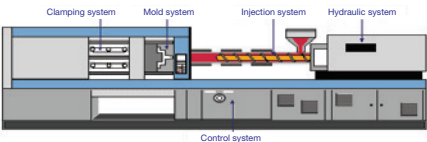
0.05mm

GATES

SHRINKAGE

60-70 % thickness

0.6-0.8%



PERIPH SPEED m/s
BACK PRESSURE bar
INJECTION PRESSURE bar
HOLD PRESSURE bar

COMMENTS

STRENGTHS

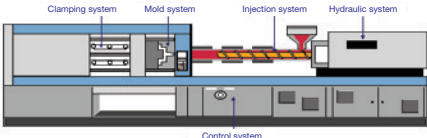
HIGH TRANSMITTANCE
IMPACT RESISTANCE UNTIL -150°C
DIMENSIONAL STABILITY

WEAKNESSES

UV RESISTANCE
HOT WATER, HYDROLYSIS
LOW RESISTANCE TO OILS AND FATS

f/e 30-70:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PBT	POLYBUTYLENE TEREPHTHALATE	80-100 °C	235-250 °C	225-240 °C	215-230 °C	270 °C	2 min

DRYING			PERIPH SPEED m/s
TEMPERATURE	TIME		0.35
120 °C	2-5 hours		BACK PRESSURE bar
		< 7	INJECTION PRESSURE bar
		1300	HOLD PRESSURE bar
		750	

VENTING DEEP	

GATES	SHRINKAGE
	1.4-2%

COMMENTS	
STRENGTHS	WEAKNESSES
DIMENSIONAL STABILITY	IMPACT RESISTANCE
OUTDOORS	STRICT DRYING, HYDROLYSIS
CHEMICAL RESISTANCE TO OILS	LOW RESISTANCE TO GASOLINES AND KETONES

f/le 160-200:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PET	POLYETHYLENE TEREPHTHALATE	130-140 °C	270-285 °C	270-285 °C	270-280 °C	290 °C	4 min

DRYING

TEMPERATURE	TIME
130°C	5 hours

VENTING
DEEP

GATES

SHRINKAGE

1.2-2%

Clamping system

Mold system

Injection system

Hydraulic system

Control system

PERIPH SPEED m/s
0.3
BACK PRESSURE bar
< 10
INJECTION PRESSURE bar
1600
HOLD PRESSURE bar
1000

COMMENTS

STRENGTHS

UV RESISTANCE

ACIDS RESISTANCE

STIFFNESS

WEAKNESSES

STRICT DRYING

PERMEABILITY TO CO₂

f/e 350:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PPO	POLYBUTYLENE OXY MODIFIED	60-110 °C	250-290 °C	220-270 °C	219-250 °C	290 °C	

DRYING

TEMPERATURE	TIME
100°C	2 hours

VENTING DEEP

GATES

SHRINKAGE

0.5-0.7%

Clamping system

Mold system

Injection system

Hydraulic system

Control system

PERIPH SPEED m/s
0.4
BACK PRESSURE bar
< 10
INJECTION PRESSURE bar
1800
HOLD PRESSURE bar
1400

COMMENTS

STRENGTHS

DIMENSIONAL STABILITY

IMPACT RESISTANCE

WEAKNESSES

IMPACT RESISTANCE

RESISTANCE TO GASOLINES AND KETONES

f/le 100-200:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PA 6	POLYAMIDE 6	60-90°C	240-270°C	230-250°C	220-240°C	300°C	

DRYING

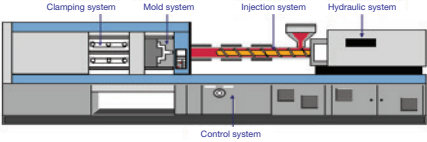
TEMPERATURE	TIME
80°C	10 hours

VENTING DEEP

GATES

SHRINKAGE

1-2%



PERIPH SPEED m/s	0.5
BACK PRESSURE bar	< 15
INJECTION PRESSURE bar	1500
HOLD PRESSURE bar	750

COMMENTS

STRENGTHS

MECHANICAL PROPERTIES

RESISTANCE TO OILS AND FATS

IMPACT AND TENACITY

WEAKNESSES

UV RESISTANCE

HUMIDITY ABSORPTION

DIMENSIONAL STABILITY

SULFURIC ACID

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PMMA	POLYMETHYL METACRYLATE	60-90°C	180-275°C	180-250°C	150-210°C	270°C	8 min

DRYING

TEMPERATURE	TIME
4°C	80-90 hours

VENTING DEEP

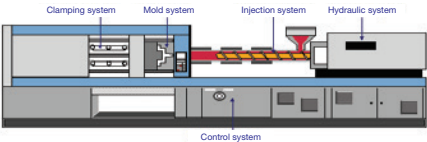
0.05mm

GATES

60-70 % thickness

SHRINKAGE

0.2-0.7%



PERIPH SPEED m/s	0.3
BACK PRESSURE bar	< 5
INJECTION PRESSURE bar	1600
HOLD PRESSURE bar	750

COMMENTS

STRENGTHS

92 % TRANSMITTANCE

UV RESISTANCE

RESISTANCE TO OILS AND DETERGENTS

WEAKNESSES

IMPACT RESISTANCE

RESISTANCE TO KETONES

f/e 110-130:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
ASA	ACRYLATE ACRYLONITRILE STYRENE	40-80°C	240-250°C	240-250°C	210-230 °C	260°C	5 min

DRYING

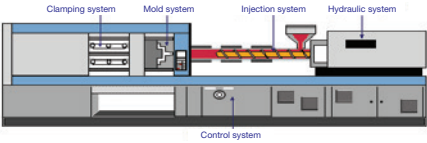
TEMPERATURE	TIME
4°C	80 hours

VENTING DEEP

GATES

SHRINKAGE

0.4-0.7%



PERIPH SPEED m/s	0.3-0.6
BACK PRESSURE bar	< 5
INJECTION PRESSURE bar	1500
HOLD PRESSURE bar	750

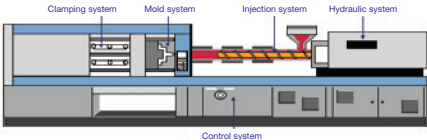
COMMENTS

STRENGTHS

RESISTANCE TO UV AND OPEN AIR

f/e 180-230:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
SAN	STYRENE ACRYLONITRILE	40-80 °C	220-230 °C	210°C	150-180 °C	240°C	3 min

DRYING			PERIPH SPEED m/s
TEMPERATURE	TIME		0.5
70°C	4 hours	BACK PRESSURE bar	< 5
		INJECTION PRESSURE bar	1500
		HOLD PRESSURE bar	750

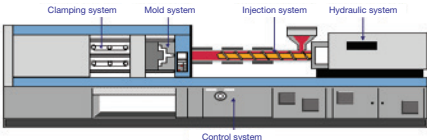
VENTING	
DEEP	

GATES	SHRINKAGE
	0.4-0.6%

COMMENTS	
STRENGTHS STIFFNESS SURFACE APPEARANCE RESISTANCE TO OILS AND FATS	WEAKNESSES HYDROCARBONS ETHER ESTER KETONES

f/e 150-230:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
HIPS	HIGH IMPACT POLYSTYRENE	20-80°C	210-255°C	190-250°C	160-190°C	250 °C	3 min

DRYING			PERIPH SPEED m/s
TEMPERATURE	TIME		0.5
70°C	3 hours	BACK PRESSURE bar	< 5
		INJECTION PRESSURE bar	1500
		HOLD PRESSURE bar	750

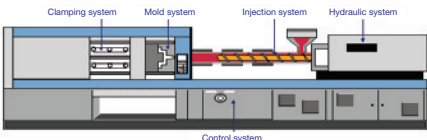
VENTING	
DEEP	

GATES	SHRINKAGE
	0.4-0.6%

COMMENTS	

f/e 250:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PS (GPPS)	POLYSTYRENE	20-8 °C	210-255 °C	210-250 °C	130-180 °C	255 °C	5 min

DRYING			PERIPH SPEED m/s
TEMPERATURE	TIME		0.5
4°C	80-90 hours	BACK PRESSURE bar	< 5
		INJECTION PRESSURE bar	1500
		HOLD PRESSURE bar	750

VENTING	
DEEP	

GATES	SHRINKAGE
	0.4-0.5%

COMMENTS	
STRENGTHS STIFFNESS TRANSPARENCE	WEAKNESSES FRAGILE LOW CONTINUOUS THERMAL RESISTANCE NO RESISTANCE TO KETONES, FATS, AND OILS

f/e 150:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PP	POLYPROPYLENE	10-80 °C	230-250°C	200-230°C	180-200°C	280°C	

DRYING

TEMPERATURE

TIME

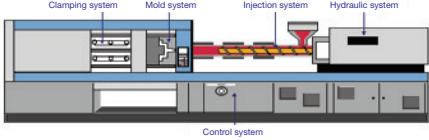
VENTING

DEEP

GATES

SHRINKAGE

1.2-2.2%



PERIPH SPEED m/s

0.7

BACK PRESSURE bar

< 20

INJECTION PRESSURE bar

1400

HOLD PRESSURE bar

800

COMMENTS	
STRENGTHS	WEAKNESSES
FLEXURAL STRENGTH	LOW IMPACT AT BELOW ZERO TEMPERATURES
IMPACT AT ROOM TEMPERATURE	DIFFICULT TO PAINT AND DECORATE
RESISTANCE TO ALCOHOL, GASOLINE, JUICES, ETC.	LOW UV RESISTANCE
	CHLORINATED HYDROCARBONS
	CONTACT WITH COPPER

f/e 350:1
L/D 25

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PE	POLYETHYLENE	20-50 °C	220-250 °C	200-220 °C	180-200 °C	280 °C	

DRYING

TEMPERATURE

TIME

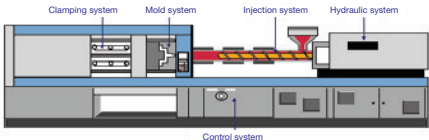
VENTING

DEEP

GATES

SHRINKAGE

1.5-2%



PERIPH SPEED m/s

0.8

BACK PRESSURE bar

< 20

INJECTION PRESSURE bar

1000

HOLD PRESSURE bar

500

COMMENTS	
STRENGTHS	WEAKNESSES
CHEMICAL RESISTANCE	UV RESISTANCE
RESISTANCE TO GASOLINES AND E FATS	SCRATCH RESISTANCE
DIELECTRIC PROPERTIES	THERMAL RESISTANCE
CHEMICAL RESISTANCE	DIFFICULT TO PAINT AND DECORATE
	CHLORINATED HYDROCARBURES

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
ABS	ACRYLONITRILE BUTADIENE STYRENE	60-90 °C	210-280 °C	210-260 °C	180-230 °C	260 °C	5 min

DRYING

TEMPERATURE

TIME

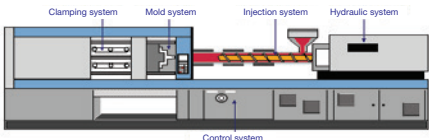
VENTING

DEEP

GATES

SHRINKAGE

0.4-0.6%



PERIPH SPEED m/s

0.5

BACK PRESSURE bar

< 5

INJECTION PRESSURE bar

1500

HOLD PRESSURE bar

750

COMMENTS	
STRENGTHS	WEAKNESSES
RESISTANCE TO GASOLINES AND OILS	LOW UV RESISTANCE
EASY TO PAINT AND DECORATE	CONTACT WITH KETONE, ETHER, BENZENE
GOOD IMPACT RESISTANCE	

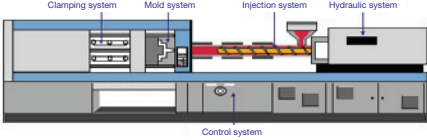
f/e 100-200:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
POM	POLYOXYMETHYLENE	50-120°C	180-215°C	170-210°C	160-220°C	220°C	7 min

DRYING	
TEMPERATURE	TIME
100°C	4 hours

VENTING	SHRINKAGE
DEEP	2%

GATES	
-------	--



PERIPH SPEED m/s
0.2
BACK PRESSURE bar
< 20
INJECTION PRESSURE bar
1700
HOLD PRESSURE bar
1700

Subrunner: 1.5 times E. Large channels are not needed, only large gates.

COMMENTS	
STRENGTHS	WEAKNESSES
RIGIDITY	UV RESISTANCE
DIMENSIONAL STABILITY	ACID RESISTANCE
WEAR AND FRICTION	NOT FLAME RETARDANT
CHEMICAL RESISTANCE TO GASOLINES, FATS, DISSOLVENTS, ETC.	

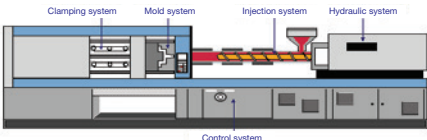
f/e 100-250:1

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
ABS-PC	BLEND ABS AND PC	60-90 °C	260-280 °C	270 °C	250 °C	280 °C	

DRYING	
TEMPERATURE	TIME
100	4 hours

VENTING	SHRINKAGE
DEEP	0.5-0.7%

GATES	
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PERIPH SPEED m/s
0.2
BACK PRESSURE bar
INJECTION PRESSURE bar
800-1500
HOLD PRESSURE bar
800

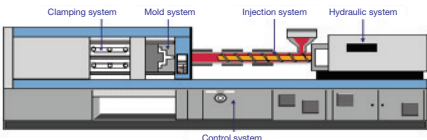
COMMENTS	
STRENGTHS	
IMPACT RESISTANCE	
SURFACE BRIGHTNESS	

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PA 66	POLYAMIDE 66	80-100 °C	290 °C	280 °C	280 °C	300 °C	

DRYING	
TEMPERATURE	TIME
80 °C	8 hours

VENTING	SHRINKAGE
DEEP	0.7-2%

GATES	
-------	--



PERIPH SPEED m/s
1
BACK PRESSURE bar
20
INJECTION PRESSURE bar
1600
HOLD PRESSURE bar
800

COMMENTS	
----------	--

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PPA	POLYPHTHALAMIDE	150°C	325°C	315°C	310°C	330°C		3 min

VENTING
DEEP
0.013mm

GATES
50 % thickness

SHRINKAGE

DRYING
TEMPERATURE
100°C

TIME
8 hours

Clamping system

Mold system

Injection system

Hydraulic system

Control system

PERIPH SPEED m/s
0.2

BACK PRESSURE bar
LOW

INJECTION PRESSURE bar

HOLD PRESSURE bar

COMMENTS

STRENGTHS

LOW INFLUENCE OF HUMIDITY

HIGH GLASS TRANSITION

DIMENSIONAL STABILITY

MECHANICAL PROPERTIES

WEAKNESSES

MATERIAL WELD LINES

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
LCP	LIQUID CRYSTAL POLYMER	10°C	350-360°C					

VENTING
DEEP

GATES
50% thickness

SHRINKAGE

DRYING
TEMPERATURE
150°C

TIME
3 hours

Clamping system

Mold system

Injection system

Hydraulic system

Control system

PERIPH SPEED m/s

BACK PRESSURE bar
60

INJECTION PRESSURE bar

HOLD PRESSURE bar

COMMENTS

STRENGTHS

ANISOTROPIC CONTRACTION (IT MAY BE NEGATIVE)

SMALL GATES ARE PREFERRED (TO APPLY SHEAR)

COMPRESSION RATIO: 2.5:1-3:1

CONTINUOUS USE TEMPERATURE > 220°C

WEAKNESSES

MATERIAL WELD LINES

TENDENCY TO PRODUCE BURRS

MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
PPS	POLYPHENYLENE SULFIDE	150°C	330°C	320°C	315°C	360°C		5 min

VENTING
DEEP

GATES

SHRINKAGE
0.1-0.6%

DRYING
TEMPERATURE
150°C

TIME
6 hours

Clamping system

Mold system

Injection system

Hydraulic system

Control system

PERIPH SPEED m/s
MIDDLE

BACK PRESSURE bar
20

INJECTION PRESSURE bar
1000

HOLD PRESSURE bar
70-80% (injection)

COMMENTS

STRENGTHS

THERMAL AND CHEMICAL RESISTANCE

MECHANICAL PROPERTIES

WEAKNESSES

IMPACT

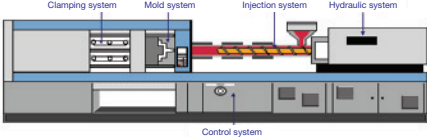
MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
TPU	POLYURETHANE	15-70°C	195-220°C	190-210°C	180-200°C	240 °C	3 min

DRYING	
TEMPERATURE	TIME
110°C	4 hours

VENTING DEEP
0.02-0.05mm

GATES
50% thickness

SHRINKAGE
1%



PERIPH SPEED m/s
0.2
BACK PRESSURE bar
> 40
INJECTION PRESSURE bar
1000
HOLD PRESSURE bar

COMMENTS	
STRENGTHS	WEAKNESSES
ABRASION, TEAR	CYCLE TIME
MECHANICAL PROPERTIES	STRICT DEHUMIDIFICATION

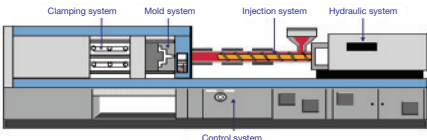
MATERIAL	NAME	MOLD TEMP	MELT TEMP	MELT TEMP	MELT TEMP	MAX MELT TEMP	RESIDENCE TIME
TPEV	THERMOPLASTIC VULCANIZED ELASTOMER	10-80°C	190-230°C	185-220°C	170-200°C	235°C	

DRYING	
TEMPERATURE	TIME
80-100°C	3 hours

VENTING DEEP
0.015mm

GATES
LITTLE

SHRINKAGE
2.1-3.2%



PERIPH SPEED m/s
HIGH
BACK PRESSURE bar
> 50
INJECTION PRESSURE bar
1000
HOLD PRESSURE bar
30-50% (injection)

COMMENTS	
STRENGTHS	WEAKNESSES
COMPRESSION SET	ABRASION, TEAR
MECHANICAL PROPERTIES	DIFFICULT FINISHINGS
SPECIAL GRADES OF BONDING	

Mold Design Guide Recommendations

17.1 Metals Versus Steels for Molds

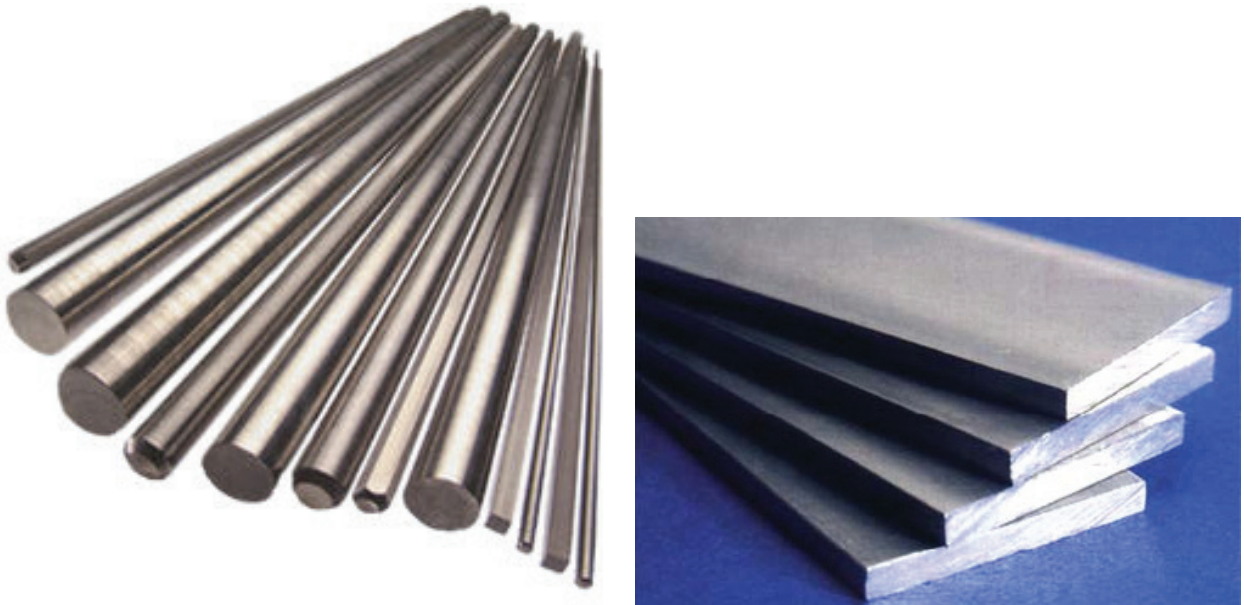


Figure 17.1 Different steel shapes for molds

- Aluminum: used for molds prototypes and pre-productions or first productions.
- Beryllium copper. This material is less durable than steel and may hob or wear faster than steel if used at the parting line.
- Beryllium copper can be used for inserts, slides, or cores to increase heat transfer rates due to their thermal conductivity and to reduce cycle.
- A2: steel-hardened to 58–60 Rockwell C; wear resistant.
- D2: steel with higher chromium content; more wear resistant; more fragile; better for small parts; more difficult to machine than A2.
- D7: steel very resistant to abrasion but more difficult to machine than A2 and D2.
- Stavax and Orvar: their chrome content and low porosity make them highly recommended for molds with mirror-polished surfaces.

Baseplates: Steel 2311, Steel 2378

Removable and replaceable cores and cavities: Steel 2344

Cavities, cores, sliders: 52 HRC, Steel 2510

Mold ejection's plates: P 20

Nickel or chromium treatments (0.01 to 0.05 mm) give mold parts and surfaces a better resistance to oxidation.

The steel selection will depend on the polymer and the quality and quantity of parts that will be produced. The wide range of different steels make the steel selection difficult; the following information aims to be a support information in order to choose the right steel.

Do not forget that for short production series and prototypes materials like aluminum or beryllium copper can be used.

W.Nr.	AUBERT & DUVAL	BÖHLER	SERMETAL	SIDENOR	STAHLMO	THYSSEN IBERICA	UDDEHOLM
1.2080	—	K100	2080	ROK	—	THYRODUR 2080	—SVERKER 1
1.2083	~X 13 T 6 W	~M310	2083 ISO-B	PLASTINOX	STM 1.2083	THYROPLAST 2083 ESR	~STAVAX ESR
1.2085	—	~M314	2316+S	—	STM 1.2317*	THYROPLAST 2085	RAMAX 5
1.2101	—	K245	—	—	—	THYRODUR 2101	—
1.2210	—	K510	—	—	—	THYRODUR 2210	—
1.2311	—	—	2311 ISO-BM	EBRO-2311	STM 1.2311-STM SP300*	THYROPLAST 2311	~LDDAX
1.2312	—	M200	2312	EBRO-2312	STM 1.2312-STM SP300*	THYROPLAST 2312	~HOLDAX
1.2316	—	~M300	2316 ISO-B	—	STM 1.2316*	THYROPLAST 2316	—
1.2343	~A.D.C 3	W300	2343 ISO-B	FINOR	STM 1.2343 MAXIMUMA	THYROTERM 2343 EFS	VIDAR SUPREME
1.2344	S.M.V 4	W302	2344 ISO-B	FINOR-V	STM 1.2344	THYROTERM 2344 EFS	ORVAR
1.2363	S.M.H	K305	2363	—	—	THYRODUR 2363	RICOR
1.2365	~S.M.R	W320	2365 ISO-B	MOLFOR	—	THYROTERM 2365 EFS	~ORO-90
1.2367	R 6110	W303	2367 ISO-B	—	—	THYROTERM 2367 EFS	~DIEVAR
1.2379	~SANCY 2	K110	2379 ISO-B	ROK-EXTRA	STM 1.2379	THYRODUR 2379	SVERKER 21
1.2380	—	—	—	—	—	THYRODUR 2380	~VANADIS-4
1.2436	—	K107	2436	—	—	THYRODUR 2436	~SVERKER 3
1.2510	—	~K460	2510	MAGNO	STM 1.2510	THYRODUR 2510	~ARNE
1.2550	—	K455	2550	CHOKER	—	THYRODUR 2550	REGIN-3
1.2581	~VOLVIC	W100	—	—	—	THYROTERM 2581	—
1.2601	—	K105	2601	—	—	THYRODUR 2601	—
1.2709	—	—	2709	—	—	THYRODUR 2709	—
1.2711	—	~W500	2711 ISO-B	—	STM 1.2711 TDO*	THYROPLAST 2711	—
1.2714	—	W500	2714	ATOR-14	STM 1.2714 TDO*	THYROTERM 2714	ALVAR 14
1.2721	—	K605	—	—	—	THYRODUR 2721	~GRANE
1.2738	—	M238	2738 ISO-BM	EBRO-2738	STM 1.2738-STM SP300*	THYROPLAST 2738	IMPAX SUPREME
1.2767	~B20 P	K600	2767 ISO-B	SUPERATOR	—	THYRODUR 2767	~CALMAX
1.2842	—	K720	2842	EXTRA FORTE	STM 1.2842	THYRODUR 2842	—
1.2886	—	W705	—	—	—	THYROTERM 2885 EFS	—
1.4980	R 25 T 2	T200	—	—	—	THERMON 4980	—

Figure 17.2 Equivalences between different steel manufacturers; source: Ascamm

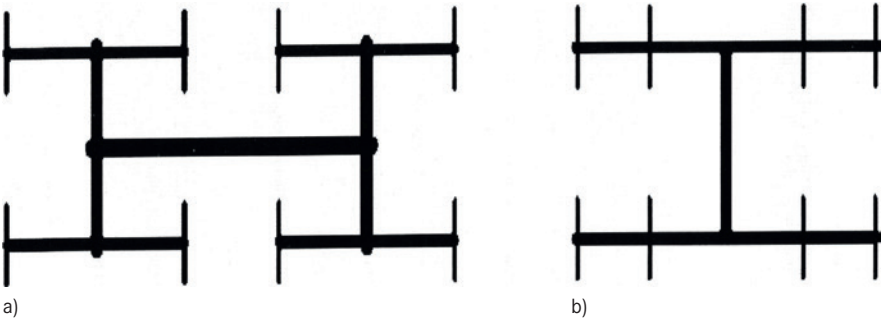
Table 17.1 Some Kinds of Steel for Molds; Source: ETP Clot

Steel type	Abbreviated designation	Number of material	Tensile strength (kp/mm ²)	Hardness (HRC)	Notes
Hardened steel	14 Ni Cr 14	1.5752	75	62–64	For medium and large molds. Easy machining. Good polishing.
Hardened steel	X 19 Cr Mo 4	1.2764	80	62–64	Good machining and polishing.
Tempered steel	X 45 Ni Cr Mo 4	1.2767	85	58–62	For small molds and complicated engravings.
Corrosion resistant steel	X 35 Cr Mo 17	1.4122	80–95		Stable to corrosion and to contact with acids.
Nitrided steel	30 Cr Mo V 9	1.8519	80–120		Molds with high dimensional accuracy.
Nitrided steel	34 Cr Al 6	1.8504	80–100		Parts subject to wear and parts with high dimensional accuracy.

17.2 Runners

Runners design: Distribution channels or runners must be balanced so that the material will perform the same path for all cavities. Thereby we obtain a homogeneous filling and pressurization of all cavities.

Figure 17.3 a) Balanced distribution channel, b) unbalanced distribution channel; source: DuPont



The section of the distribution channel can be in different shapes. The most suitable are round and trapezoidal. In this latter case it should be noted that the free passage section will be in a shape of circle inscribed in the trapeze.

Section of the distribution channel

Figure 17.4 Different runners section shapes

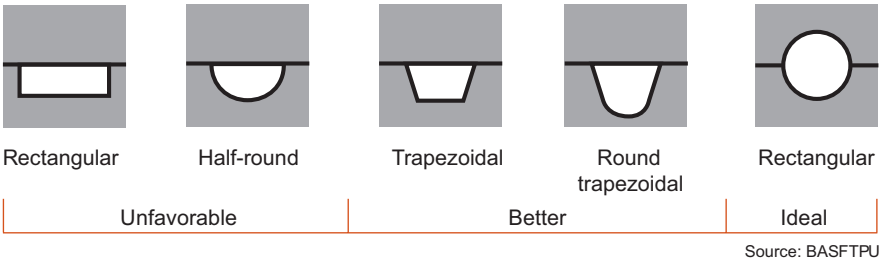


Figure 17.5 Unbalanced runner example

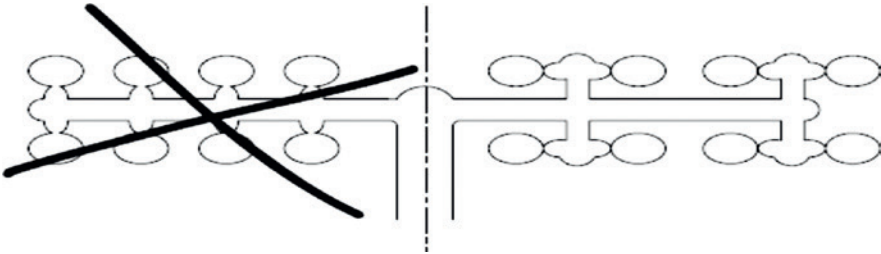


Figure 17.5 shows an unbalanced distribution channels system example. The solution shown on the right, with channels for trapping cold drops, provides balance during filling and pressurization.

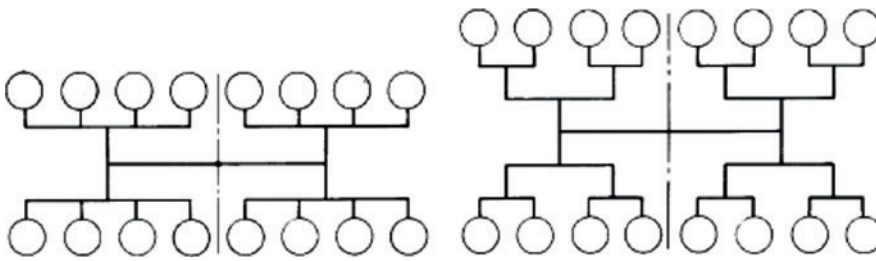


Figure 17.6 Unbalanced and balanced runner differences

Runners design

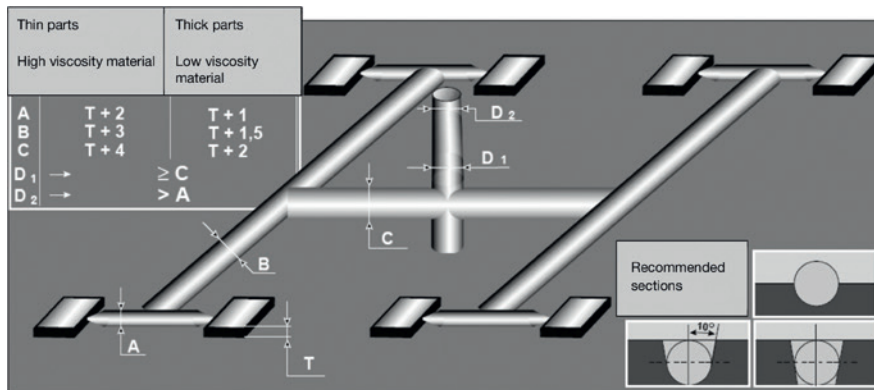


Figure 17.7 Runner dimensions calculation example; source: DuPont

For a right pressurization of all the runners system, the section should be increased at every step or runner level. The thickness of the piece is the basic value for calculating the entire runner system.

This difference in size distribution channels makes the system properly pressurize and can reach the cavity with minimal possible pressure loss.

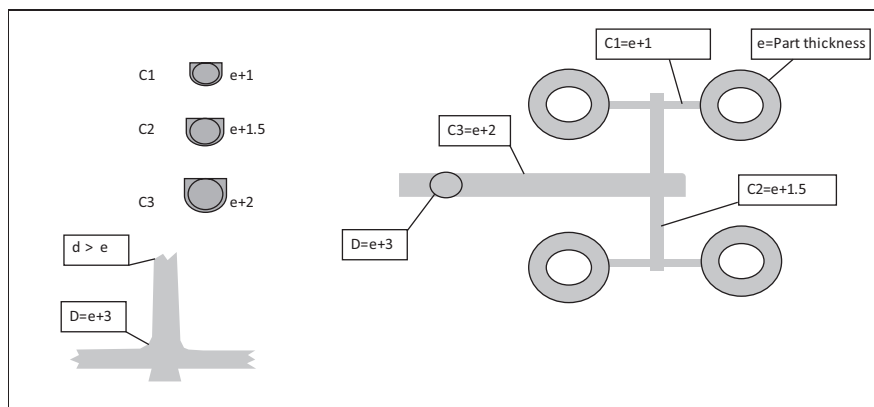


Figure 17.8 Runner dimensions calculation

Correct dimensioning of runner channels along the path followed by the melt material allows a good pressurization of the channel system with the lowest possible loss of pressure.

Torpedo and mold insulation

In Figure 17.9 (top), the torpedo is thermally insulated from the mold by the polymer. Possible degradation of the polymer can cause gases, blasts, and black spots due to the high temperature or long residence time.

Alternatively, a hot runner tip made of DuPont Vespel® can be positioned to isolate this area and avoid retentions, color changes, etc., in thermally sensitive or transparent materials.

Hot Runners

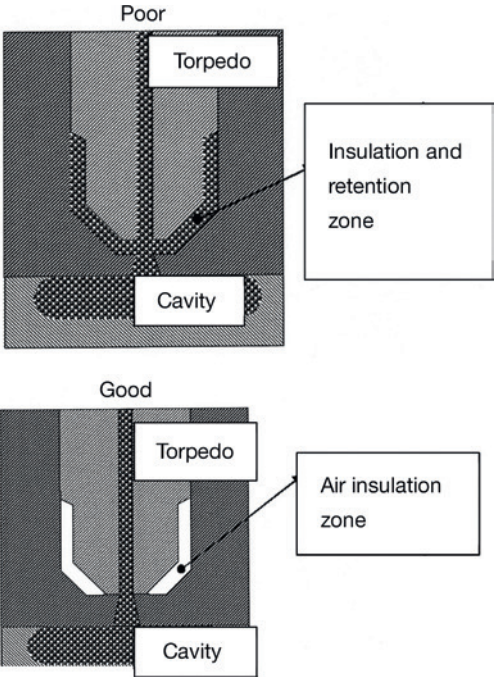


Figure 17.9 Insulation hot runner nozzle

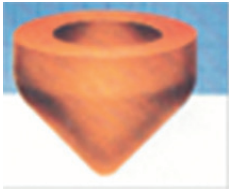


Figure 17.10 Hot runner tip for torpedo insulation; source: DuPont

In Figure 17.9 (bottom), the torpedo is thermally insulated from the mold by an air gap.

Direction changes within the hot block must ensure that there will be no material retaining point through the radii in the corners.

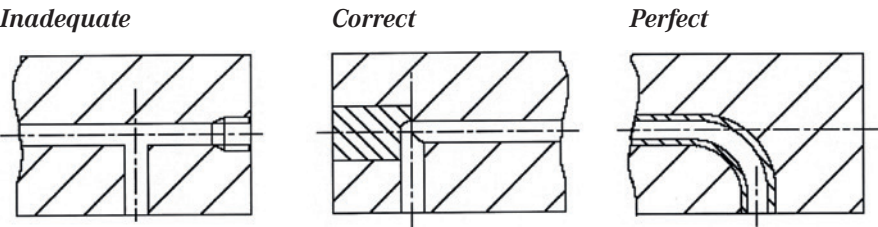


Figure 17.11 Hot runner manifold; different flow path designs

Possible typical problems (Figure 17.12):

- 1, 2 Chimney effect
- 3 Thermal conduction
- 4 Heat loss
- 5 Possibility of solidification
- 6 Bolt with unfavorable design

- 7 Absence of anti-rotation shape
- 8 Loss of heat in thermal conduction
- 9 Flow divided by fillets between holes
- 10 Insufficient diameter passage
- 11 Unfavorable centered part
- 12 Unfavorable design of insulating surface
- 14 Conical injection point
- 15 Incorrect installation of thermocouple

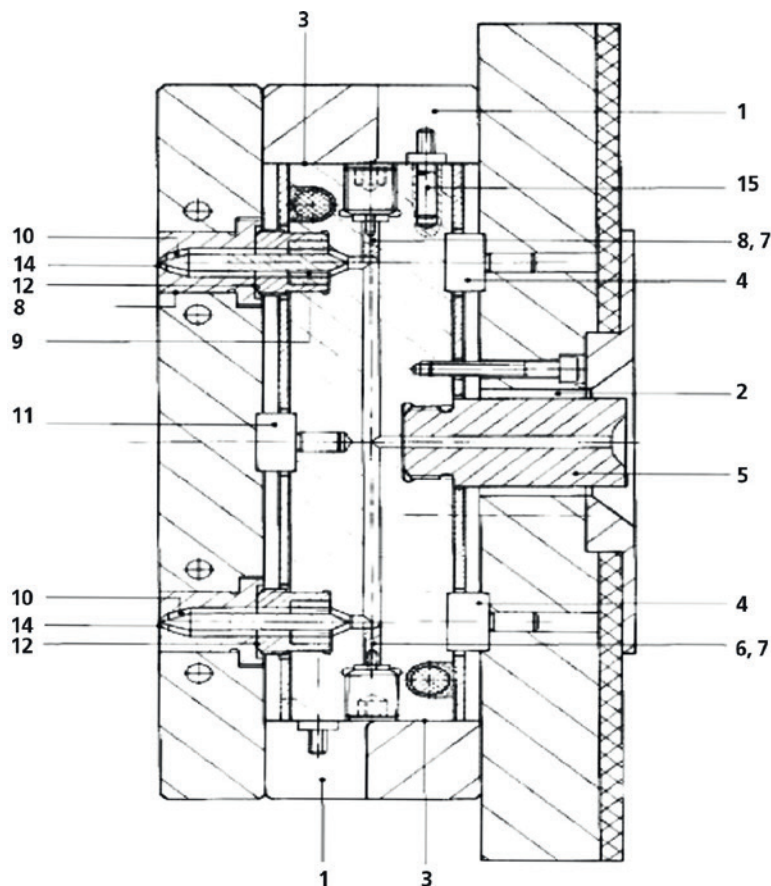


Figure 17.12 Possible typical problems; source: Ascamm

The diagram in Figure 17.12 shows the most typical problems with hot runners channels.

The chimney effect occurs when the convection air can circulate through the mold for cooling the hot runner block. When this occurs, the hot runner requests more calorific energy to maintain the set point temperatures and degradation may occur.

The areas of contact between the hot block and the mold must be minimized in order to reduce heat transfer from the hot block to the mold.

The design of passage of material, suitably dimensioned, avoids sharp edges and high shear zones.

The thermocouple must be well located and in contact with the block.

17.3 Types of Gates

17.3.1 Most Common Gates

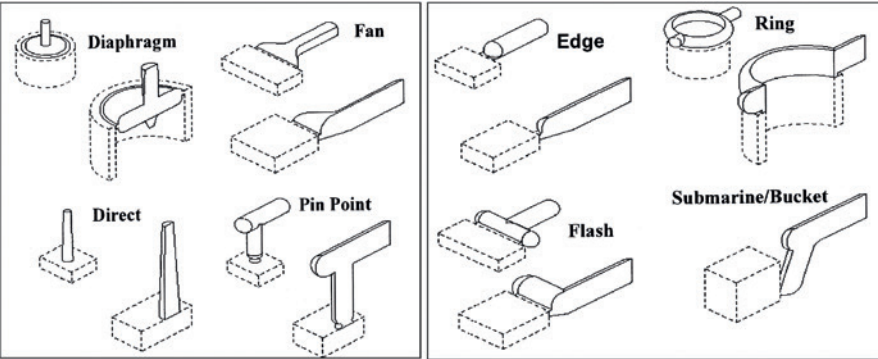


Figure 17.13 Different gate designs;
source: DuPont

Some recommendations on the sizing of gates (submarine and direct to part) are shown in Figure 17.14.

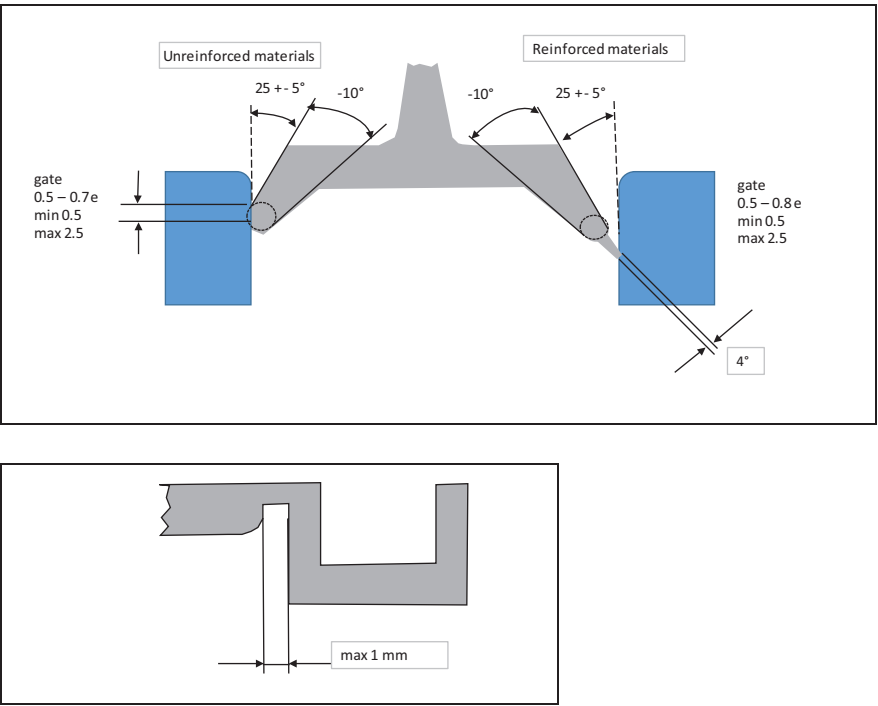


Figure 17.14 Gates design examples

Beware of the land of gates: this must not exceed 1 mm, as shown in the drawing in Figure 17.14.

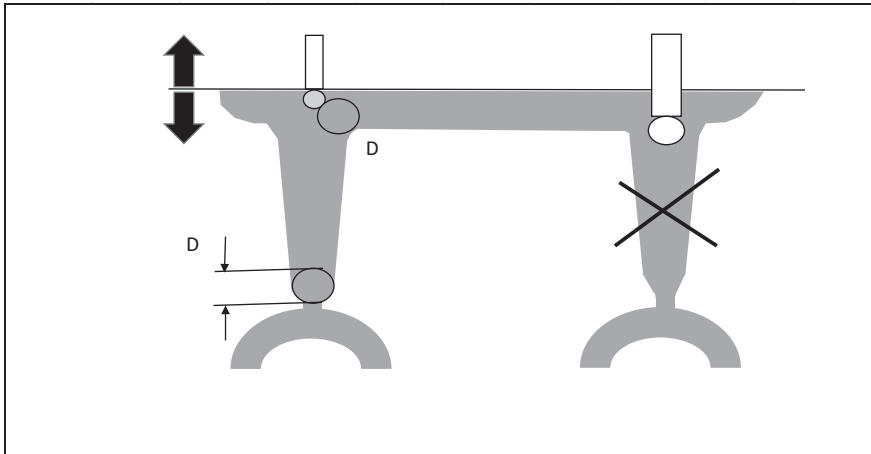


Figure 17.15 Design of gates for three-platen molds with capillary gates direct to cavities

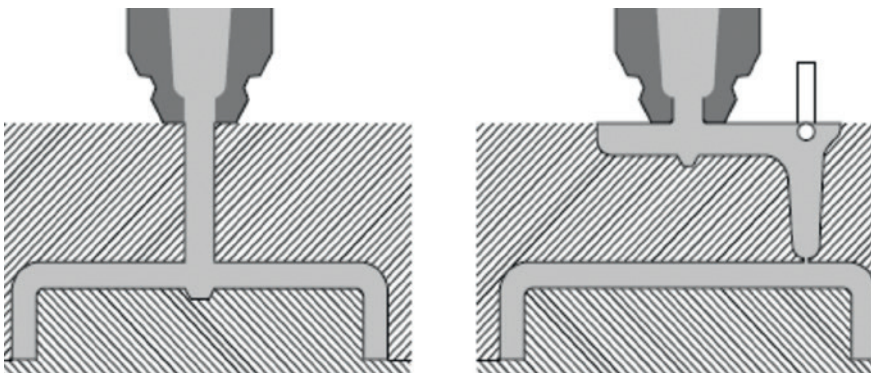


Figure 17.16 Direct and indirect gates to break the flow in a one cavity mold

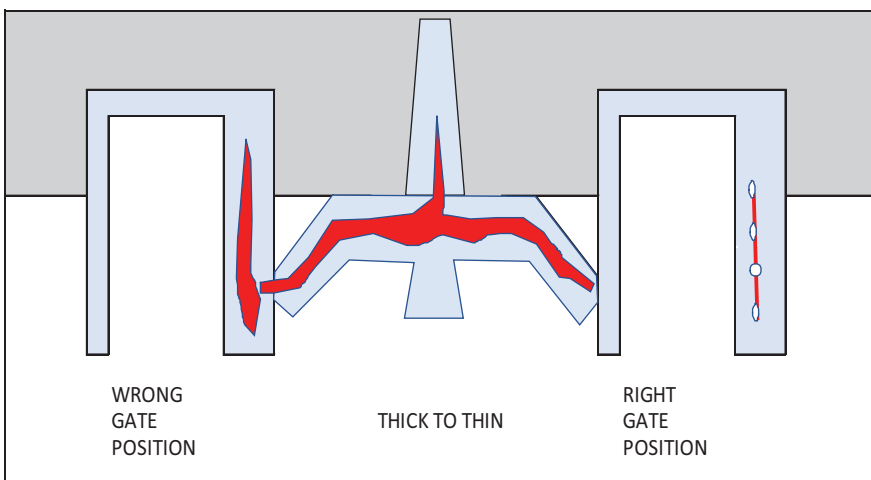


Figure 17.17 Correct and incorrect gate position

Figure 17.17 shows a simulation of injection at the end of the filling, before the final stage of holding pressure. The gate should be placed always in the thick section of the part, that is, thick to thin.

Gates must be designed taking into account the areas of greater thickness to assure good effectiveness of hold pressure stage.

17.4 Mold Cooling

The mold temperature control is critical to obtain pieces without deformation and with high crystallinity.

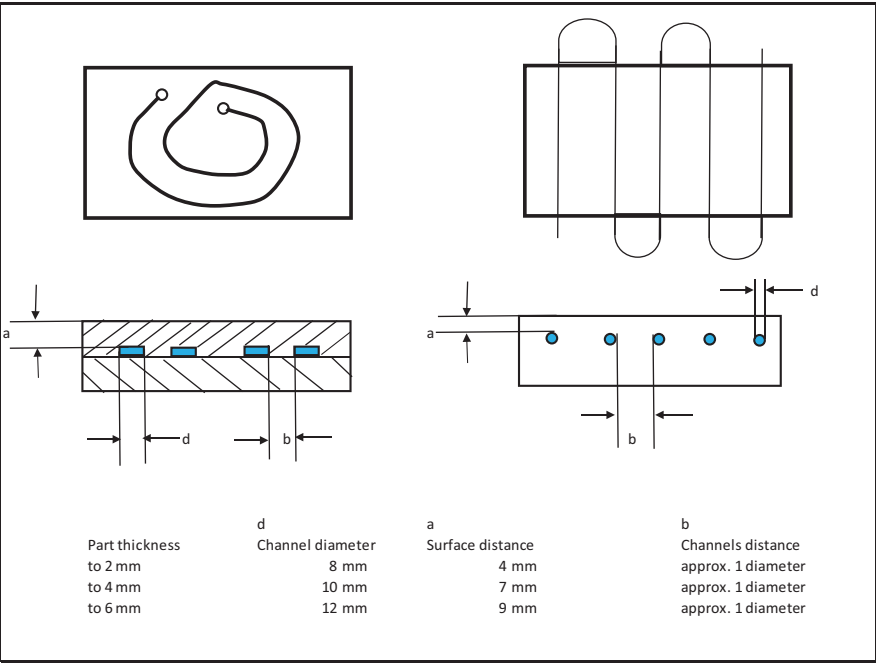


Figure 17.18 Cooling mold channels design recommendations

When designing the cooling system, we must take into account the passage diameters of the cooling channels, the distances between channels, and the distance to the surface of the cavity.

17.5 Cooling System in Cores

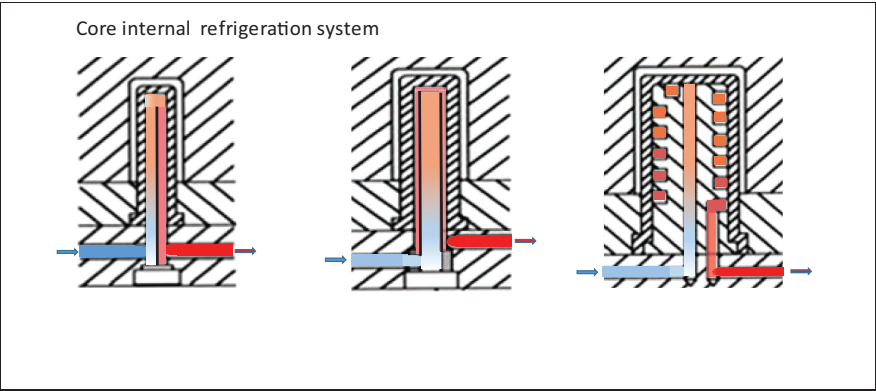


Figure 17.19 Different designs for core cooling system

Different types of cooling can be designed to ensure circulation through cores. Stereolithography systems are used to build 3D microchannel cooling systems reaching places unthinkable with conventional machining methods.

**Key points:**

- The differential of the water temperature in the inlet and outlet of the mold should not exceed 3 to 4 °C.
- If the difference is greater, we will cool an excessive water path or have laminar flow. To avoid this, we must put more circuits, remove bridges, etc.
- If the difference is lower, we are not dragging calories from the mold.
- If we double the diameter of passage, we will quadruple the possible flow.
- We need to remove restrictions on the quick couplings, bridges, etc.

17.6 Venting

17.6.1 Deep

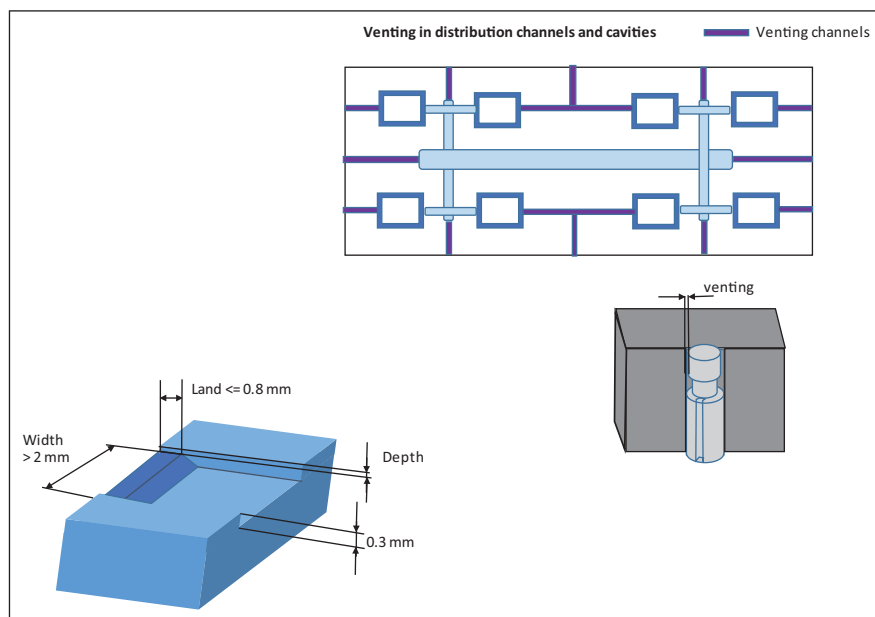


Figure 17.20 Venting design

Depth for semi-crystalline plastics

Polyamide with glass fiber	< 0.03 mm
Ionomer	< 0.03 mm
LCP	< 0.01 mm
PBT	< 0.02 mm
Polyamide	< 0.03 mm
POM	< 0.03 mm

Depth for semi-crystalline plastics

PP	< 0.025 mm
PPA	< 0.015 mm
PPS	< 0.01 mm
TPU	< 0.02 mm
TPV	< 0.025 mm

Depth for amorphous plastics

Material	Easy flow	Reinforced with glass fiber
ABS	0.05	0.07
SAN	0.05	0.07
PS HI	0.05	0.07
PC	0.04	0.07
PSU	0.025	

**Key points:**

- The land should be between 0.8 and 3 mm. If it is too short, there will be little steel surface and it will not be maintained open to airflow.
- If the length and shape of the tunnel are excessive, volatile elements from the additive pack moving with the gases leave residues in the ventilation channel, preventing release into the atmosphere of gases.
- We need to ventilate 25–30% of the parting line or place a gas outlet for every 25 mm of parting line. Each output should be about 5 mm wide.
- The mirror-polished channels to atmosphere A1 are self-cleaning (SPI Finish A-1 – Grade # 3, 6000 Diamond Grit Buff).
- We need to ventilate the distribution channels in each rotation of 90°. The ventilation channel for each runner should be as wide as the runner. The sprue center ejector should be well ventilated too.
- Deep venting in runners: 0.03 mm for high flow materials; 0.08 mm for medium flow materials; and 0.12 mm for low flow materials.

17.6.2 Venting for Runners

If we ventilate the channel system properly, we prevent trapped air from circulating through the cavity.

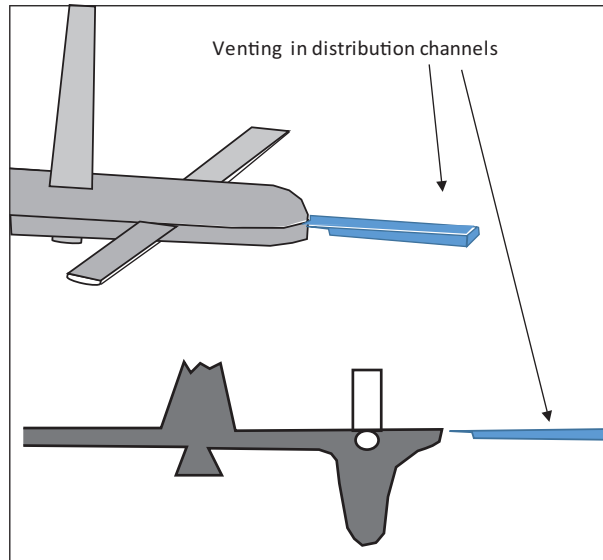


Figure 17.21 Cold runners venting

17.6.3 Venting in Distribution Channels

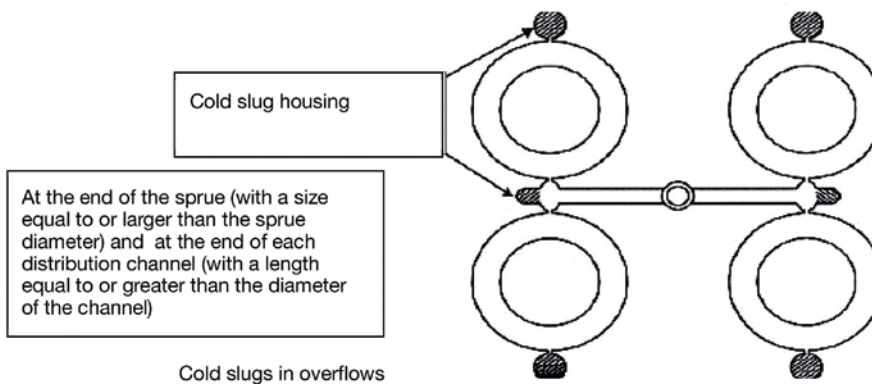


Figure 17.22 Cold slug in cold runners; source: DuPont

17.6.4 Venting in Ejectors

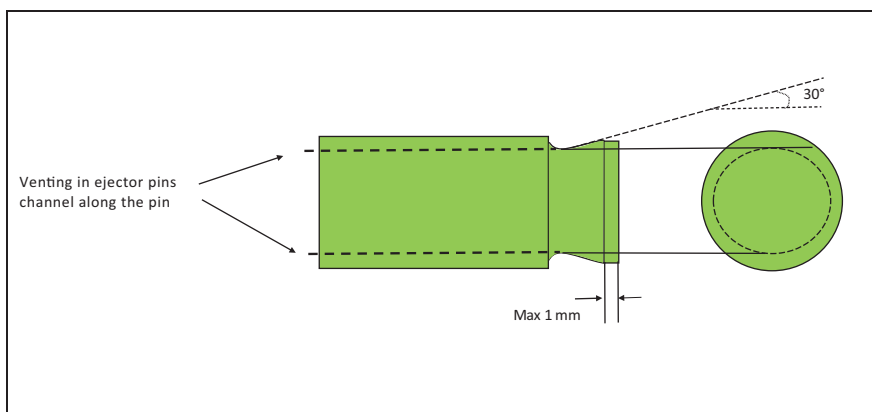


Figure 17.23 Ejector venting recommendations

17.7 Draft Angles

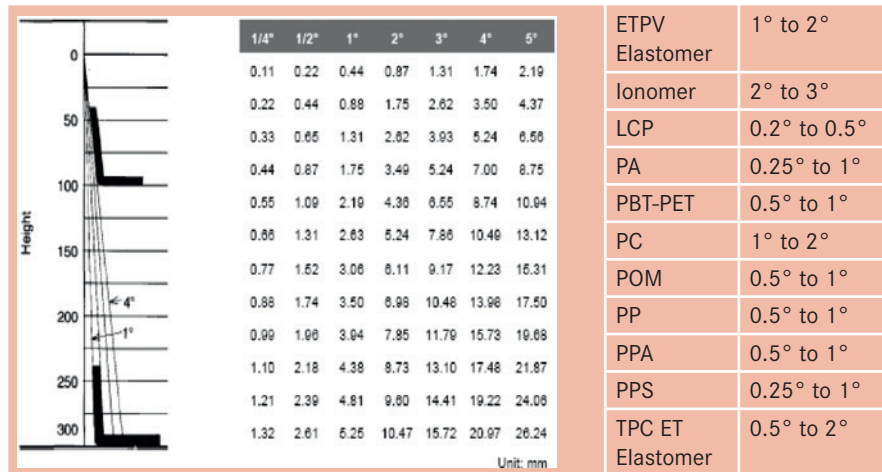


Figure 17.24 Demolding level depending on the angle and length; source: DuPont

17.8 Shrinkage

The polymers' shrinkage in the part is complex to predict. Shrinkage is a value influenced by variables such as the temperature of melted material, the mold temperature, the part thickness, the cavity pressure (which in turn is dependent on gate dimension, the runner, etc.), the cycle time, possible reinforcements causing anisotropic contractions, etc. However, polymers manufacturers test specimens and provide specific values for each grade and polymer family.

Table 17.2 Generic Shrinkage of Some Polymers

EVA	0.2% to 0.8%
GPPS	0.4% to 0.6%
LCP	−0.07% to 0.5%
PA 66	1.2% to 1.6%
PA 66 30% FV	0.3% flow 1.1% across
PBT	1.5% to 1.7%
PBT 30% FV	0.3% flow 1.1% across
PC	0.5% to 0.7%
PE	1% to 3%
PET	30% FV 0.2% flow 0.8% across
POM	1.9% to 2.2%
PMMA	0.4% to 0.7%
PP	1% to 2%
PP + FV	0.5% to 0.9%
ABS	0.6% to 0.9%
SAN	0.4% to 0.6%
ASA	0.3% to 0.8%
PP	1.3% to 1.6%
PA	0.25% to 1.5%

Gates: Types and Recommendations

18.1 Fan Edge

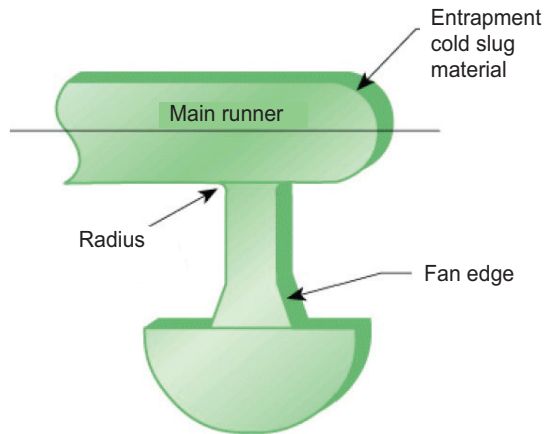


Figure 18.1 Fan edge

- Side gate to prevent flow restrictions; it is used in multi-cavity molds.
- It can be used to create a uniform flow front in wide parts and to remove jetting.
- **Disadvantages:** Requires later cut operation.
- Depth: 80–100% of the thickness of the part.
- Land: not more than 0.5–1 mm (otherwise shear excess brightness appears).
- Round channels.
- Gate opened to the center of the channel.
- Trapezoidal channels must not be used.
- Angle: it can be 15°.

18.2 Submarine or Tunnel Gate

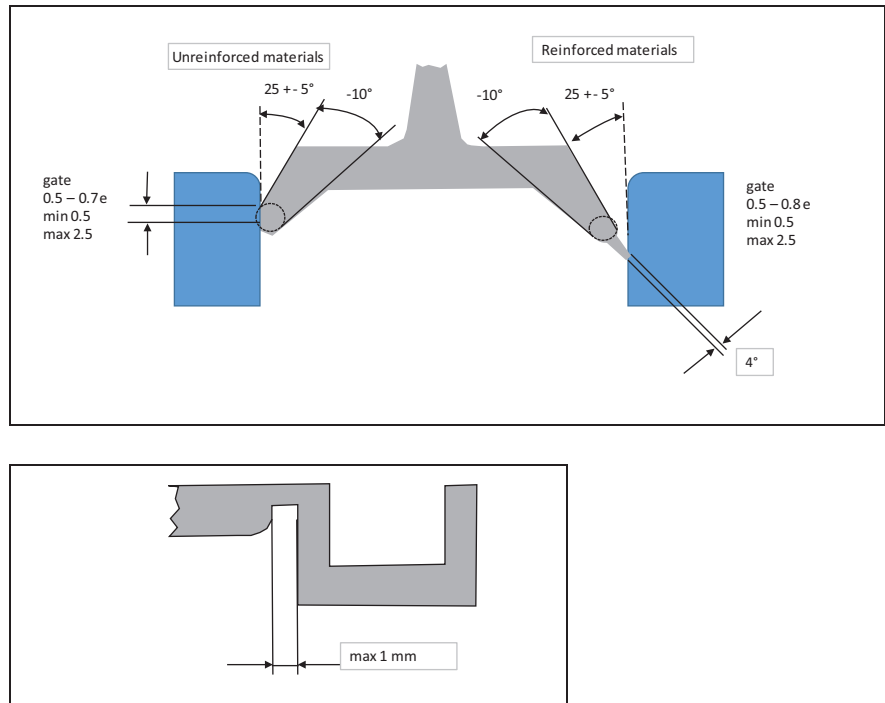


Figure 18.2 Submarine or tunnel gate

- Gate placed below the parting line.
- Automatic separation of runner and part during ejection.
- **Disadvantages:** The reinforced materials can be harmed. (See Chapter 17.)

18.3 Pin Point Gate

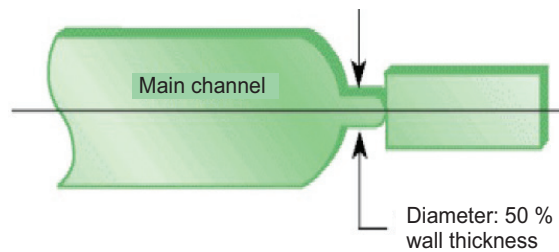


Figure 18.3 Pin point gate

Restricted gate located between the runner and the part. This gate is normally used in small thicknesses.

Preferably, the gate must be located in the center of the runner.

18.4 Tab Gate

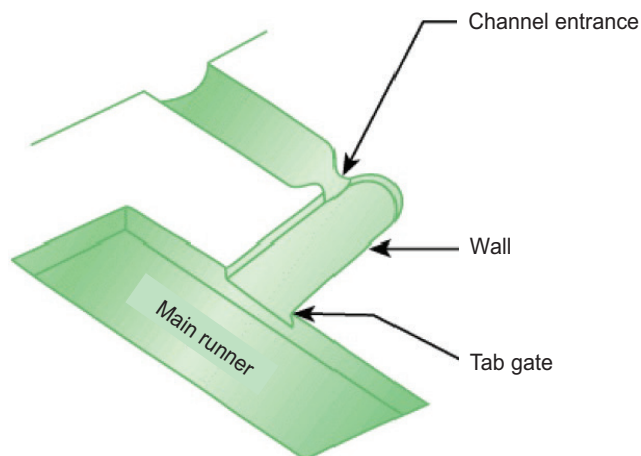
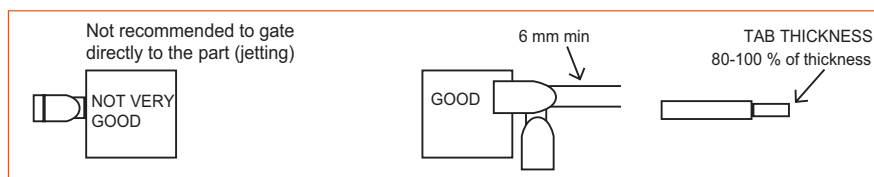


Figure 18.4 Tab gate

Gate used to direct the flow when big volumes are needed to fill the cavity. The tab helps to prevent potential jetting and surface defects caused by the shear.

- The channel should be round and the input must be centered on the axis.
- This device improves jetting, reduces shear stress, and is good for flat parts.
- Depth: 80–100% of the thickness.
- Width: 6 mm.



Recommended for:

- Thin and flat pieces.
- Reducing stress in the cavity.
- The tab prevents cross flow lines and in the same direction of flow.
- The entry must always be centered with the channel.

18.5 Sprue Gate or Direct Gate

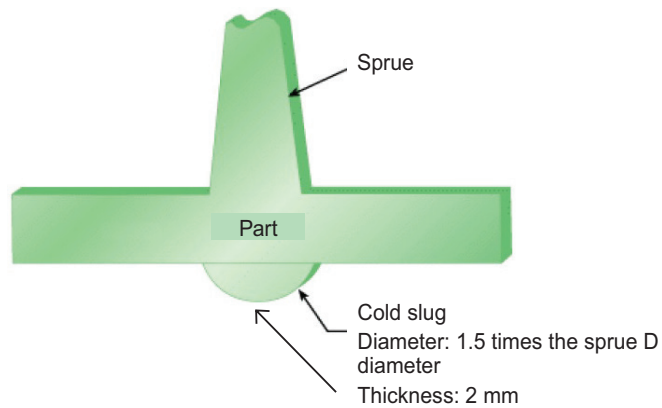
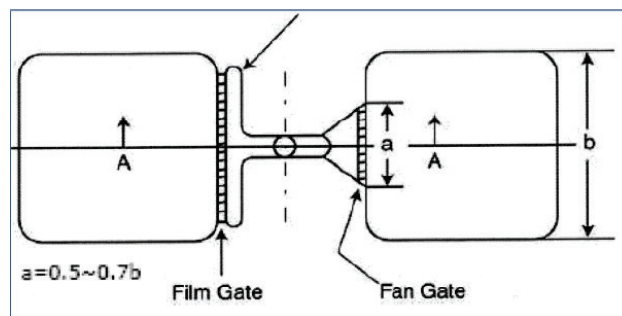


Figure 18.5 Sprue gate or direct gate

- Direct gate when symmetrical filling of the cavity is required.
- Widely used in cylindrical parts.
- Larger diameter sprue = thickness of the part.



18.6 Flash Gate

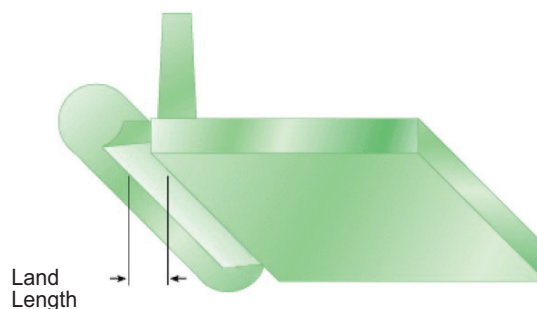


Figure 18.6 Flash gate

- Long side entry, but with little passage section for easy deburring.
- Land or entry length: no more than 0.7–1 mm.

18.7 Outer Ring

Gate used to obtain concentricity while injecting round pieces.

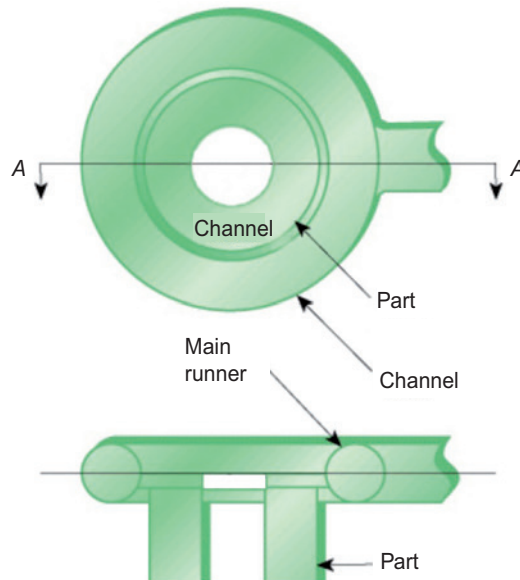


Figure 18.7 Outer ring

18.8 Inner Ring

Gate used to obtain concentricity while injecting round pieces.

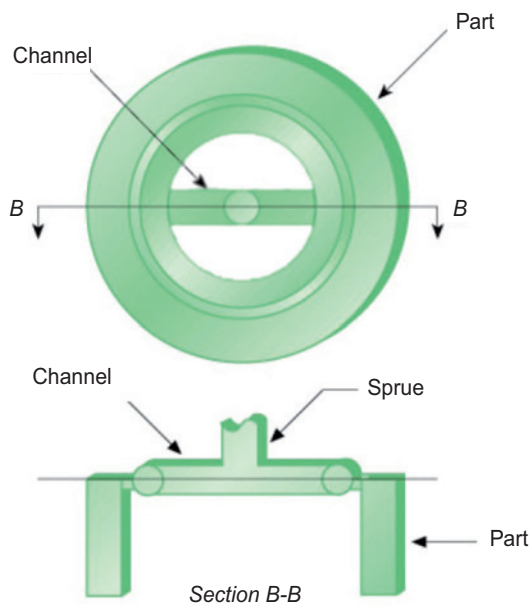


Figure 18.8 Inner ring

Because of its inner shape, it can only be used in molds that have a single cavity.

Disadvantages:

- Complicated straining machining of the runner.
- There may be differences between the part shrinkage close to the gate and at the end of the filling path.

18.9 Overlaged Jump Gate

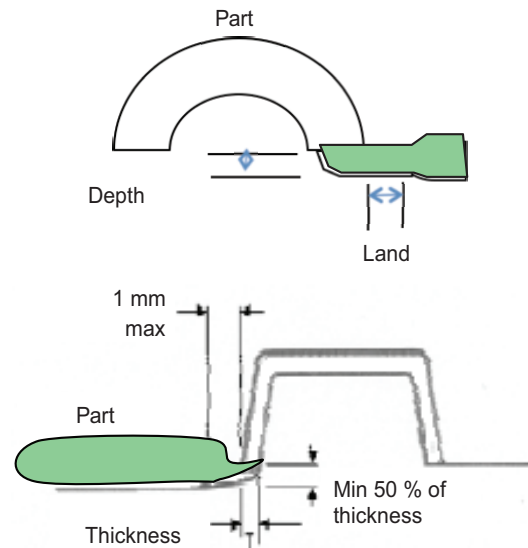


Figure 18.9 Overlaged jump gate

Depth: 50–80%

Width: 1–12 mm

Length: max 1 mm

Gate in non-visible areas of the part.

Disadvantages:

- Difficulty to remove without leaving marks.
- A narrow entrance may cause jetting.

18.10 Pin Gate

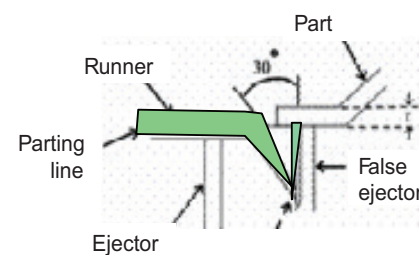
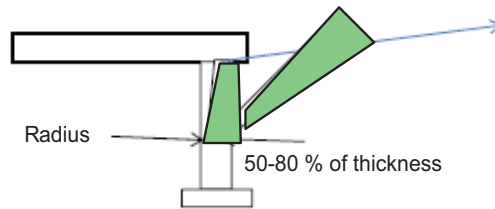


Figure 18.10 Pin gate

Located in areas where it would be necessary to have a vertical wall. An ejector can be placed to locate the submarine gate.

Disadvantages:

- The reinforced materials may be harmed.
- Flow can be frozen.



18.11 Most Common Injection Points

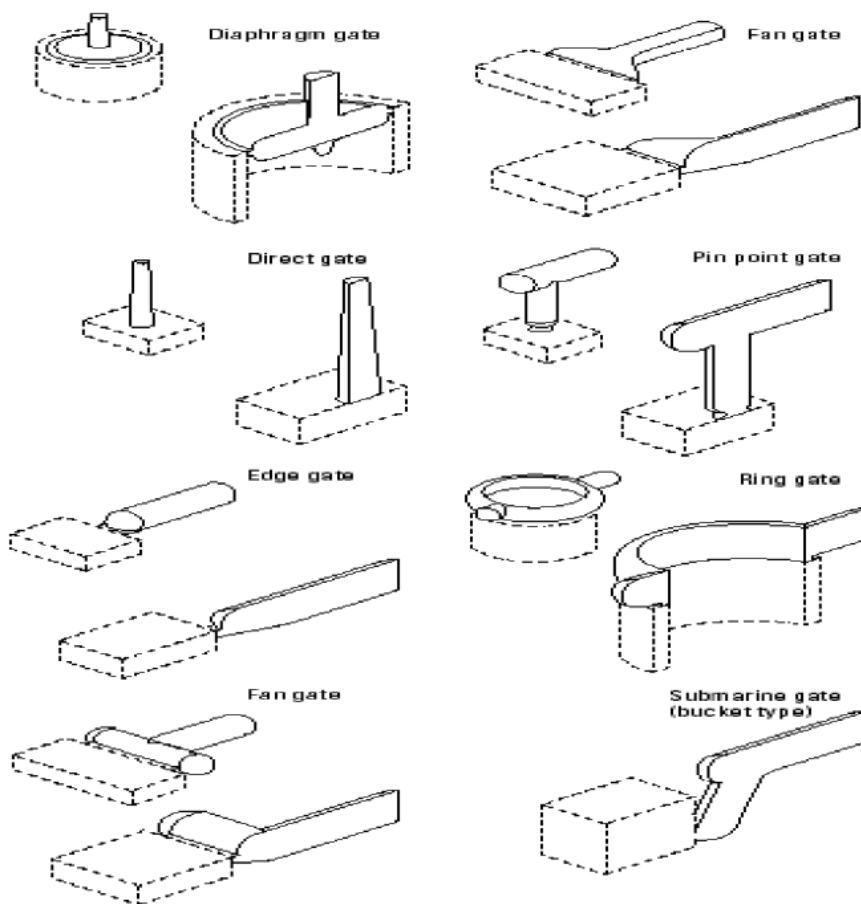
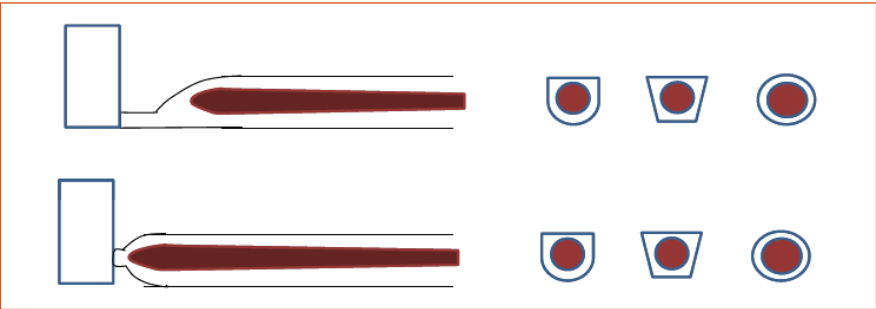


Figure 18.11 Most common injection points; source: DuPont

18.12 Central Flow Distribution Channels

In comparison with the gates centered with the runner, the gates displaced from the central axis do not use well the liquid vein, they generate more shear and friction, and cause aesthetic defects near the gate.



Plastic Parts Design: Recommendations

Source: DuPont Technical Info

The principles used in the design of metal parts are not suitable for thermoplastic materials, because these behave differently.

19.1 Recommendations

When designing a plastic part, we must consider the following:

- Use reinforcing ribs instead of thickness increments
- Design adequate thickness
- Design parts with uniform thickness
- Add radii
- Add draft angles
- Design a part with the right dimensional tolerances required
- Design multifunctional components
- Use simple elements and easy assembly techniques
- Place gate in the zone of greater thickness
- Make sure that the runner channels and the sprue are well dimensioned

19.1.1 Ribs and Reinforcements Designs

Plastics have no comparable mechanical strength and properties to metals. However, a good design can improve them and even make them a good alternative to these materials.

A common mistake is: Metal design = Plastic design → Part does not work in the application.

The thickness of ribs should not be more than 50% of the thickness of the plastic part. Thus, sink marks will not be caused by the accumulation of mass at the intersection of two walls.

Reinforcement ribs can be added, but we must consider that these will tend to generate sink marks by mass accumulation in intersection areas.

The taper shape and draft angle must be kept in mind. Depending on the material employed, the usual values are between 1° and 2°.

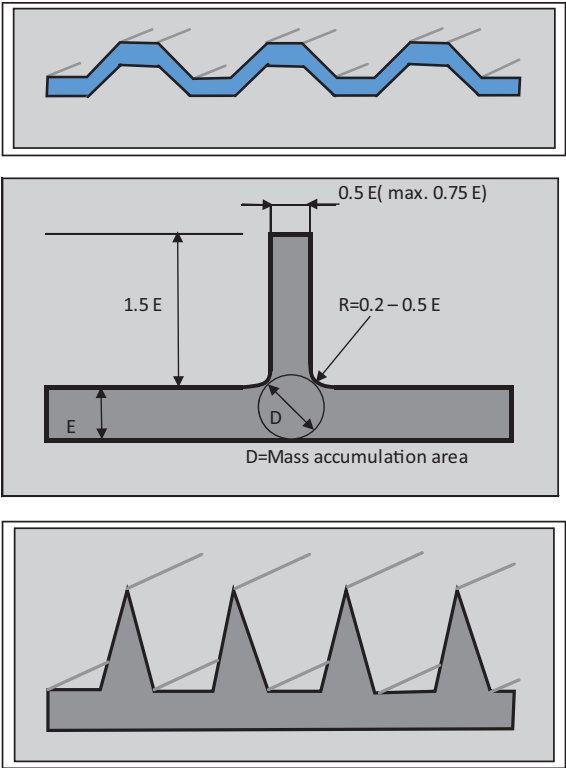


Figure 19.1 Possible reinforcement designs

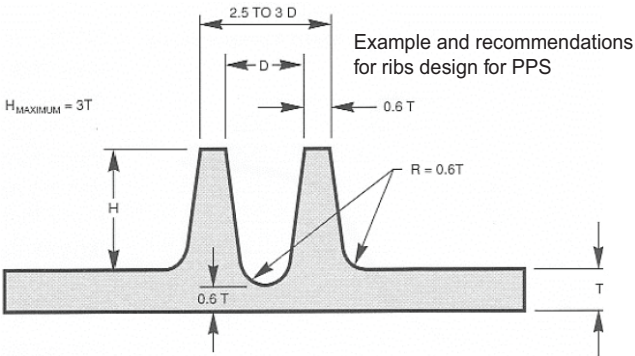


Figure 19.2 Example and recommendations for ribs design for PPS; source: Chevron Philips

19.1.1.1 Relative Torsion Resistance vs Reference

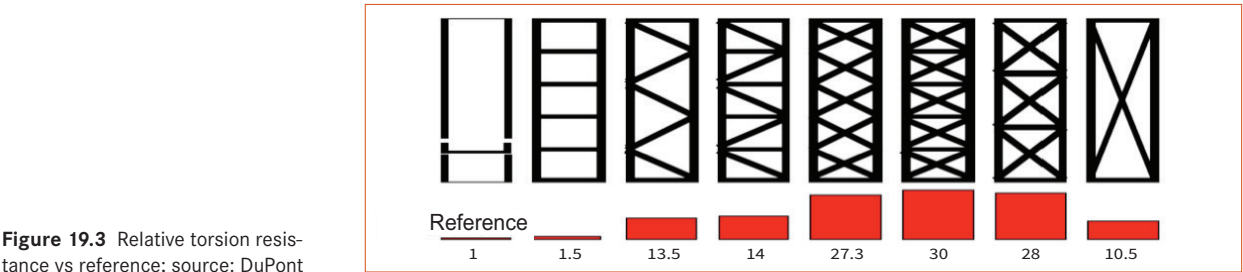


Figure 19.3 Relative torsion resistance vs reference; source: DuPont

As Figure 19.3 shows, changing the design with reinforced ribs, the torsional resistance may increase up to 30 times higher than the initial design or reference (without ribs). Ribs are more effective if they are high, not wide.

In the case of torsional loads, system rigidity is determined by the polar moment of inertia (I) and length. The formula used is:

$$I_{x-x} = B \cdot H^3/12$$

where B is the width, H the height, and I_{x-x} the moment of inertia.

19.1.1.2 Deformation at Constant Load

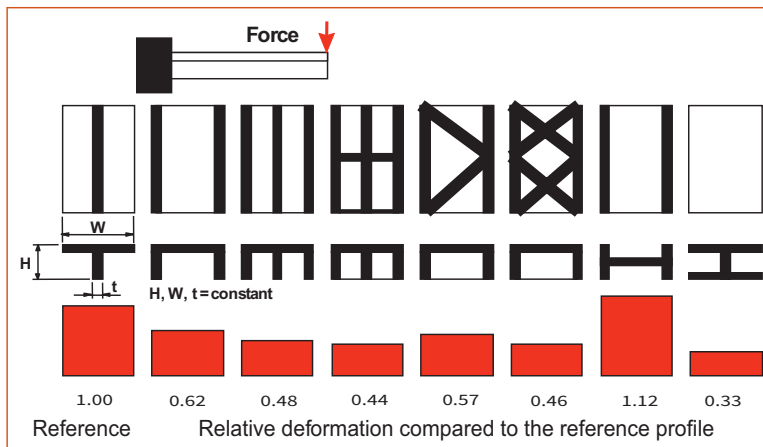


Figure 19.4 Deformation at constant load; source: DuPont

By applying a constant load on a T-shaped profile fixed at one side and comparing it with a profile reinforced with ribs, we can see that, whereas the reference profile value is 1, the deformation at constant load can be reduced down to 0.33.

19.1.2 Tensile Stresses

The deformation (d) of a system subjected to a tensile stress of length L and area A (i. e., constant) can be calculated by applying this formula:

$$d = (F \cdot L) / (Y \cdot A)$$

F is the tensile stress and Y is the elastic modulus

According to this formula, rigidity can be increased by increasing the modulus (Y) or the specimen area (A).

The section should be as uniform as possible in order to distribute evenly the stress.

In the case of a part subjected to flexion the ribs should be perpendicular to the flexion moment. Ribs must be high, not wide, to obtain greater rigidity.

Rigidity of Profiles with Different Thicknesses

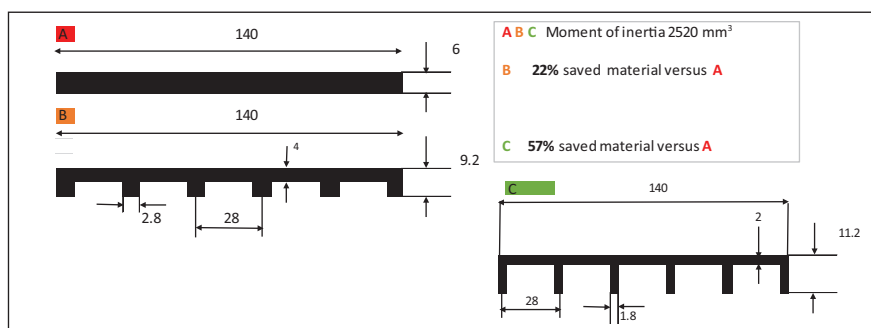


Figure 19.5 Saving material solutions

Different ribs designs make it possible to increase the stiffness and save material.

Calculation of flexion

d = Deformation E = Elastic Modulus
F = Force I_{x-x} = Moment of inertia
L = Length

The moment of inertia and length determine the rigidity of the system when deformation in flexion is calculated.

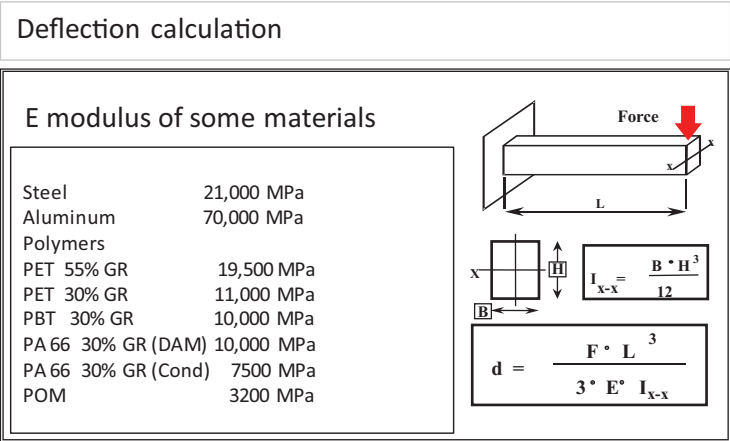


Figure 19.6 E modulus of metals versus that of some polymers, and calculation of moment of inertia and deformation

Analyzing the flexure deformation formula in Figure 19.6, it can be deduced that the stiffness can be increased by decreasing L (length) or increasing I_{x-x} (moment of inertia). In this case, to increase I_{x-x}, the H value has more influence than the B value since, according to the formula of moment of inertia (Figure 19.6), it is cubed.

For optimum resistance to flexion the material should be located as far as possible from the neutral axis so the moment of inertia will be increased.

19.1.3 Thickness Design

A constant thickness allows the pieces to have less deformations and internal stresses. There are several design solutions to reduce areas of greater thickness.

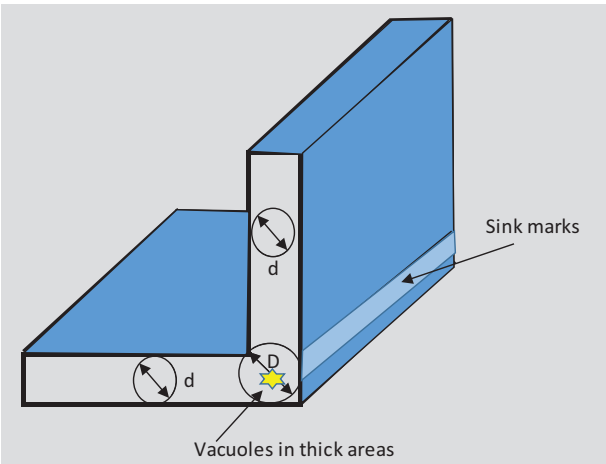


Figure 19.7 Internal and external shrinkage

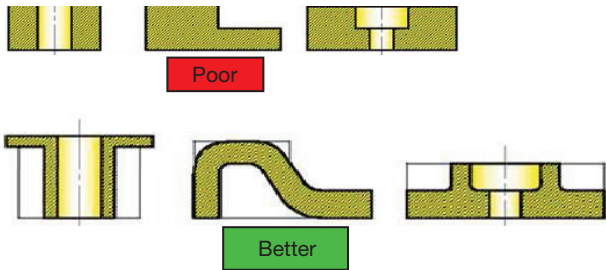


Figure 19.8 Improved designs for avoiding thickness problems; source: DuPont

In Figure 19.7 and Figure 19.8 we can see various examples of designs focused on reducing thicknesses and avoiding problems.

19.1.3.1 Changes in Thickness

Changes in thickness should be progressively realized, not abruptly. We must also provide radii whenever possible. Thus, the shear stress will be improved in that area.

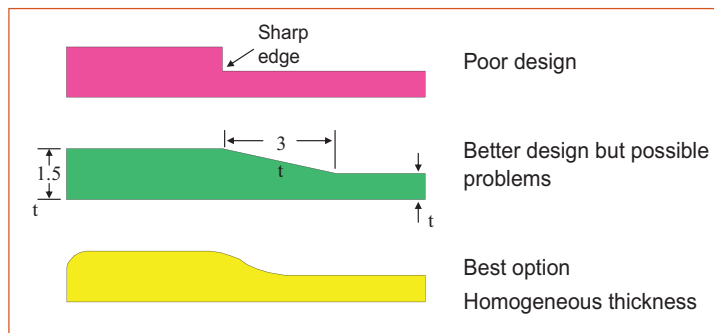


Figure 19.9 Changes in thickness—design examples

19.1.3.2 Homogeneous Thicknesses

Material accumulation zones are poorly cooled by the mold cooling system, generating areas of greatest shrinkage and subsequent deformations and warpage.

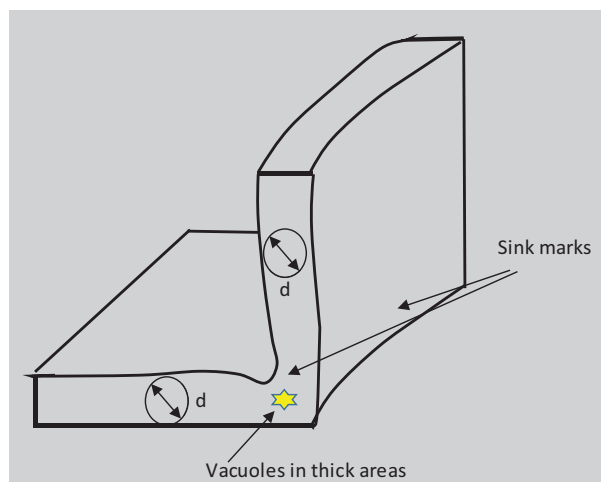
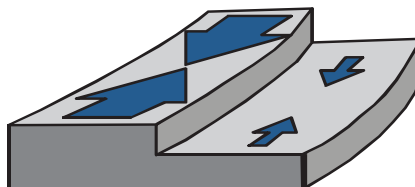


Figure 19.10 Deformation caused by different thicknesses in some areas

When parts cool, they are deformed by the different thicknesses and differential shrinkage, generating some effects as may be seen in the image.



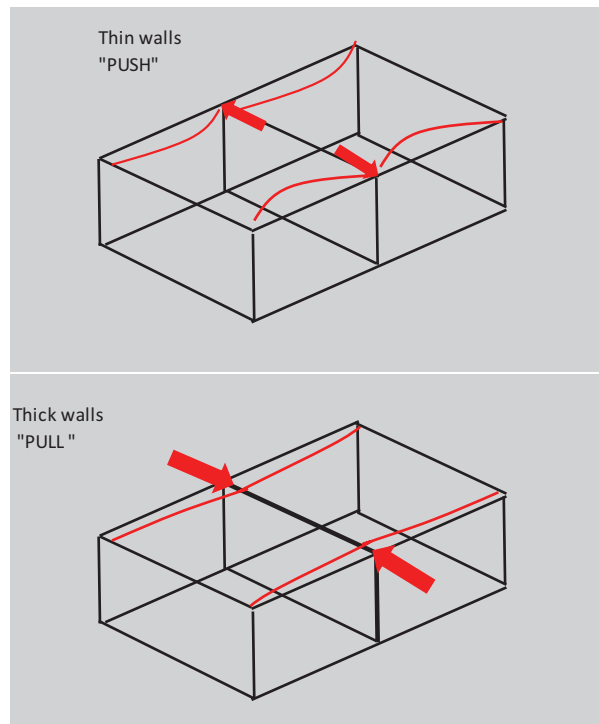


Figure 19.11 Differential shrinkage due to different rib thicknesses

- Thick ribs “pull” (higher shrinkage)
- Thin ribs “push” (lower shrinkage)

19.1.4 Sharp Corners and Radii

Sharp edges should be avoided mainly for two reasons:

1. When the cavity is filled, they increase the shear effect even in extreme values, degrading the polymer and reducing the mechanical and aesthetic properties.
2. When the piece is in use, stress is concentrated on sharp edges, causing less impact and flexion resistance.

Figure 19.12 shows some solutions to reduce sharp edges.

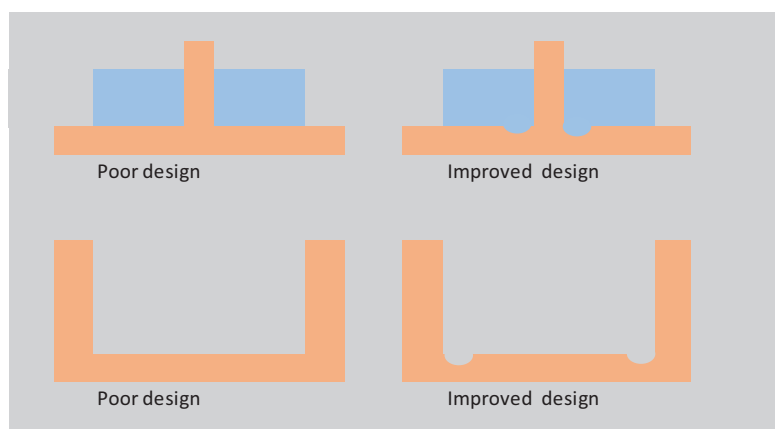


Figure 19.12 Solutions for avoiding sharp edges

Sharp corners act as stress concentrators, causing areas with lower flexural resistance. In Figure 19.13 we can see that from a radio-thickness ratio of 0.8, the stress concentration factor is reduced.

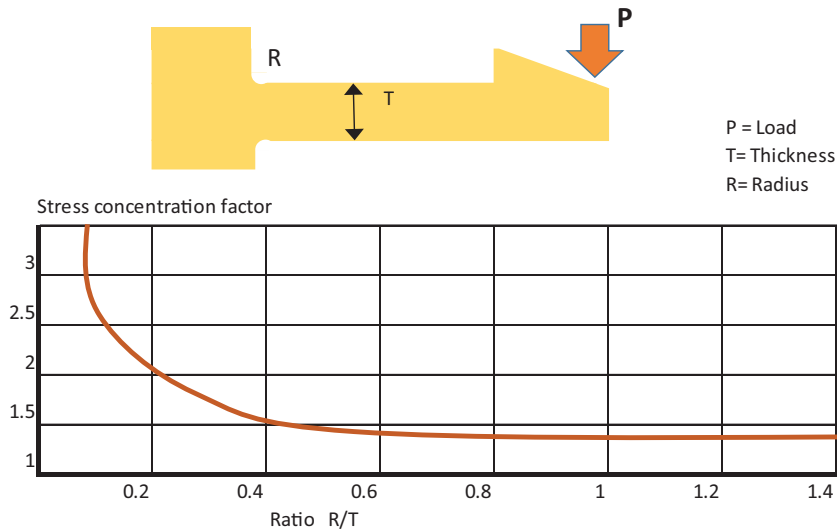


Figure 19.13 Stress concentration factor versus ratio radius to thickness

The smaller the radius, the larger the stress concentration factor. Consequently, lower load may be supported.

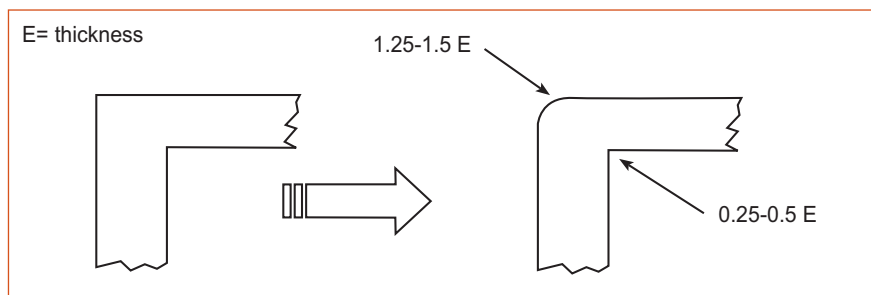


Figure 19.14 Recommended radius as a function of thickness

19.1.5 Influence of the Notches in the Impact Resistance

The diagram in Figure 19.15 shows how the notches with small radii have an impact strength up to 40 times smaller than the notches with large radii.

The impact energy is concentrated in the smaller radii. Therefore, the impact resistance is smaller compared to larger radii.

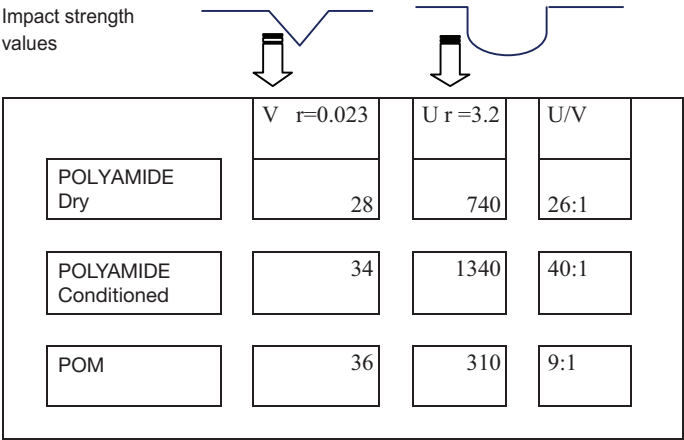


Figure 19.15 Impact resistance with different notch shapes; source: DuPont

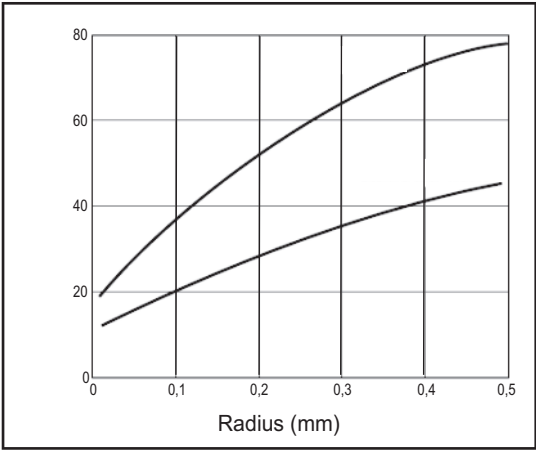


Figure 19.16 Impact resistance according to radius; source: DuPont

19.1.6 Slots and Undercuts

- A round shape facilitates demolding.
- As the ejectors will apply more force with undercuts, ejectors' diameters must be oversized.
- We should reduce the cycle to prevent a high level of shrinkage into the mold that would make the ejection more difficult.

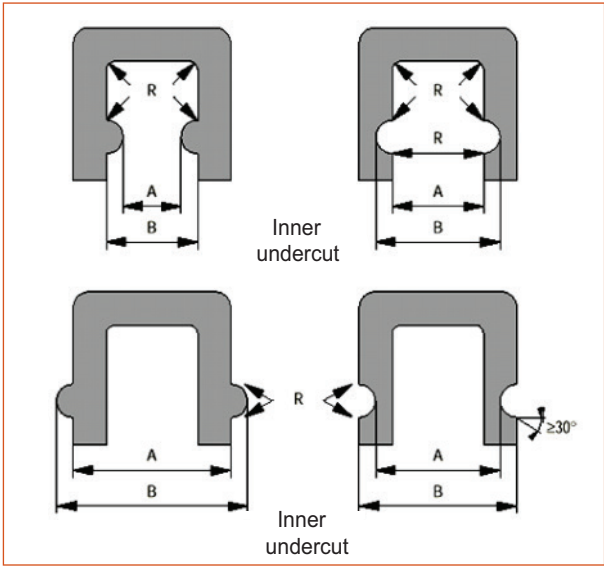


Figure 19.17 Internal and external undercuts; source: DuPont

Sometimes the part and mold design have areas without draft angle. These areas must be force-ejected, so it is very important to consider the size and shape of the undercut or slot in addition to the molding conditions.

The maximum undercut depth is defined by the ratio between the diameters A and B. This ratio should not exceed the elastic limits of recovery of each material to prevent permanent deformations of the parts.

The ratio between A and B should not exceed the allowed percentage of material elongation.

19.1.7 Snap-Fit

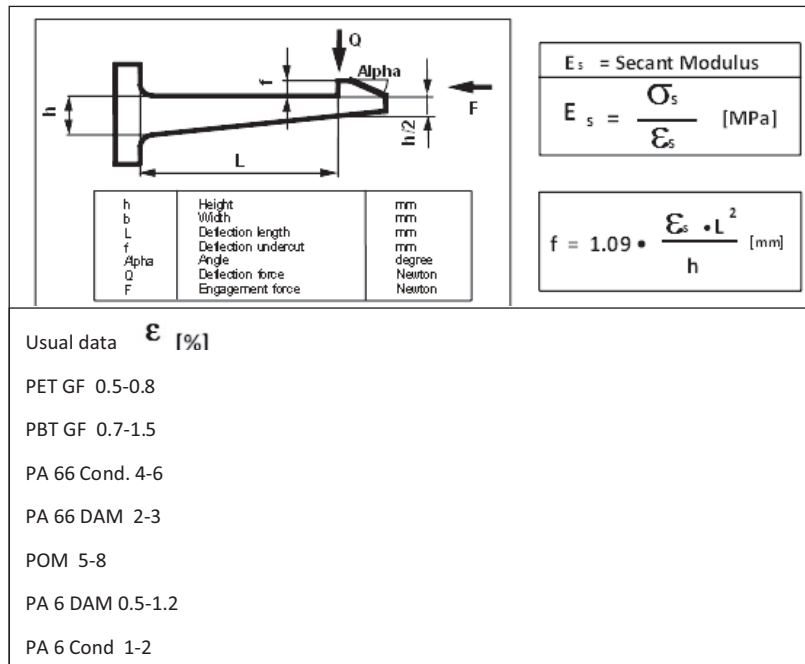


Figure 19.18 Snap-fit calculation

The maximum value for the elastic stretch varies with each polymer (%). Using a formula, we can calculate the required deformation depending on the length and thickness of a snap-fit.

Material	Strain (%)
PS	2
ABS	2
SAN	2
PMMA	2
LDPE	5
HDPE	4
PP	4
PA	3
POM	4
PC	2

19.1.8 Rigidity

The rigidity of parts can be improved by design, with rectangular  and V-shaped grooves. We must move as much material as possible on the neutral axis to enhance the moment of inertia. For working in flexion parts, ribs should be placed perpendicularly to the flexural moment.

19.1.9 Creep and Relaxation

The behavior of the plastic subjected to load over time is affected by load, time, and temperature. Under a constant load, the deformation of the material will be increased according to time and temperature. In these cases, two phenomena occur: creep and relaxation.

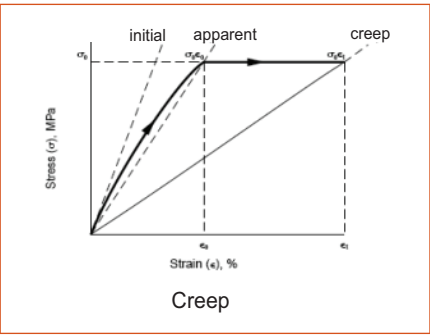


Figure 19.19 Creep; source: DuPont

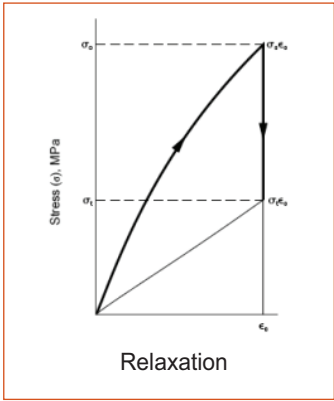


Figure 19.20 Relaxation; source: DuPont

If stress or load is maintained permanently, the plastic will be deformed, will strain, and the module will decrease. This effect is called creep.

If, on the contrary, the elongation is fixed, the necessary strength to hold it out will decrease and, therefore, the module will also decrease. This effect is called relaxation.

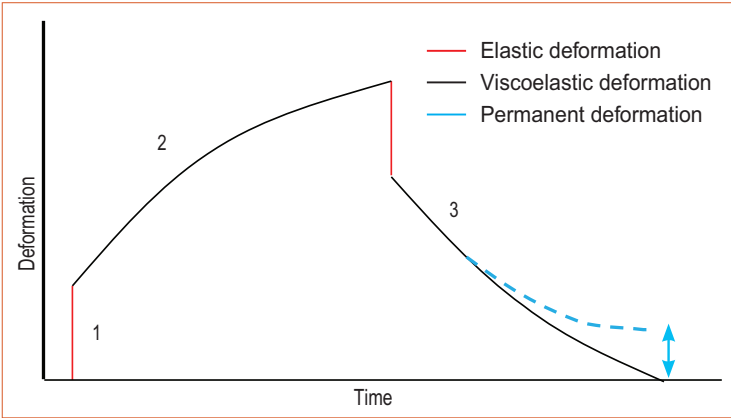


Figure 19.21 Viscoelastic and elastic behavior of polymers under load vs time

An initial momentary load produces a deformation which is recoverable if this load ceases within the elastic deformation (number 1 in Figure 19.21). If the load increases, a viscoelastic deformation will be produced (number 2). This deformation will be recovered slowly when the load ceases but can leave a permanent deformation depending on the force level achieved (number 3).

19.1.10 Tubular Frames, Screw Holes

The screw holes are used for assembling the parts. Usually, assembly is performed with screws, inserts, or some type of quick connector.

A rule is that the hole should have an outside diameter 2 to 2.4 times the diameter of the screw or insert.

To avoid shrinkage or sink marks in the ribs that hold the tubular frame, the tube thickness should be equal to 1/2 of the outer wall of the part. Also, sharp edges must be eliminated with radii and chamfers.

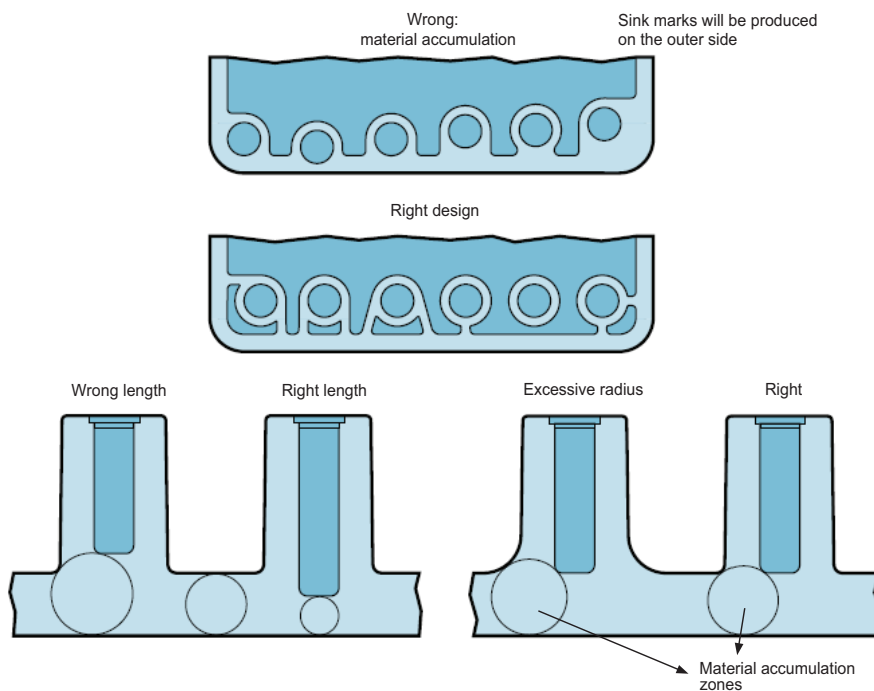


Figure 19.22 Design solutions for avoiding sink marks

Injection: Some Practical Tips

20.1 Inspection of Runners and Gates Systems

1. Start with the subrunner that fills the gate: the thickness of the runner depends on the type of material (e.g., PBT + fiberglass = 1 to 1.5 times the thickness of the part).
2. Define the thickness of the remaining runners (increase every runner change: 0.5–1 mm depending on the type of material).
3. Set the sprue and the nozzle diameters (this one, 10% smaller than the sprue small diameter).
4. Define the dimensions of the gate. These dimensions depend on the material. The depth varies between 50 and 90% of the thickness of the part.

Smaller diameter sprue: for large parts, this can be equal to the greater thickness of the part. In cases of high viscosity material, it may be up to 1.5 times the thickness of the part.

Key point: the smallest diameter of the sprue must be greater than the diameter of the runner that fills the gate. In this way the system will be properly pressurized.

In some balanced systems, the smaller diameter of the sprue corresponds to the greater thickness. Then will follow the main runner, side runners, and so on.

When hot runners are used, the nozzle diameter must be equal to the pitch diameter of the hot runner (flow tube) to avoid loss of pressure and shear.

20.1.1 Gate Depth, Width, and Length

The **gate depth** controls the freeze time.

- Depth for easy-flow materials: 50% of the thickness of the part (PP-PE)
- Depth for medium-viscosity materials: 75% of the thickness of the part (ABS-SAN-ASA)
- Depth for high-viscosity materials: 90% of the thickness of the part (PC-PPO-PA filled)

If the depth is not enough, it may cause gloss at the gate.

The **gate width** controls the volume or flow injection. For large parts it can be up to 10 times the depth of the gate (it is usually two times the depth).

For small parts, the width is two times the depth. For larger pieces, three times the depth. For small parts, the width is equal to the depth.

The **length** should not exceed 0.5 times the depth of the entrance and in no case more than 1 mm. If this becomes excessive, excessive shear occurs at the entrance.

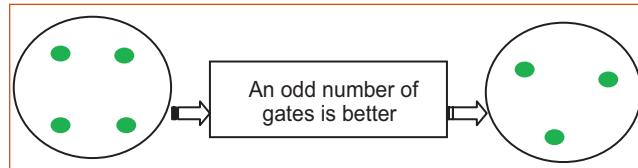
Defects like gloss, blush, jetting, etc., are symptoms of small gates.

20.1.1.1 Defects Due to the Gates

- Gloss: usually due to lack of depth of the gate
- Flow line at the entrance: may be due to too great a length
- Blush: usually due to small gate and/or too great length

For Round or Concentric Parts

You should use an odd number of gates, placed halfway between the center and the outside of the piece. Side gates go well with flat parts.



Edge gates: they always have round runners. Gates must be machined in the center axis of the inner runner to tap the liquid vein. Trapezoidal runners and side gates displaced from the axis generate stress and defects.

Materials	Depth	Width	Length
ABS	75–90% of width	2 × depth	0.5 depth (< 1 mm)
ABS F Retardant	90% of width	approx. equal to runner	0.5 depth (< 1 mm)
ABS-PC	90% of width	2 × depth	0.5 depth (< 1 mm)
PA 66 FV	90% of width If there are oily marks around the gate, the entry is small. Runner: 1.5 times the thickness of the part.		
PA 66	50% of width		
POM	90% of width If the part has a thickness of 1.5 to 3 mm, the subrunners must be 1.5 times the thickness of the part. For thick parts, the main runner should be as the section of the part. Small runners can be used, but gates must be large (at least 75% of the thickness of the part). High mold temperatures give more rigid parts. Low mold temperatures give more flexible parts, as they have less crystallinity.		
PS	High depth impact: 75% Easy fluidity: 50–60% of width		

20.1.2 Gates and Runners Design

Example of Definition of Gate Dimensions According to the Type of Material and Piece Thickness

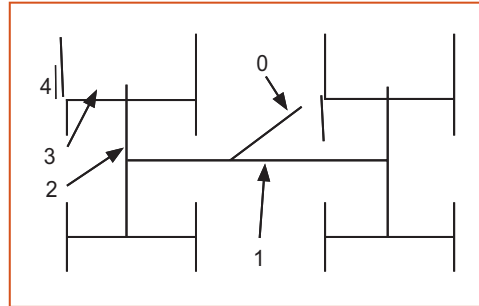


Figure 20.1 Cold runner, different runners, and subrunners levels

Example: ABS part (2.5 mm thick), 16 cavity mold, and runner like Figure 20.1.

- Diameter of runner that fills the ABS gate (part thickness $\times$ 2): $2.5 \times 2 = \varnothing 5$ mm (runner 4).
- Secondary runner diameter (n° 3): previous runner diameter + 0.5 to 1 mm = $\varnothing 5.5$ to 6 mm.
- Next runner diameter (n° 2): previous runner diameter + 0.5 to 1 mm = $\varnothing 6$ to 7 mm.
- Main runner diameter (n° 1): previous runner diameter + 0.5 to 1 mm = $\varnothing 6.5$ to 8 mm.
- Sprue diameter (big diameter) D: main runner diameter + 20% = $\varnothing 7.8$ to 9.6 mm. (It must be larger than the main runner to pressurize well the rest of runners.)
- Sprue diameter (small diameter) d: This diameter dimension will depend on the length and taper of the sprue. It should be bigger than the runner that fills the gate.
- Nozzle diameter: sprue diameter - 10 % = $\varnothing 7$ to 8.6 mm. (10% smaller than the diameter of the sprue.)

Unbalanced Runners

The filling of unbalanced runners can be slightly improved by the injection speed.

The higher the injection speed, there will be more pressure on parts close to the sprue and less on the more remote parts.

The lower the injection speed, there will be more pressure on remote parts of the sprue and less on the parts that are closer.

20.1.3 Spiral Effect or Flow Distribution

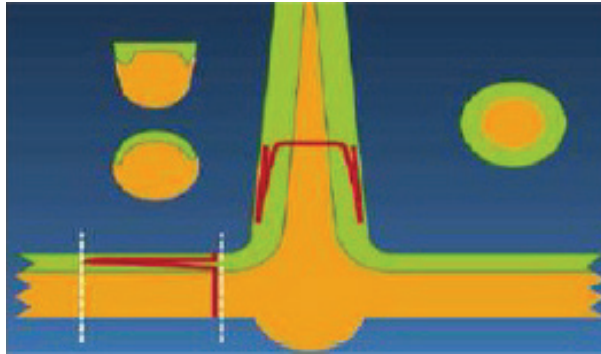


Figure 20.2 Cold and hot flow into the runner; source: DuPont

The material, as it flows through the distribution runners, varies its speed due to the cold walls of the mold, the rotations of the runners, and the shear between the outside layer and the interior hot flow. This causes in each turn a variable filling speed profile and differing cavities filling despite having identical gates and equal flow paths.

In cases of more than four cavities, imbalances can occur during filling due to an accumulation of shear in direction changes. This causes dimensional differences and over-internal-injection-pressure in cavities that have been filled earlier than the rest of the cavities.

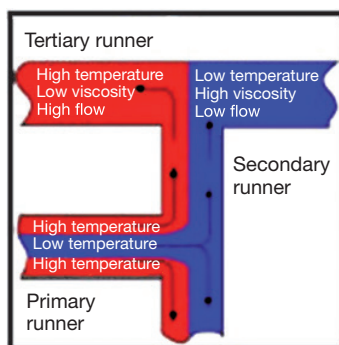
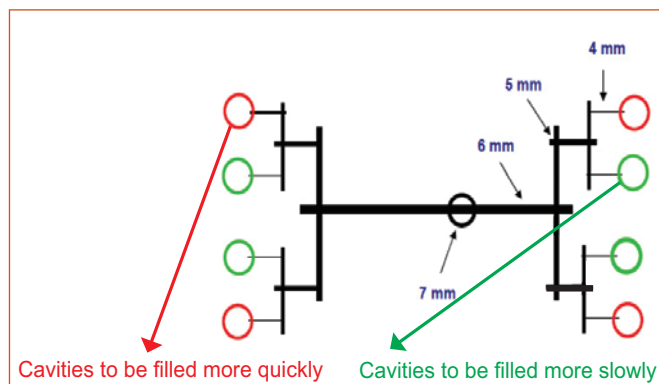


Figure 20.3 Temperature differences into the flow during flow path

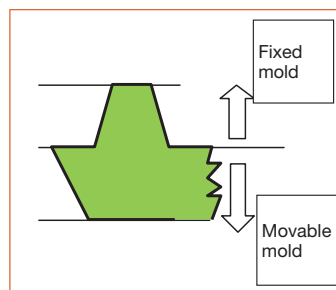


Figure 20.4 Example of runner design with flow path on the two sides of the mold

One solution that can minimize the spiral effect is to move the runner section in every change of direction from one side of the mold to the opposite mold side. This promotes the mixing of flow during filling and balances the different flow filling speeds and temperatures.

Alternating runners between the fixed and movable sides of the mold at each change of direction reduces the spiral effect. Thus, the turbulent mixing flow reduces the differences in flow rate during filling of the runners.

20.1.4 Nozzles in Processes with Hot Runners

To avoid restrictions when working with hot runner molds, use nozzles whose pitch diameter is similar to the diameter of the flow tube.

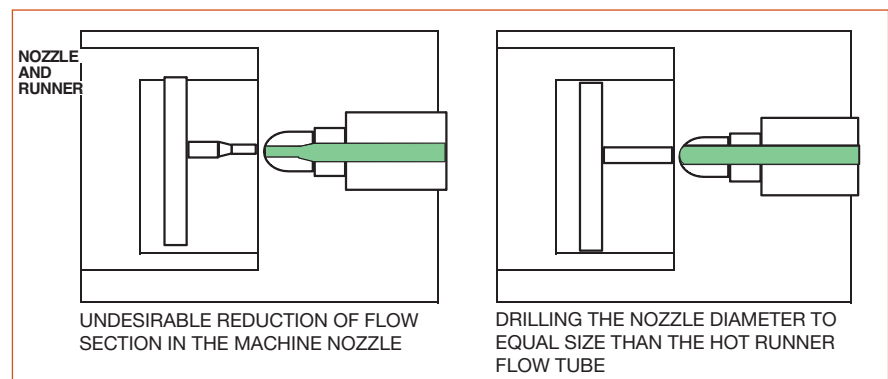


Figure 20.5 Hot runner nozzle flow path recommendation

20.1.5 Cooling

Its effectiveness depends on the smaller diameter restrictions. Bridges are not recommended. Direct coolant gates and exits are better.

Temperature differences between the input and output must not exceed 3–5 degrees. Greater differences indicate that we are cooling too many circuits and/or the flow diameter is small. Minor differences indicate that the required heat is not being removed.

If we double the diameter of the coolant passage, we approximately quadruple the flow.

Turbulent flow within the channels will drag up to five times more heat than laminar flow.

Some moldmakers prepare the molds with cooling in the mold base plate to prevent heat conductivity from spreading through the machine and reducing the temperature of the mold.

Molds may be cooled below zero degrees with a mixture of water and ethyl glycol 50% but these low temperatures could cause condensation in the mold.

20.1.6 Purging or Cleaning of the Injection Unit

Never mix POM with PVC or TPE V with POM.

The change of material in the injection unit can be long and complex when significant variations in morphology and/or temperatures of the materials involved are produced. To minimize this sudden temperature change, intermediate materials are used for purging or cleaning of the injection unit.

When changing materials or color, screws cleaners are also used. These products may be liquid or pellets.

Initial material	Final material	Intermediate material
ABS	PP	
ABS	PSU	HDPE
ABS	PC	regrinded acrylic
ABS	PBT	HDPE
POM	PC	HDPE
POM	PVC	HDPE
POM	PSU	HDPE
acrylic	PP	
acrylic	PA	
ASA	ABS	regrinded acrylic
ASA	PC	regrinded acrylic
PE	ASA	regrinded acrylic
ABS	ASA	regrinded acrylic
PP	PC	HDPE

20.1.7 Venting

Insufficient gas outputs (venting) causes the appearance of matte areas on the part in a first step of bad design. If the problem is more pronounced, streaks and spots, and even burned areas, will appear on the surface. These effects are also harmful to the mold.

The depth should allow the exit of air and gases, but not of the molten plastic.

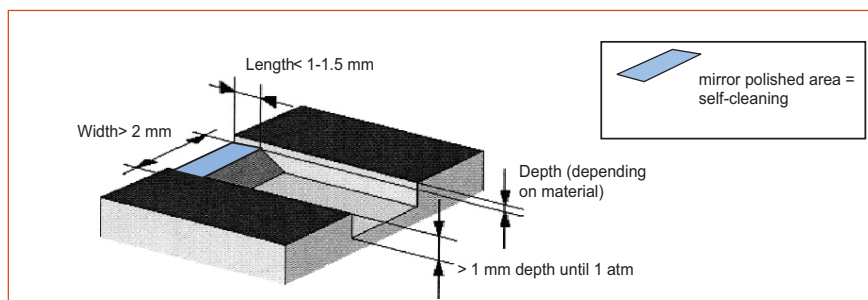


Figure 20.6 Venting design example and recommendations

The length of the venting should not exceed 1–1.5 mm. Otherwise, the steel can deflect during closure and prevent gases to escape. Also, if the land is excessive, volatile elements carried by the gases may condense more easily on the surface and reduce the air flow.

The width should be 5–8 mm.

Runners should be aired whenever the runner completes a 90 degree turn.

In runners venting small flashes may occur. If so, there would be no problem. These flashes are due to excessive depth of the output. The gas exit runner can be as wide as the sprue. Flashes are due to the depth, not width.

It is possible to polish the venting outlets toward the air outlet to prevent accumulation of residues of gases.

There must be a venting for every 25 mm of parting line and have a full ventilation from 20 to 30% of the parting line.

Ideally, the air pressure inside the cavity should not increase during filling. If this pressure increases, it means that the volume of incoming material is greater than the volume of the air withdrawn.

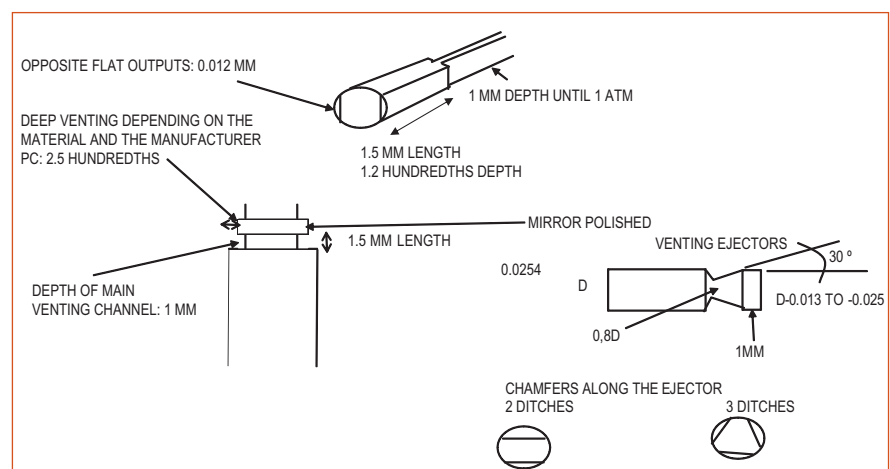


Figure 20.7 Ejector venting design recommendations

Table 20.1 Venting Depth Recommendation for Some Polymers

Polymer	Easy flow [mm]	High viscosity/glass filled [mm]
ABS, SAN, HIPS	0.0508	0.0762
POM	0.0127	0.0381
PMMA	0.0508	0.0762
CA,CAB	0.0254	0.0381
PA 66	0.0127	
PA 66 15% FV	0.0127	0.0381
PC	0.0381	0.0762
PE	0.0254	0.0508
PP	0.0254	0.0508
PPO	0.0254	0.0762
PPS	0.0127	

Polymer	Easy flow [mm]	High viscosity/glass filled [mm]
PSU	0.0254	
PS GP	0.0254	0.0508
PVC	0.0254	0.0508
TPU	0.02	
PBT	0.03	
PET	0.02	
PPA	0.015	

20.1.8 POM Foaming Test

When POM, like all polymers, is subjected to melting temperatures and a long residence time, this can lead to degradation. The melting temperatures recommended for POM homopolymers are about 210–220 °C. At these temperatures we expect that no degradation occurs in approximately 20 to 30 minutes.

In some cases, POM homopolymers may be incompatible with some component of the color masterbatch. Loss of mechanical properties and even flaws clearly visible to the naked eye may occur.

When we suspect that some kind of degradation may have taken place, either thermal or due to incompatibility of the components, we can use the so-called foaming test.

Foaming Test (Source: DuPont)

Follow these steps:

1. Work in a normal injection process for at least 30 minutes. Thus, the material will remain on the spindle during the normal time and will be subjected to internal pressure and compression, lamination, etc.
2. Stop the injection machine and allow the material to stand a while depending on temperature and the material used (colored or not).
 - a) 200 °C (melt temperature) or natural color timeout: 20 minutes
 - b) 215 °C (melt temperature) or colored material timeout: 5 minutes
3. Perform a purge or ejection of material in a container.
4. When the purge has cooled and solidified, cut it in half. Observe the holes produced inside the mass. If there is no degradation, the holes should have a matte inner surface, because gases produced by degradation, when expanded, generate bubbles with bright interior.
5. Immerse the molten purge in water. If the purge sinks in the liquid, there will be a few bubbles of gas (and degradation is nonexistent). However, if the purge floats, there will be an excess of bubbles inside.

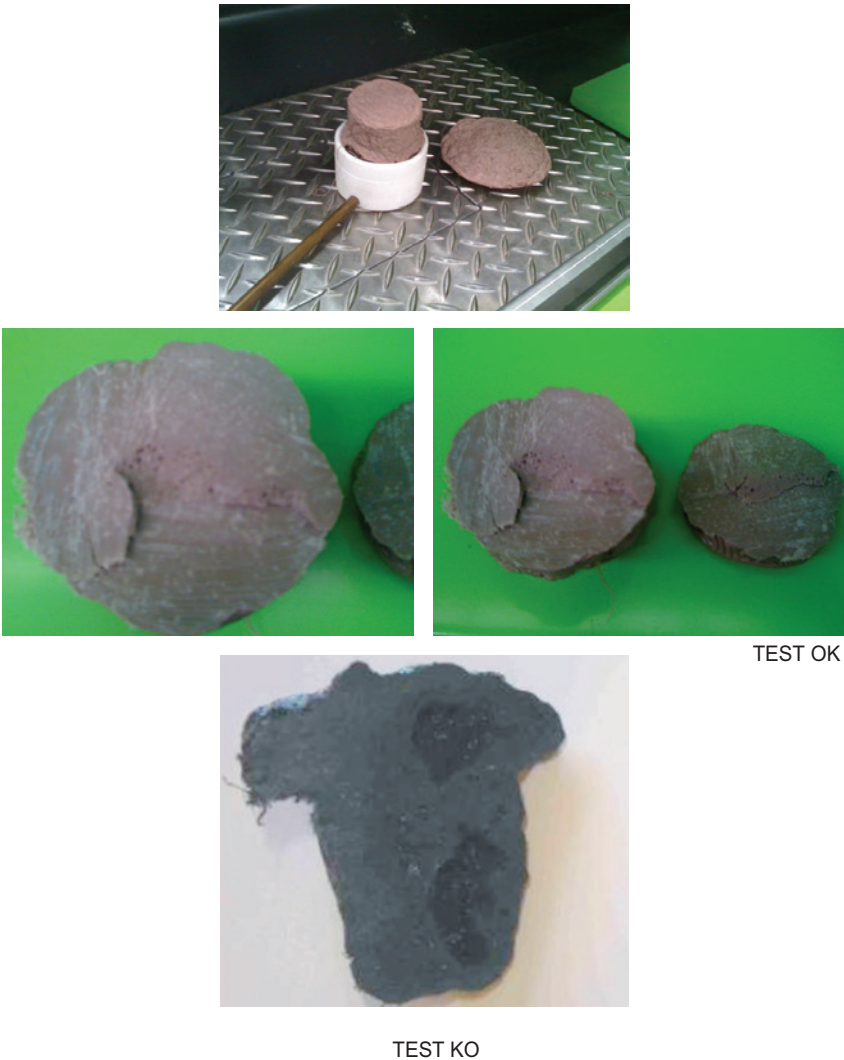


Figure 20.8 Foaming test;
source: DuPont

20.1.9 Surface Tension

The minimum surface tension in a surface for painting should be at least 38 to 40 mN/m. This surface tension allows the drop of applied product to spread and wet uniformly the surface to be painted and thereby get quality surfaces.

Plastics have usually a surface tension below 28 mN/m. It should be noted whether plastics are amorphous or semi-crystalline. The semi-crystalline plastics, due to their structure and their lower surface tension, do not easily become wet with liquids on their surface.

Standard test: > 38 mN/m*
To paint: 40 mN/m necessary
Plastics: 28 mN/m
Water: 73 mN/m
To paint with water-based paints: 72 mN/m

* Made with tension test inks (e.g., Plasmatreat®).

The test could be done during production; it is basically to make use of commercially available inks for measuring surface tension.

Suppose that the ink has a tension of 38 mN/m. By applying it to the plastic surface, we have to observe the marks or lines.

1. If the marks are reduced or bind in less than 3 seconds, the plastic has a lower surface tension than the ink ($< 38 \text{ mN/m}$).



2. If the marks remain for more than 3 seconds, the plastic has a higher surface tension than the ink ($> 38 \text{ mN/m}$).



$1 \text{ mN/m} = 1 \text{ dyn/cm}$

mN/m (millinewton/meter) is a measurement of energy/area.

20.1.9.1 Contact Angle

Contact angle is the angle formed by the drop of product on the surface to be impregnated.

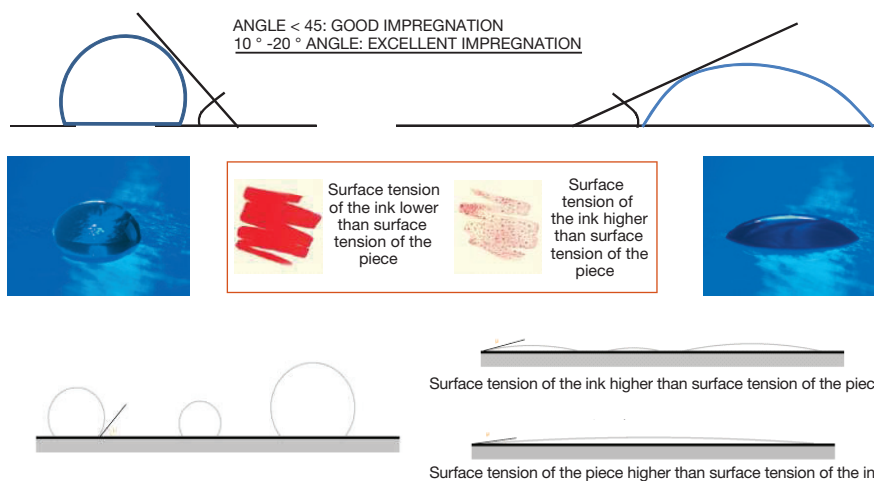


Figure 20.9 Contact angle

If the surface tension of the ink is greater than the surface tension of the part, the ink will come in contact with the part homogeneously. However, if its surface tension is greater, the contact will be correct.

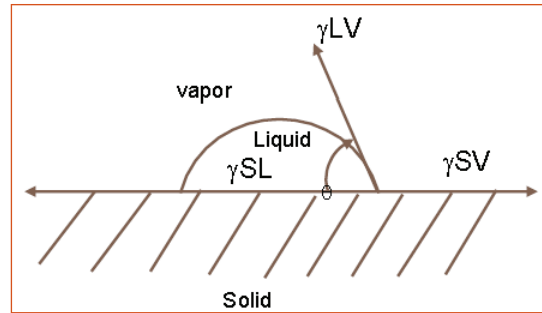


Figure 20.10 Contact angle between a liquid and a solid substrate

20.1.9.2 Industrial Methods for Activating the Surface or Increasing Surface Tension

These treatments modify the surface tension, although the effect may be reduced over time.

20.1.9.2.1 Corona Treatment

An electrical discharge of high voltage and high frequency is applied on the surface.

20.1.9.2.2 Atmospheric Plasma Treatment

Energy changes the state of matter. If more energy is applied to a gas, this is ionized and becomes plasma, the fourth state of matter.



Figure 20.11 Fourth state of matter: plasma; source: Plasmamatreat

Part 4

Scientific Molding

Scientific Molding or Injection by Advanced Methods

The term *scientific molding* and some of its methods were developed in the U. S. A. at the end of the 20th century. The objective was to develop concepts to understand better the injection of thermoplastics by applying science. Thus, robust processes with low scrap, better cycle time, and optimized costs could be established.

Nowadays there are various centers, consulting firms, and professional consultants in the United States dedicated to the training of technical personnel in these methodologies. In Europe, this methodology and concepts have not been as widespread as in the U. S. A. and there are not many institutions providing technical training based on these concepts of scientific molding.

21.1 Knowledge and Training are Tools for the Future

Current theories on economic growth are based on the improvement of knowledge and learning, which are considered engines of future value creation and, therefore, benefits for society and business. This improvement in the knowledge and learning is given through training.

Benjamin Franklin (1706–1790, U. S. statesman and scientist) said: “An investment in knowledge pays the best interest”.

The aim of improving knowledge in thermoplastic injection processing is to improve and control all our processes. In this way we will have more robust and consistent processes to provide better performances and lower costs to become more competitive in an increasingly strong local and international competition.

21.2 The Process

The injection process is very complex. Many variables must be taken into account in defining and establishing robust and consistent processes and to solve problems that can occur during manufacturing.

During manufacture many root causes may provoke incidents, and deviations may appear. These deviations often have different root causes:

- Problems with the material (contamination, pre-drying, regrinding, etc.)
- Part design problems (thickness, nerves, ribs, release angles, sharp corners, etc.)
- Mold design (position and size gates, polishing, venting, cooling, etc.)
- Process problems (parameters, human factor, packaging, etc.)
- Machine problems (machine inaccuracy, mechanical parts, faulty peripherals, etc.)
- Other variables

21.3 Some Concepts Related to Scientific Molding

21.3.1 Molding Processor

Molding processors are workers trained to define injection processes, do trouble-shooting, repairs of machinery, equipment, processes, etc.

21.3.2 Science

Science is defined by the Merriam-Webster’s Dictionary¹ as *the state of knowing: knowledge as distinguished from ignorance or misunderstanding*.

21.3.3 Intelligence

Intelligence is the ability to learn facts and skills and apply them, especially when highly developed. Intelligence is the ability to solve problems.

If we join *intelligence*, *science*, and *molding processor*, we have the advanced technician definition:



A well-prepared worker who uses his knowledge consciously to define processes and to solve problems.

With the application and understanding of the tools of *scientific molding*, a cultural change occurs in the way we do, from the empirical method, from trial and error, to the scientific method, to the application of the state of knowledge in daily manufacturing.

Empirical method	Scientific method
■ Based on experiences	■ Based on experiments
■ Based on repetition	■ Data are analyzed
■ Collection of information from the process is not analyzed	■ Conclusions
	■ Summary, registration of information

This change allows us to optimize and control the process, in addition to parameterizing more robust processes and, in many cases, understanding why processes have deviated from the standard.

An advanced technician knows the whole process (mold, machine, material, and technology). This advanced technician analyzes the problems and determines what happened, acts consciously, and verifies the results of each change made in the process.

This methodology makes it possible to repeat the process several times taking as basis reference the process when the part is correct and performs optimally. It is

¹ <https://www.merriam-webster.com/>

essential to obtain and record the parameters and process conditions. The more information is recorded, the more likely it is to repeat the process on future occasions. The outputs of the process must be taken into account.

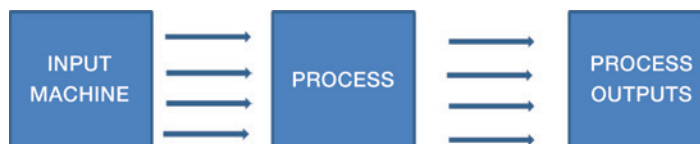
21.4 Machine Inputs vs Process Outputs

An “empirical” molding processor documents input values or machine settings, such as programmed temperatures, programmed pressures, programmed injection rates, programmed times, or programmed closings.

An “advanced” technician documents output values. These values are independent from the machine.

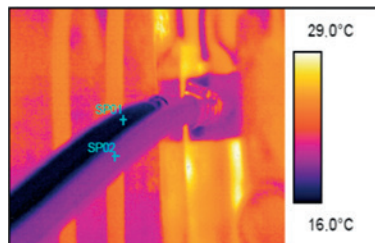
Process outputs:

- Real temperatures measured with pyrometer
- Real times, injection times, etc.
- Real pressure applied, peak value of injection pressure, compaction, etc.
- Weight of the pieces
- Other information (e.g., measures between cavities)

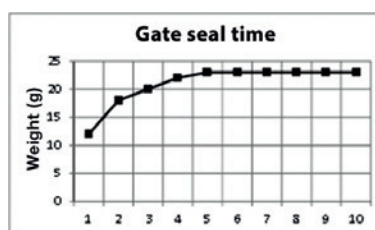


Process Outputs

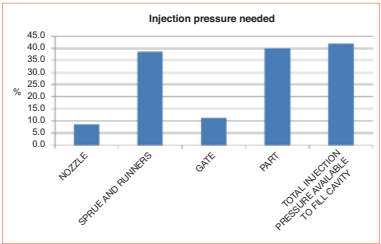
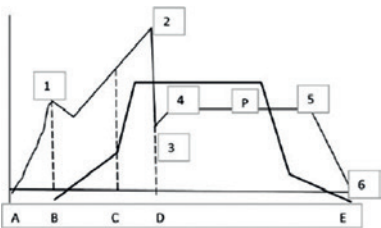
- Temperature
- Melt temperature
 - Cavity temperature
 - Coolant temperature (inlet and outlet)
 - Air temperature dehumidifier



- Time
- Real filling time (the most critical time of the process)
 - Real hold pressure time
 - Real dosing time
 - Gate seal time
 - Real cycle time



- Pressure
- Filling pressure at switch point
 - Real hold pressure
 - Real back pressure
 - Delta P
 - Intensification ratio



- Weight
- Weight cavities
 - Weight obtained at switch point
 - Final weight with sealed gate
 - Shot weight



- Additional data
- Measures for cavities
 - Balanced filling of cavities
 - Tn, real clamping force
 - Photos of defects
 - Miscellaneous remarks

An advanced technician takes into account and calculates the following outputs:

- Residence time of the material in the screw
- Peripheral speed of the screw
- Intensification ratio
- Ratio (dose vs screw diameter)
- Delta P
- Turbulent flow, Reynolds number NR

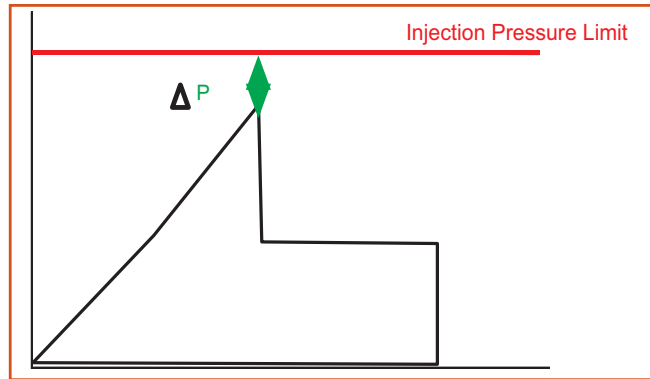


Figure 21.1 Delta P scheme

When the process is documented, an advanced technician can quickly identify what has changed. In addition, he or she:

- Knows the history of the process, mold, material, etc.
- Knows the properties and characteristics of the material
- Determines the physical causes that change the right process conditions
- Acts with knowledge and intelligence
- Verifies the result of each process change made

Faced with a problem, a typical “empirical” technician consults technical guides to determine which parameter should be changed. Instead, an advanced technician asks what has changed and what may be the physical cause that caused the problem.

Documenting the entire process and all its changes is crucial for this type of analysis methodology.

21.5 New Processing Tools

An advanced technician can evaluate the process with the following tools:

- Relative viscosity method (in-mold rheology)
- Gate seal analysis
- Process window
- Injection speed machine performance
- Pressure loss analysis
- Gate shear analysis
- Delta P
- Portability between machines

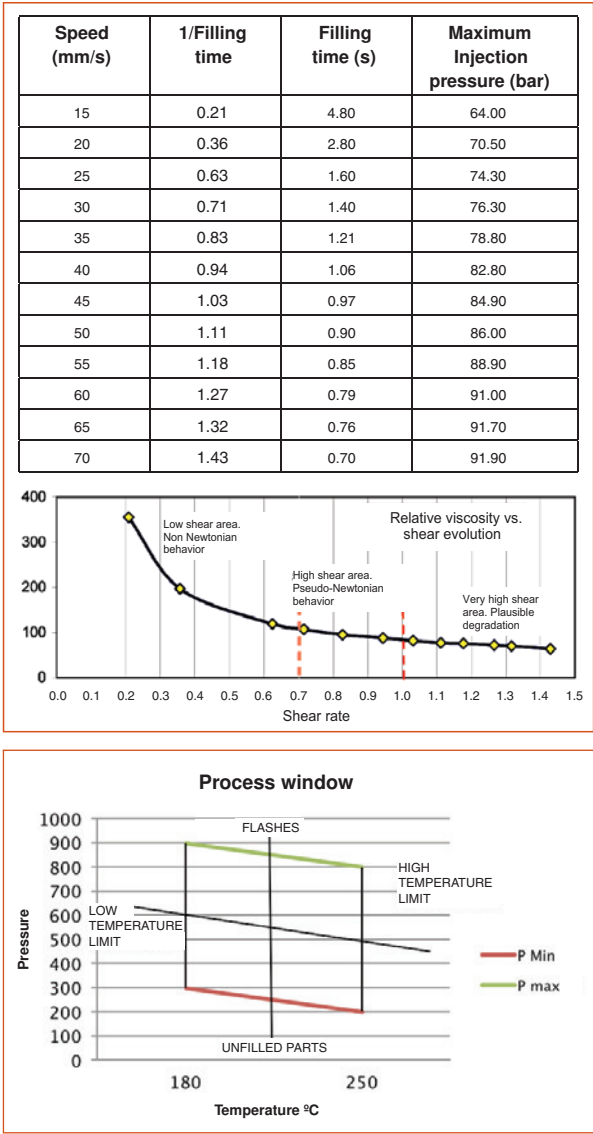


Figure 21.2 Scientific injection molding tools, viscosity curve, and process window

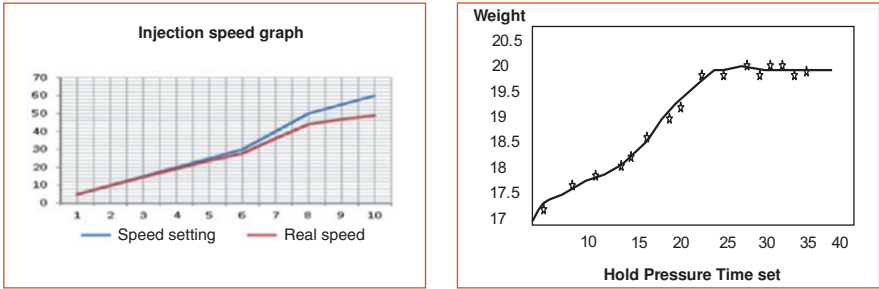


Figure 21.3 Scientific injection molding tools: speed linearization and gate seal

To apply these tools, it is only necessary to spend a little time to perform the experiments that this methodology includes, usually during the mold or process approval or when any deviation is detected. The time invested in developing these tests and using the information they provide is a good investment in order to get better productivity.

These tools are explained in detail in the following pages. In addition, spreadsheets are included for each one. (See Chapter 22.)



Scientific molding

Application of technical knowledge on plastic injection molding by reasoning and experimentation.

21.6 Advanced Methods—Scientific Injection Molding Tools

21.6.1 Relative Viscosity Analysis or In-Mold Rheology Test

This test method allows us to see the effect of injection rate on the viscosity of the material, given the non-Newtonian behavior of plastic when shear rate is applied.

With this test we can see the behavior of the material-mold-machine set from the point of view of the viscosity behavior of the plastic. We can choose the injection rate necessary to maintain viscosity as constant as possible and so that the process can absorb and self-adapt to differences in plastic viscosity (different batches) or different injection speed.

To determine the optimum injection speed range, we can perform a test of relative viscosity to get a viscosity curve.

The method is based on the possibility of separating or disconnecting the phases of filling and holding the cavity, and carrying them out independently.

The viscosity curve is created with the data obtained filling the mold approximately 95% at different injection speed rates, depending on the characteristics of the mold material and injection machine. Thus, in this test, the real injection pressure value and the filling time are obtained in every test condition for the different injection speeds.

With these values it is possible to calculate the points that make up the graph of viscosity according to the shear rate. Normally, the graph has an L shape. The optimum injection speed zone is in the most stable and flat zone of the curve near the “elbow”.

Molding in the most stable and flat area of the curve, the process will be less affected by variations in plastic viscosity, injection speed, or injection pressure, i.e., certain variations in injection speed and/or injection pressure will not affect seriously the material viscosity and vice versa. This has as result a most consistent and repetitive process.

Doing this test, we can determine the accuracy of the injection machine used. Also, in the spreadsheet “Injection Speed Machine Performance”, we can determine the level of compliance of the injection speed rates programmed into the machine and whether the injection speeds are properly calibrated. With this assessment of the

level of compliance of the programmed injection speeds, we can determine the accuracy of our machine, given that the injection speed is the most critical speed of the whole process.

Scientific Molding Calculations and Portability

Table 21.1 Rheological Study in Machine

	Required speed (mm/s)	Filling time (s)	Filling pressure (bar)	Real speed obtained (mm/s)
1	5	4.4	782	5.00
2	10	2.25	766	9.78
3	15	1.51	782	14.57
4	20	1.15	814	19.13
5	25	0.93	853	23.66
6	30	0.79	884	27.85
7	40	0.61	974	36.07
8	50	0.5	1052	44.00
9	55	0.47	1089	46.81
10	60	0.45	1115	48.89
Void	35	1.6		13.75

Dosage stroke 55

Switch stroke 33

Net dosage stroke 22 mm

Table 21.2 Relative Viscosity Test (Based on Table 21.1)

	Required speed (mm/s)	Filling time (s)	Filling pressure (bar)	Shear rate $1/t_{\text{filling}}$ (s^{-1})	Relative viscosity $P \times T$	Obtained speed (mm/s)	Percentage obtained (%)
1	5	4.4	782	0.23	3440.80	5.00	100.00
2	10	2.25	766	0.44	1723.50	9.78	97.78
3	15	1.51	782	0.66	1180.82	14.57	97.13
4	20	1.15	814	0.87	936.10	19.13	95.65
5	25	0.93	853	1.08	793.29	23.66	94.62
6	30	0.79	884	1.27	698.36	27.85	92.83
7	40	0.61	974	1.64	594.14	36.07	90.16
8	50	0.5	1052	2.00	526.00	44.00	88.00
9	55	0.47	1089	2.13	511.83	46.81	85.11
10	60	0.45	1115	2.22	501.75	48.89	81.48

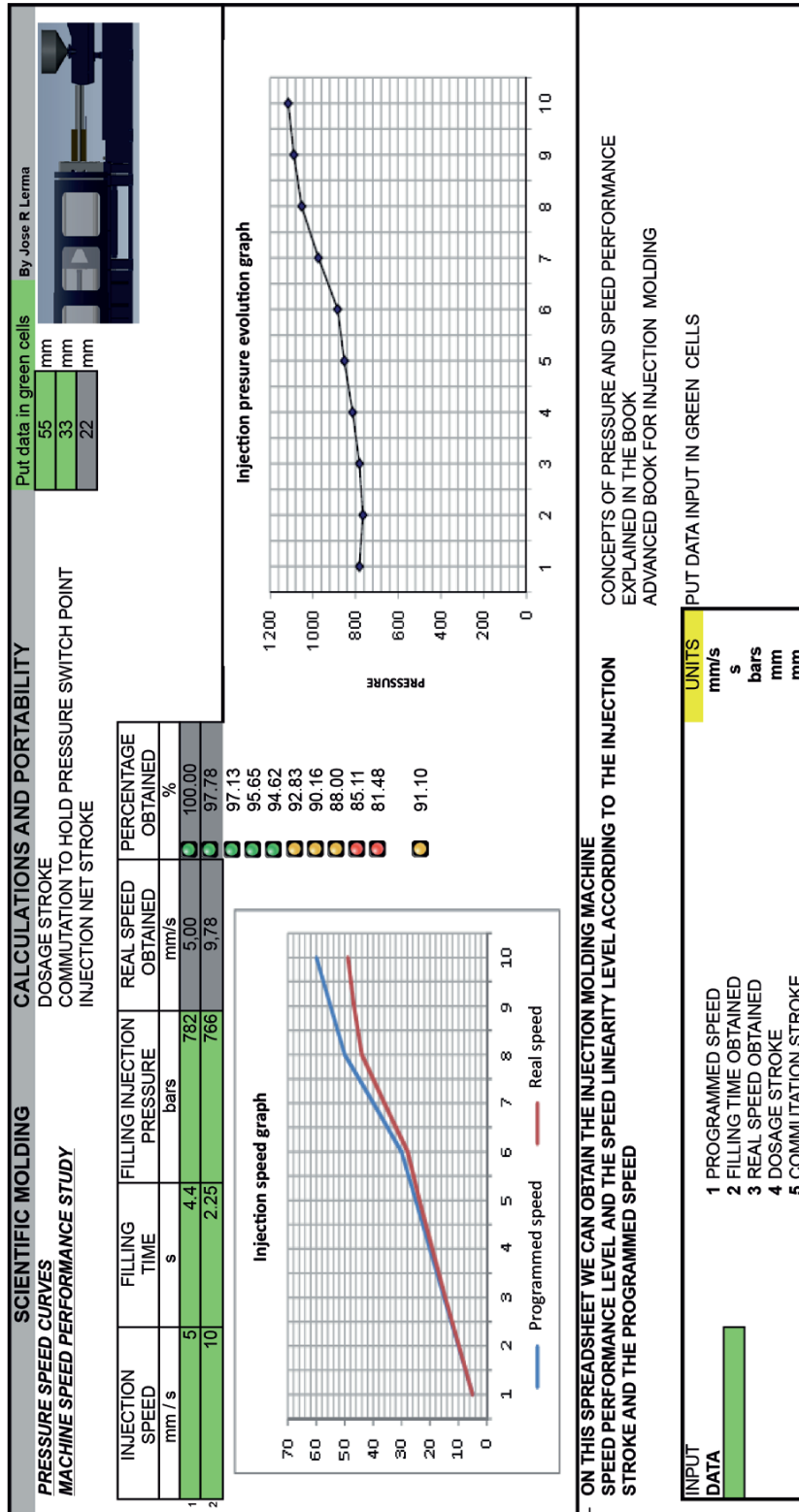


Figure 21.4 Injection speed linearization study

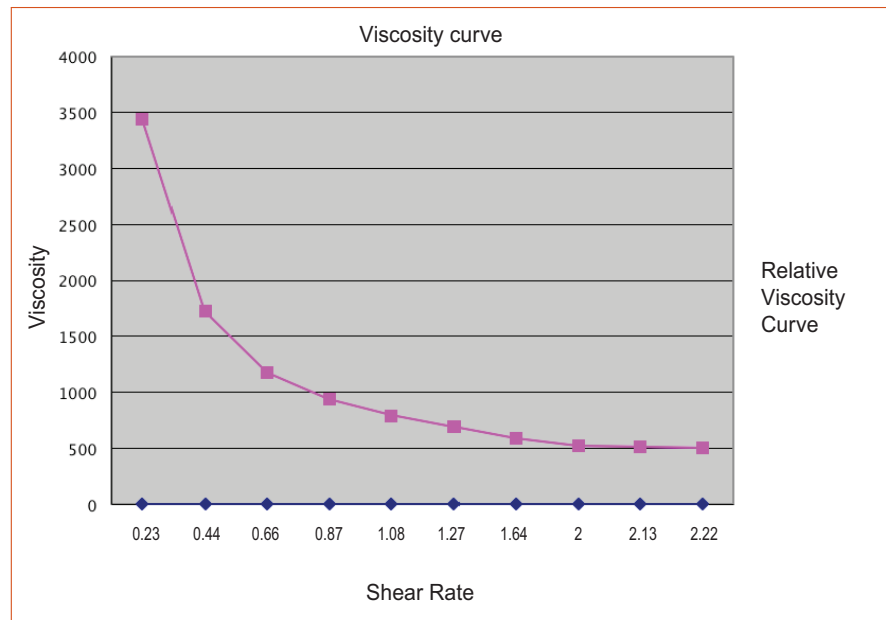


Figure 21.5 Relative viscosity curve

During injection, the thermoplastic is subjected to various stresses of different magnitude while the cavities are filled. If due to the stress applied by the filling speed, the viscosity value is in the vertical slope of the curve, small fluctuations in injection speed greatly affect the viscosity of the material and vice versa. However, applying speed to obtain the viscosity values on the flat part of the curve or Newtonian area, we will have a more robust and stable process.

How to Proceed

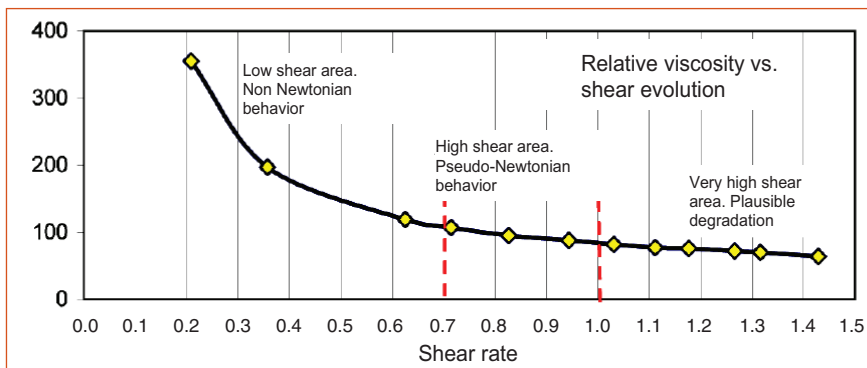
Relative viscosity method or in-mold rheology

1. Set the melt temperature in the machine and check that the melt temperature is the one recommended by the manufacturer of the raw material.
2. Set up the machine with holding pressure and holding pressure time to zero.
3. Set a high injection pressure limit so that it does not affect and does not limit the process.
4. Set a cooling time to ensure that the parts will be solidified when they are demolded.
5. Look for the switching point by systematic progressive filling (see Chapter 15).
6. Ensure that the switching point is somewhat premature since in the test at high speeds it could have flashes and damage the mold (it could be 95% of the total volume, for example).
7. Set the low test injection speed.
8. Proceed with a regular increase of injection speed setting intervals, so the objective is tested and carried out at 10 different speeds between the minimum and maximum machine injection speed.

9. On each cycle at different injection speeds we must take the data corresponding to the maximum injection pressure and injection time needed to fill. With these data, we will prepare the table for the calculation of the relative viscosity or in-mold rheology.
10. It is recommended to do several injected shots into each speed change in the range tested.
11. With the values obtained and reported in Table 21.3, we can build the in-mold rheology curve (Figure 21.6).

Table 21.3 Data Table

Speed (mm/s)	1/Filling time (1/s)	Filling time (s)	Maximum injection pressure (bar)	Shear rate (s^{-1})	Relative viscosity
15	0.21	4.80	64.00	0.21	355
20	0.36	2.80	70.50	0.36	197
25	0.63	1.60	74.30	0.63	119
30	0.71	1.40	76.30	0.71	107
35	0.83	1.21	78.80	0.83	95
40	0.94	1.06	82.80	0.94	88
45	1.03	0.97	84.90	1.03	82
50	1.11	0.90	86.00	1.11	77
55	1.18	0.85	88.90	1.18	76
60	1.27	0.79	91.00	1.27	72
65	1.32	0.76	91.70	1.32	70
70	1.43	0.70	91.90	1.43	64

**Figure 21.6** Viscosity curve

Working with set parameters within the optimum working zone, certain changes in injection speed will not affect the viscosity, thereby obtaining a more robust process.

There may be occasions where the speed obtained through the relative viscosity method is not applicable in the process (e.g., filling with long flow path or with large thicknesses and optical and aesthetics quality).

21.6.2 Delta P: Determination Method

If we set the right Delta P value, the process can absorb differences in the behavior of the viscosity of the material.

Looking at the previous test (in-mold rheology), we can see the strong influence of the injection speed on changes in material viscosity. Therefore, the injection speed must be very well controlled. The injection rate (and filling time) is the most critical of the process variables, so we have to have a very close tolerance in this time of filling. Some experts place the recommended tolerance values during the filling time in ± 0.04 seconds, due to the high influence of the injection speed on the polymer viscosity (shear thinning). For these tolerances, the machine, not the technician, must regulate itself to maintain constant cycles and consistent quality parts.

For the machine to regulate itself at this critical parameter, a correct setting of Delta P has to be mandatory. Imagine the cruising speed control of a car: When we set the cruise speed (e.g., 100 km/h) and need to climb a steep slope, the vehicle will require more power to maintain the set speed. Similarly, in a steep descent, the vehicle will have to yield power because it is not necessary to go to the speed set on the cruise control.

This analogy can be applied to the injection process in the stage of volumetric filling of the cavities. However, we always have the vehicle available to the 100% power, while in our injection machine we can regulate this “power” available, which is the target injection pressure or the injection pressure limit. Furthermore, if we set the injection pressure limit (equivalent to the power of the car) at maximum and it happened that one or more cavities were closed, the injection machine could use all available energy (pressure) to reach the programmed injection speed values and to reach the switch point to the hold phase point. This would cause damage to the mold and parts would be produced in improper conditions, bad dimensions, etc.

On the contrary, if we programmed an injection pressure limit lower than that needed to obtain the required injection speed rate, we will prevent the machine available pressure to reach the setting injection speed, having in this moment the so-called “pressure-limited process”.

In the latter case, we would slow the rate of injection speed or filling speed, and it is strongly discouraged to inject parts using a pressure-limited process. This is a common mistake in some injection factories. Delta P is the difference (in bars) between the injection pressure limit programmed into the machine and the real injection pressure required to fill the cavities during the filling stage of the mold.

We should not adjust the injection pressure to the maximum allowed unless necessary.

A poorly programmed Delta P may have a lower or higher value than the optimal setting value:

If Delta P is programmed with a value below the optimum, we will work with a pressure-limited process. The machine will not be able to self-regulate the pressure required to reach the programmed injection speed rate. This situation should be avoided. It is one of the worst mistakes in the injection process. When the required

pressure reaches the programmed limit, the curve flattens and the flow front slows down and loses control of the cavity filling.

If Delta P is excessively high and a cavity is clogged (e.g., in multi-cavity molds), there will be excessive flashes and we can even damage the mold, the parting lines, slides, etc.

A suitable value for Delta P is 15–30 hydraulic bars or 150–300 specific pressure bars.

To determine the Delta P of a specific injection machine it is necessary to use a mold that requires for filling the cavities an injection pressure of more than 60% of the maximum value available in the machine.

Determination of Delta P

Previously:

We should be able to see and read in each cycle the peak of maximum injection pressure during filling in the first injection phase before switching to hold pressure stage.

We must ensure that we can also see the value of the injection time from the start of injection until reaching the switching point or the filling time.

Machine configuration

1. The type of switching to hold phase must be programmed to switch by stroke.
2. The setting injection speed rate can be obtained from a relative viscosity test or the known injection speed of operation of the mold can be used.
3. Ensure that the hold pressure phase is zero (the hold pressure is zero and the hold pressure time is also zero).
4. Check whether injecting short or incomplete parts could cause problems, for example, by ejectors, slides, etc. In the case that you may have problems, calculate the amount of material volume necessary to fill the cavity percentage requested. Verify and control that during the dosage stage molten material is not going into the cavity due to the back pressure during this stage, which could happen with low-fluidity materials. If this happens, delay the dosage stage until the gates are completely sealed to avoid erroneous cavity filling inputs. In each cycle we should get short pieces and always have a material cushion available.
5. Inject and compare the value of injection peak pressure at the time of switching with the one set as injection pressure limit value. The real injection peak pressure in the switching point can be:
 - a) Same or similar to the injection pressure limit set
 - b) Lower than the injection pressure limit set

In case a, we note in Table 21.4 the injection pressure value and filling time and gradually increase the injection pressure limit in 10 bar steps until the real injection time is constant and stops shrinking. This repeatability of the injection time indicates that the injection pressure is not limiting the process.

In case b (real injection pressure lower than programmed), we are molding without a limited pressure. We must reduce the injection pressure limit programmed until the actual filling time increases. Just at this moment we are, intentionally, working with a limited injection pressure process, to determine the value of Delta P. Now, we will increase the limit of injection pressure in 10 bar steps until the real injection filling time is constant. We will set the injection pressure limit 150–300 (specific injection pressure) bars above the actual real injection pressure peak.

Table 21.4 Delta P Data

Cycle	Set injection pressure limit (bar)	Filling time (s)	Injection pressure – Real peak (bar)	Delta P
1	1100	2.4	1050	BAD
2	1200	2.2	1130	BAD
3	1300	1.9	1200	BAD
4	1400	1.85	1280	BAD
5	1500	1.7	1310	BAD
6	1600	1.65	1405	BAD
7	1700	1.6	1447	BAD
8	1800*	1.6	1450	Filling time repeat*
9	1900	1.6	1451	OK
10	2000	1.6	1450	

* 1900 or 1950 Delta P value

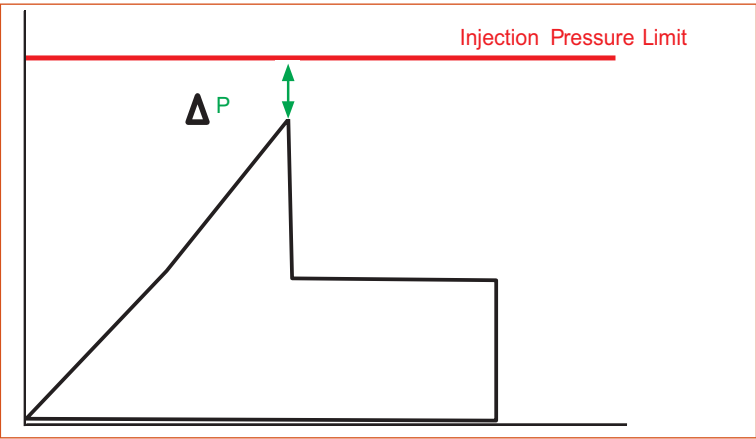


Figure 21.7 Injection pressure, delta P, and injection pressure limit

21.6.3 Process Window: Determination Method (for Holding Injection Pressure Phase)

The cavity filling with molten plastic material is carried out in two clearly different stages. The first stage corresponds to the volumetric filling of the cavity. At this stage we control the speed of cavities filling rate and the mold and the melt temperatures. The second stage corresponds to the hold pressure stage or volumetric

shrinkage compensation that occurs when the material is cooled within the mold. At this stage we will control the hold pressure and its time of application.

This second stage determines the weight and dimensions of the injected parts. If this hold pressure is applied insufficiently, we will obtain incomplete parts, sink marks, lower dimensions and weight, vacuoles, etc. Conversely, if the hold pressure stage is applied excessively, we can get big parts, flashes, internal stress, complicated ejections, etc.

To optimize this hold pressure stage we can use the methodology called “process window” or also “diagram molding”, where the “area” in which our process (the machine-mold-material and parameters) will produce acceptable parts will be determined. The goal is to have the “area” of the process window as big as possible, so in this way we will have a robust and stable process.

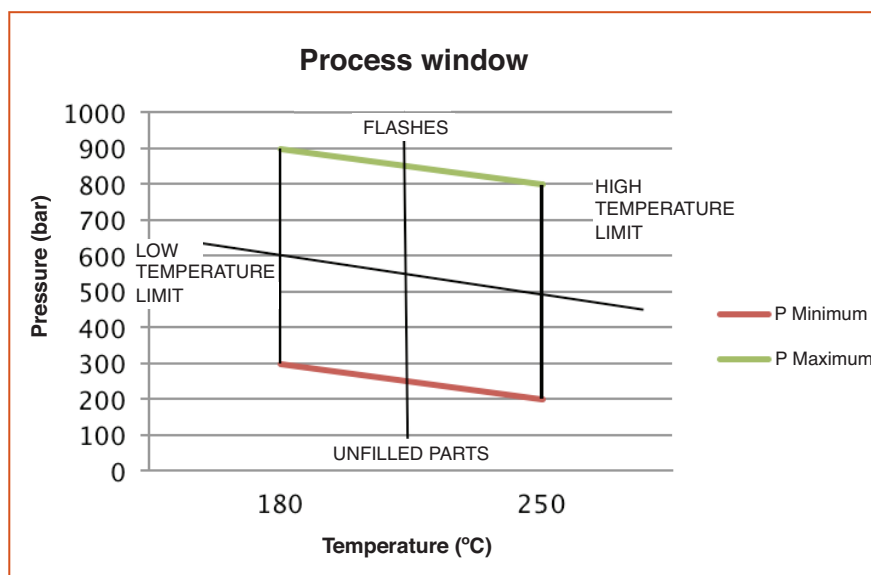


Figure 21.8 Process window

In Figure 21.8 we can see that the parts produced outside the limits of the process window area have flashes or short parts depending on the pressure of the hold pressure stage. If exceeded limits affect the melt temperature, the parts may have flashes for degradation, loss of mechanical properties, or unmelted and inhomogeneous melt and, thus, the parts will be unacceptable.

If the defined process stands as centered as possible in the process window, it will be much more robust and consistent and absorb small variations that may occur during manufacturing.

How to Determine the Process Window

Previous machine configuration:

1. Set the melt processing temperatures at the lower value of the manufacturer's recommendations.
2. Set the injection speed obtained by in-mold viscosity test.
3. Set the hold pressure time and holding pressure to zero.
4. Set a cooling time slightly larger than necessary.

Injection process starts:

- Start and adjust the switching point to hold pressure stage to 95 to 98% of the total filling of the cavity.
- Make several consecutive cycles to stabilize the process.
- Set a greater hold pressure time than necessary to ensure that the gates are frozen.
- Increase holding pressure in pressure intervals until getting acceptable parts.
- This pressure and temperature are the points on the graph (Figure 21.8) “low temperature, low pressure”, left lower vertex.
- Increase pressure compaction pressure intervals and note when the pressure is excessive (parts with flashes or deformations, mold grips, etc.). This point should be noted as “low temperature, high pressure” (left upper vertex).
- Repeat the above two steps, but with the melt temperature at the maximum of the material manufacturer’s recommendations.
- This time, the points found are:
 - High temperature, low pressure
 - High temperature, high pressure

(In the right lower and right upper vortex.)
- If we combine these four points found, the process window or diagram of molding area is created.
- Place the process parameters as centered to the defined area as possible.

The process window area indicates the amount of variability that the defined process can absorb before it starts to inject or produce defective parts (i. e., to work outside the process window area). When the process window obtained is narrow (and thus not very robust), it is interesting to define actions to increase the area. These actions will be determined by defects or problems encountered during this test.

So, with this test not only can we determine the window process area; furthermore, we can know easily which are the improvement actions that should be taken in order to increase this area.

21.6.4 Gate Seal Study

The open passage of material through the gate passage will be available during a certain time and this time will vary according to processing conditions (melt temperature, mold temperature, etc.) and gate dimensions.

We must know the time that the gates take to freeze to avoid excessive holding pressure time and therefore productivity losses. The gate seal time is determined by:

- Pressure drop in cavity (a sensor cavity is required)
- Part’s weight evolution control

Cavity pressure drop:

To determine the optimum time for holding pressure through this system, if we set a short time of holding pressure, the cavity pressure will fall sharply when the hydraulic pressure ceases. But if the time is long enough, when we remove the injection pressure the cavity pressure remains and falls slowly, indicating that the gate had been sealed.

Part weight control:

The optimal time is the one when the maximum weight of the injected parts has been achieved. At first, increasing the holding pressure time we get weight increases, until the weight stops growing despite the hold pressure time increases. At that time we can conclude that we have the gate frozen and do not contribute to putting more material into the cavity to compensate for the loss of volume during shrinkage. In this moment the weight graph becomes flat.

Machine configuration:

1. Set injection speed obtained during the relative viscosity test.
2. Set cooling time to ensure cool and solid parts for ejection from the mold.
3. Set the time hold pressure time to zero and increase this value, weighing the parts. Do not contemplate the runners when the weights are controlled.

Set the correct hold pressure time by controlling the weight of the injected parts.

An injection process with hold pressure lower to the optimum time or an injection process with a gate not sealed (i.e., open) means having a time-dependent process. According to the application time of the holding pressure, we will obtain parts with different dimensions, properties, weights, etc. In other words, the process will not be consistent and repetitive.

On the contrary, an excessively long holding pressure time, once the gate has been sealed, is an energy expenditure, an excessive cycle time, a waste we cannot afford. As I often say in my seminars, when I visit factories I like to see big sink marks in the runners with correct parts. Otherwise, we are manufacturing “precious runners” that no one will appreciate and no one will pay.

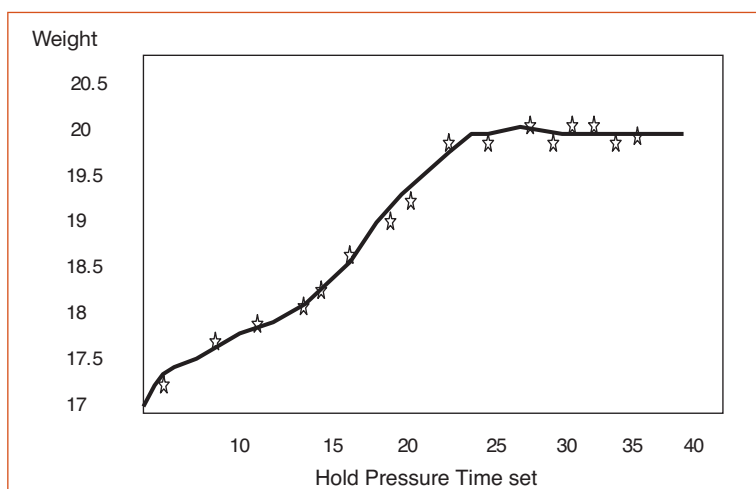


Figure 21.9 Gate seal study curve

Select the hold pressure time with sealed gates. This value is located on the flat region of the curve in Figure 21.9, just after the elbow, where the weights are stable.

21.6.5 Method and Analysis of Injection Pressure Losses along the Filling System

During filling, the plastic in contact with the mold begins to cool and generate a cool skin due to the cooling system of the mold. The thickness of this skin increases due to this cooling. Furthermore, the boundary layers of the flow in contact with the cool skin, in their advance during filling, generate shear stresses, which in turn generate heat. This pseudo-balance of cooling and heat allows the filling of big cavities and long flow paths. However, the pressure required to push and advance the flow front through distribution channels, sprue, gates, and cavities is increasing, generating an inevitable loss of pressure in every flow path step.

The injection molding machine will require a certain injection pressure level to perform the injection speed set programmed. This necessary total injection pressure should never exceed the maximum pressure programmed or injection pressure limit. If exceeded, this would be a pressure-limited process, a situation to be avoided because it is a situation out of process control.

To analyze the pressure loss generated by each one of the steps in the filling path system, from the screw tip to the cavity, it is interesting to perform the analysis of the pressure loss.

It is interesting to take advantage of the development of the progressive filling test to determine the times of passage of flow through the sprue, the main runner, the secondary runners or subrunners, gates, cavities, and, of course, the pressure needed to eject material to the air through the machine nozzle.

With these data, conveniently tabulated, we obtain the percentages of pressure loss and pressure drops for each step of the filling path of the material from the screw tip to the cavity. This analysis will allow us to make decisions and prioritize them in order to reduce the pressure losses in the system if necessary.

Machine configuration to test pressure losses:

1. Set the injection pressure limit to the maximum limit allowed by the injection machine.
2. Set the hold pressure time and hold pressure to zero.
3. Purge material or eject the material through the nozzle to the air and record the real necessary pressure to do it.
4. Conduct a progressive filling, as described in Chapter 15: changing the switch point, we fill through the sprue and then the main runner, sub-runners, the cavity gates, and, finally, the cavities. Register the maximum peak pressure to fill each stage.

In the example in Figure 21.10, we can see that at the end of the filling stage we have available, for an eventual readjustment of pressure, just 1.8% of the total available pressure of the machine. We are very close to having and starting a “pressure-limited process”. To avoid this problem in the example, it would be necessary to improve and reduce the pressure drop in the sprue and the runners, which is 38.5%.

PRESSURE NEEDED TO PURGE THROUGH NOZZLE		145	BARS
PRESSURE NEEDED TO FILL SPRUE AND RUNNER		800	BARS
PRESSURE NEEDED TO FILL SPRUE, RUNNER AND GATE		990	BARS
PRESSURE NEEDED TO FILL THE CAVITY AT 96-98%		1670	BARS
PRESSURE LOSS			%
NOZZLE	145	8.5	
SPRUE AND RUNNER	655	38.5	
GATE	190	11.2	
PART	680	40.0	
TOTAL INJECTION PRESSURE AVAILABLE TO FILL CAVITY	710	41.8	
AVAILABLE PRESSURE IN RESERVE	30	1.8	

Figure 21.10 Loss of pressure: example of calculation

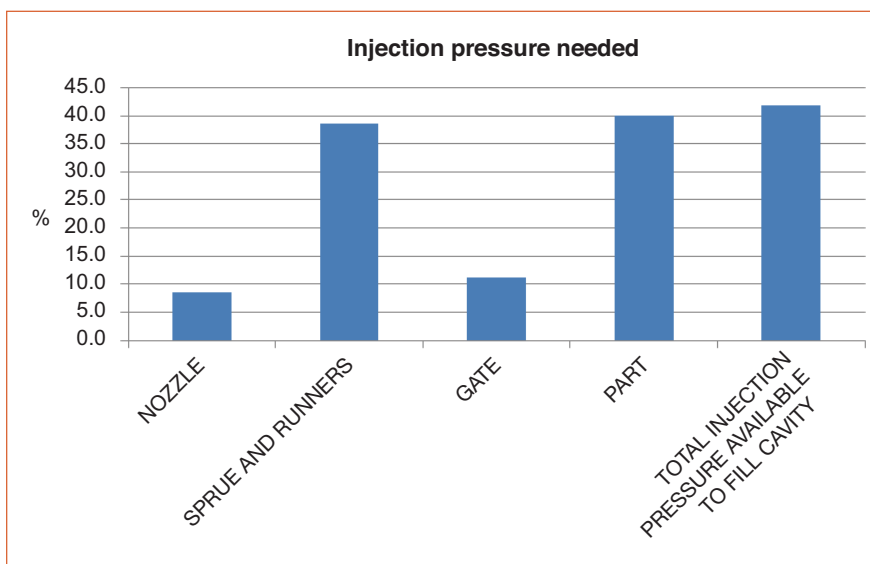


Figure 21.11 Injection pressure needed

It is recommended that the total maximum pressure used to fill the system and the cavities be 90% of the maximum available pressure in the injection machine.

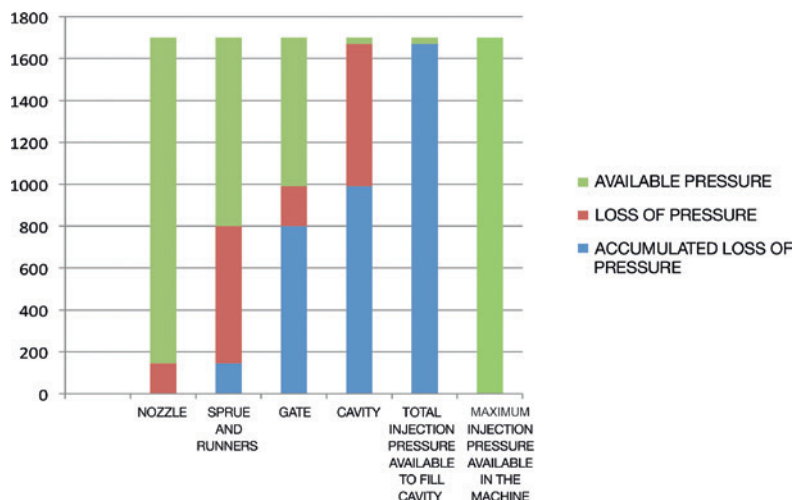


Figure 21.12 Graph example of pressure losses along the flow path

21.6.6 Machine Portability

We spend time and effort in the process definition in order to produce good parts. We need that this process validation and definition produce good parts again with different serial production batches at different times. These new batches could be produced in the same machine or in different ones, or even in different facilities.

We hope to get identical parts to those approved in different batches on the same machine and even on different machines, but this does not always happen. When we change the mold and we start the production again, there are multiple variables that can affect the correct repetition of the process. Two things to have in mind:

One is that we should register all the outputs when the process was right and approved. The other is to move or convert inputs and outputs from the correct process on any machine with similar or different characteristics. This is called portability.

- It is essential to be able to use different machines with different features to make the same mold and parts.
- It is essential also to repeat a correct process on the same machine later, to be able to produce identical parts in different moments, batches, etc.
- The difficulty to repeat the process on different machines and times is minimized using good portability. To do this we must:
 - Always use specific units for each magnitude or parameter
 - Have perfect knowledge of the characteristics of our machinery (screw diameter, intensification ratio, maximum dose stroke, clamping force T_n , Delta P, etc.)

Table 21.5 Specific Units

Parameter	Units
Injection volume	cm ³
Injection speed	cm ³ /s
Filling time	s
Specific injection pressure	bar
Specific hold pressure	bar
Cushion	cm ³
Switching point	cm ³
Specific switching pressure	bar
Peripheral screw speed	m/s
Back pressure	bar
Cycle time	s
Hold pressure time	s
Cooling time	s
Melt temperature	°C
Mold temperature	°C

If we know all this information, parameters, and outputs in the right specific units, we can build conversion systems so that the same parameters and outputs from the right process can be replicated exactly on different injection machines with different features or on the same machine but in different moments.

SCIENTIFIC MOLDING CALCULATIONS AND PORTABILITY				Put data in green cells	By José R. Lerma																								
PORTABILITY UNIVERSAL PARAMETERS SHEET																													
PART NAME		MATERIAL	ABS	DATE																									
MOLD NUMBER		DENSITY	0.95 g/cm3																										
MACHINE A 150 TN		MACHINE B 480 TN																											
SCREW DIAMETER	50 mm	SCREW DIAMETER	70 mm																										
DOSAGE STROKE	115 mm	DOSAGE STROKE	54.70 mm																										
VOLUME DOSAGE	225.8 cm3	VOLUME DOSAGE	225.80 cm3																										
WEIGHT	200 g	WEIGHT	200 g																										
MAXIMUM DOSAGE STROKE	300 mm	MAXIMUM DOSAGE STROKE	500 mm																										
RESIDENCE TIME	2.61 minutes	RESIDENCE TIME	7.68 minutes																										
DOSAGE/SCREW DIAM RATIO	2.30 diameters	DOS./SCREW DIAM RATIO	0.78 diameters																										
INJECTION UNIT UTILIZATION	38.3 %	INJ. UNIT UTILIZATION	10.9 %																										
CYCLE TIME	45 sc	CYCLE TIME	45 sc																										
FILLING TIME	2 sc	FILLING TIME	2 sc																										
INJ. LINEAL SPEED REAL	55 mm/s	INJ. LINEAL SPEED REAL	28.06 mm/s																										
INJ. VOLUME SPEED REAL	107.99 cm3 /s	INJ. VOLUME SPEED REAL	107.99 cm3/s																										
INTENSIFICATION RATIO	10 :1	INTENSIFICATION RATIO	8 :1																										
SPECIFIC INJ. PRESSURE	1400 bar	SPECIFIC INJ. PRESSURE	1400 bar																										
HYDRAULIC INJ. PRESSURE	140 bar	HYDRAULIC INJ. PRESSURE	175 bar																										
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SCREW RPM	80 rpm	SCREW RPM	57.14 rpm																										
SCREW PERIPHERAL SPEED	0.21 m/s	SCREW PERIPHERAL SPEED	0.21 m/s																										
COOLING TIME	15 s	COOLING TIME	15 s																										
ON THIS SPREADSHEET WE CAN TRANSLATE THE OPTIMAL PARAMETER FROM ONE MACHINE TO ANOTHER INJECTION MACHINE WITH DIFFERENT CHARACTERISTICS AND ASSURE EXACTLY THE SAME INITIAL PROCESS WE CAN DEFINE OUR UNIVERSAL PARAMETER SPREADSHEET FOR THE RIGHT PORTABILITY OF INJECTION PROCESSES BETWEEN DIFFERENT MACHINES				CONCEPT OF UNIVERSAL PARAMETERS SHEET EXPLAINED IN BOOK PUT DATA IN GREEN CELLS																									
<table border="1"> <thead> <tr> <th>INPUT DATA</th> <th>UNITS</th> </tr> </thead> <tbody> <tr><td>1 SCREW DIAMETER</td><td>mm</td></tr> <tr><td>2 DOSAGE</td><td>cm3</td></tr> <tr><td>3 DOSAGE</td><td>mm</td></tr> <tr><td>4 WEIGHT</td><td>g</td></tr> <tr><td>5 MAXIMUM DOSAGE</td><td>mm</td></tr> <tr><td>6 CYCLE TIME</td><td>sc</td></tr> <tr><td>7 FILLING TIME</td><td>sc</td></tr> <tr><td>8 FILLING PRESSURE</td><td>bars</td></tr> <tr><td>9 INTENSIFICATION RATIO</td><td>value:1</td></tr> <tr><td>10 FILLING CAVITY STROKE</td><td>mm</td></tr> <tr><td>11 PERIPHERAL RPM SCREW</td><td>rpm</td></tr> </tbody> </table>				INPUT DATA	UNITS	1 SCREW DIAMETER	mm	2 DOSAGE	cm3	3 DOSAGE	mm	4 WEIGHT	g	5 MAXIMUM DOSAGE	mm	6 CYCLE TIME	sc	7 FILLING TIME	sc	8 FILLING PRESSURE	bars	9 INTENSIFICATION RATIO	value:1	10 FILLING CAVITY STROKE	mm	11 PERIPHERAL RPM SCREW	rpm		
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Figure 21.13 Portability spreadsheet example

21.6.7 Cavities Balance Study

Table 21.6 Cavities Balancing Study Table

	High speed	Medium speed	Low speed
Speed (mm/s)	60	30	20
Injection time (s)	0.5	1	1.5
Average weight of 10 injection shots or cycles (g)	High speed	Medium speed	Low speed
1	1.27	1.31	1.30
2	1.27	1.30	1.30
3	1.27	1.32	1.31

Table 21.6 Cavities Balancing Study Table (*continuation*)

	High speed	Medium speed	Low speed
4	1.30	1.30	1.30
5	1.28	1.30	1.30
6	1.31	1.31	1.30
7	1.32	1.30	1.30
8	1.30	1.30	1.30
Max. weight (g)	1.32	1.32	1.31
Min. weight (g)	1.27	1.3	1.3
Range (g)	0.05	0.02	0.01
Imbalanced (%)	3.8	1.5	0.8

When the melted material enters the mold and travels up the cavities, it begins to cool and travel at a certain speed, with decreasing temperature and a given pressure. The quality of production depends on the uniformity of these variables in all and each of the mold cavities. All this means that, in order to fill multiple cavities at equal pressure, temperature, and filling speed, it is necessary to make a correct cavity balance (i.e., balancing the filling). The goal should be reaching the end of the filling stage under the same conditions in different cavities to get a consistent process and equal parts.

Machine configuration to determine the balance of cavities:

1. Set hold pressure and hold pressure time to zero.
2. Set the cooling time so that we ensure the correct release and ejection.
3. Set injection speed obtained from a relative viscosity test or in-mold rheology.
4. Conduct a progressive filling, as described in Chapter 15: changing the switch point, we fill through the sprue, the main runner, sub-runners, the cavity gates, and, finally, the cavities.

Looking at the progressive filling, with short parts, we can see the real situation of the cavities balanced filling and make corrections (usually correcting fuller parts). Deviations between cavities up to 3%, depending on the sector and the final application, are acceptable. Fill and do test with different injection speeds, low, medium, and high. Calculate averages of 10 consecutive injection shots; see Table 21.6 to determine deviations. Consider possible spiral effect discussed in Chapter 20.

21.6.8 Study of Shear Stress at the Gates

Very often, when a mold is machined gates are usually small, since, if it is necessary, it is easier and cheaper to increase the gate size rather than to reduce it. Unfortunately, sometimes molders decide to adapt the injection parameters setting to the inadequate gate size. This leads to manufacturing parts with higher melt temperature than recommended and, what is worse, manufacturing parts with a higher shear rate that exceeds what is allowed by the material used.

This will cause an important loss of material properties in addition to aesthetic defects, streaks, cracks, marks in the gate, gases, internal pores, brightness, etc.

To calculate the gates' correct dimensions, taking into account the maximum allowed shear for the material used and the filling speed, the following formulas can be used. The formulas give us the shear rate or friction generated by passing a molten polymer through a gate with round or rectangular section.

Round section gate

$$\text{shear rate} = \frac{4Q}{3,142 \cdot r^3}$$

Rectangular section gate

$$\text{shear rate} = 6 \times Q (\text{gate length} \times \text{gate width}^2)$$

Q indicates the flow rate and r is the gate radius.

By applying these formulas, we must not exceed the values of maximum shear friction recommended by the material manufacturer.

	Max. shear allowed (s ⁻¹)
PP	100,000
PC	40,000
ABS	50,000
ABS chrome plating grade	30,000
PMMA	40,000
PES	50,000
PET	50,000
PBT	50,000
PA 12, PA 612	60,000
PA 66	60,000
PA 6	60,000
LDPE	40,000
HIPS	40,000
GPS	40,000
EVA	30,000
POM	40,000
PPO	35,000
PPS	50,000
PSU	50,000
PUR	40,000
PVC	20,000
SAN	40,000
SAN	40,000

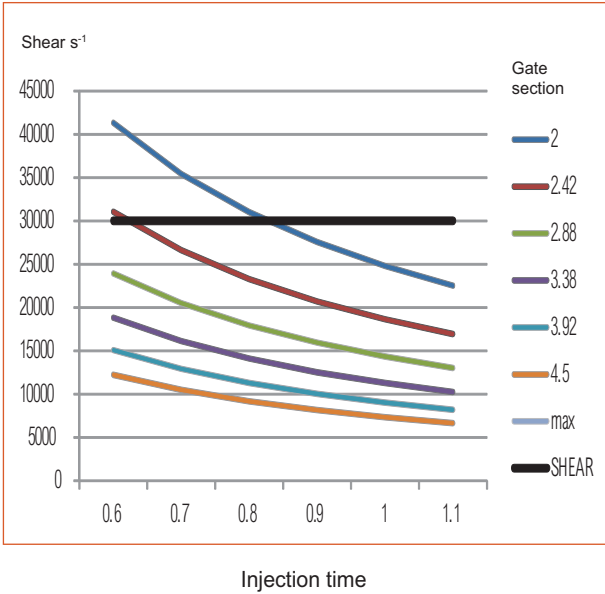


Figure 21.14 Shear calculation with different filling times and gates sections

21.6.9 Blank Templates

21.6.9.1 Gate Seal Study, Blank Template

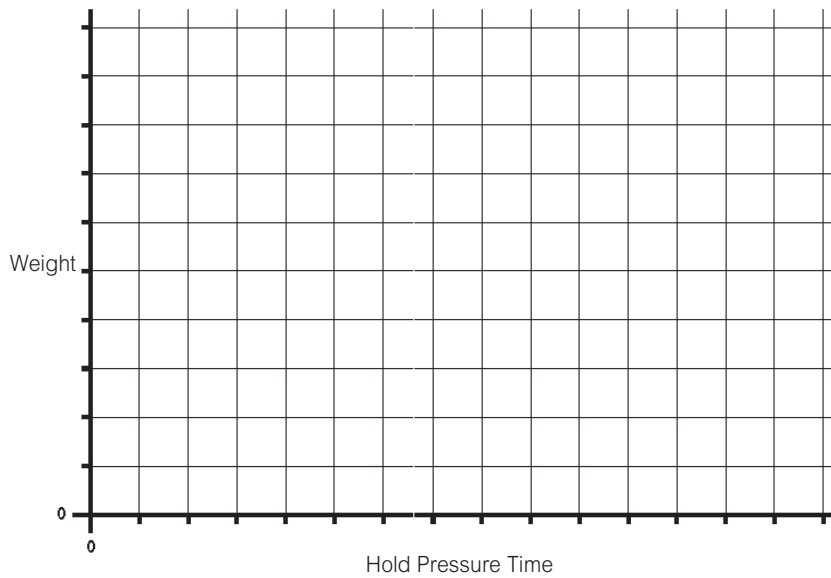


Part

Material

Melt temperature

Mold temperature



Gate is sealed between s and s.

S H O T S	Weight	Hold Pressure Time
	1	
	2	
	3	
	4	
	5	
	6	
	7	
	8	
	9	
	10	

21.6.9.2 In-Mold Rheology, Blank Template

Dosage stroke		mm
Switch point		mm
Net injection stroke		mm

	Speed (mm/s)	Filling time (s)	Filling pressure (bar)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
Ejection material (in the air)			

Using Spreadsheets: Advanced Molding and Machine Portability

22.1 Thermoplastic Processing by Injection—Advanced Manual

ADVANCED SCIENTIFIC INJECTION MOLDING TOOLS						José R. Lerma
PORTABILITY	DOSAGE	Go				
	INTENSIFICATION RATIO	Go	SCIENTIFIC MOLDING	DELTA P STUDY	Go	
	FILLING TIME/SPEED	Go		MACHINE SPEED PERFORMANCE STUDY	Go	
	PORTABILITY GENERAL DATA SHEET	Go		IN-MOLD RHEOLOGY STUDY	Go	
PROCESS ANALYSIS & OPTIMIZATION	PERIPHERAL SCREW SPEED	Go	THEORETICAL CLAMPING FORCE	Go	PROCESS WINDOW STUDY	Go
	RESIDENCE TIME	Go	TRAVERSE OPTIMAL TEMPERATURE	Go	CAVITY BALANCE STUDY	Go
	MULTIPLE DRYING TIME	Go	TURBULENT FLOW / REYNOLDS N.	Go	SCREW TIP HERMETICITY STUDY	Go
	SHEAR IN ROUND GATES	Go	SHEAR IN RECTANGULAR GATES	Go	DROP PRESSURE STUDY	Go

Figure 22.1

Attention: Be careful if you decide to use any of the following recommendations. The author assumes no responsibility for incidents or accidents, damage to equipment or people, or any unfavorable results that may occur.

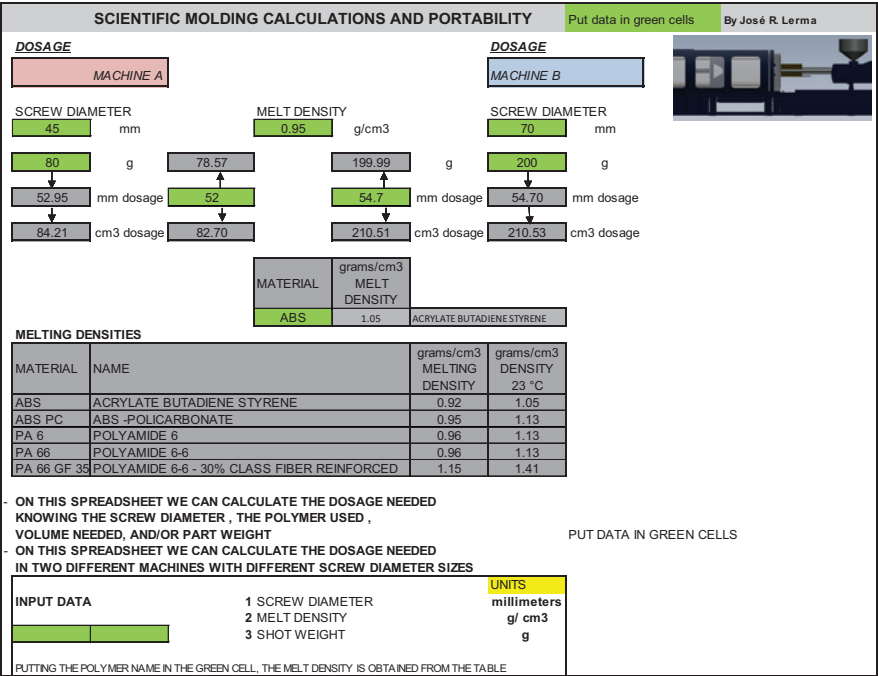


Figure 22.2

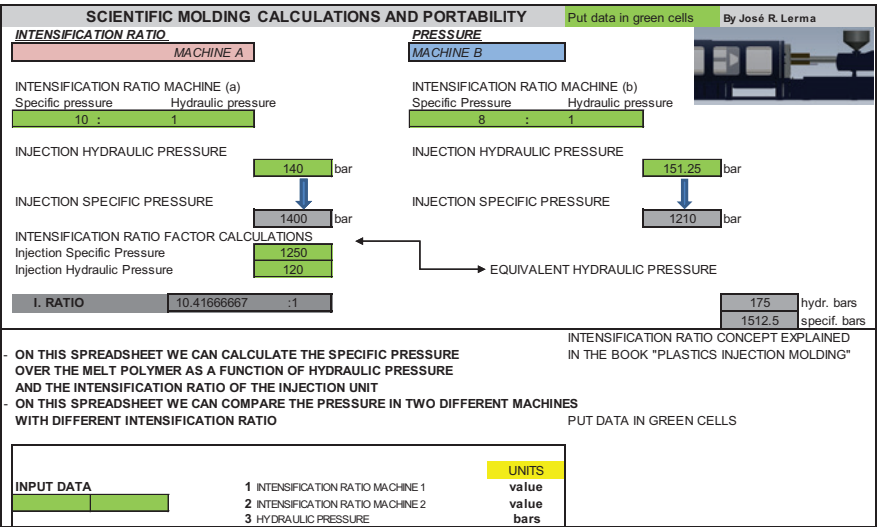


Figure 22.3

SCIENTIFIC MOLDING CALCULATIONS AND PORTABILITY				Put data in green cells	By José R. Lerma																								
PORTABILITY UNIVERSAL PARAMETERS SHEET																													
PART NAME		MATERIAL	ABS	DATE																									
MOLD NUMBER		DENSITY	0.95 g/cm3																										
MACHINE A 150 TN		MACHINE B 480 TN																											
SCREW DIAMETER	50 mm	SCREW DIAMETER	70 mm																										
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SCREW PERIPHERAL SPEED	0.21 m/s	SCREW PERIPHERAL SPEED	0.21 m/s																										
COOLING TIME	15 s	COOLING TIME	15 s																										
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Figure 22.4

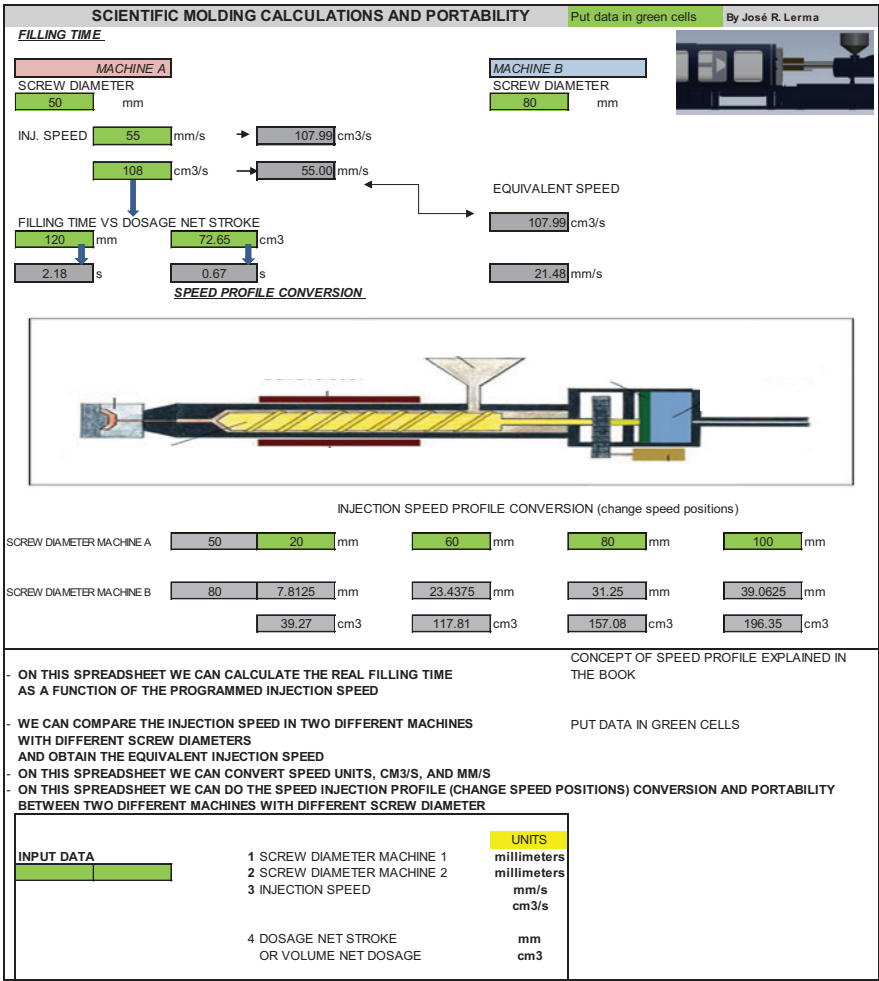


Figure 22.5

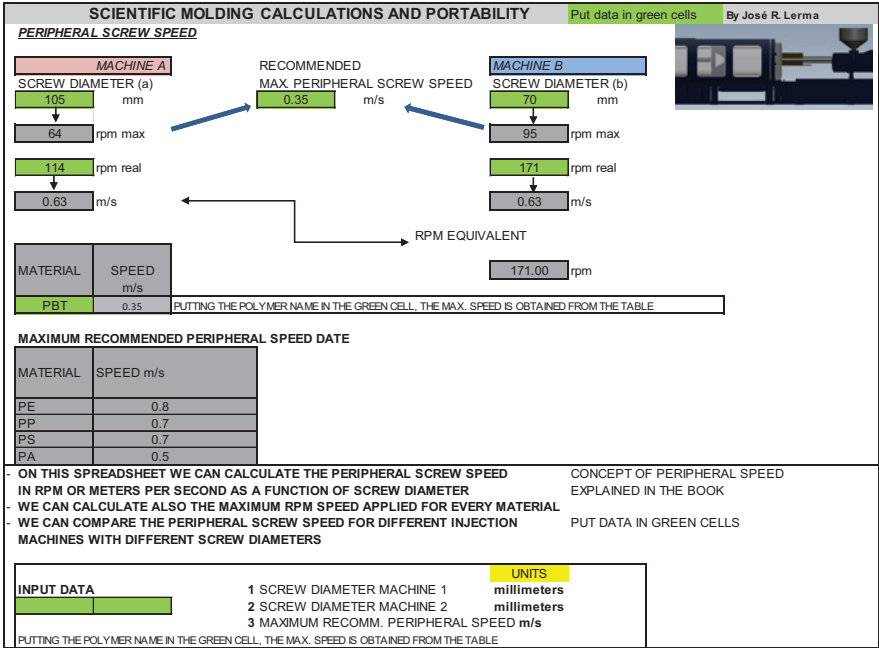


Figure 22.6

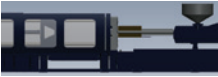
SCIENTIFIC MOLDING CALCULATIONS AND PORTABILITY				Put data in green cells		By José R. Lerma	
RESIDENCE TIME AND RATIO DOSAGE STROKE /SCREW DIAMETER							
MACHINE A				MACHINE B			
SCREW DIAMETER (a)	55 mm	MAXIMUM DOSAGE	200 mm	SCREW DIAMETER(b)	70 mm	MAXIMUM DOSAGE	350 mm
NET DOSAGE (without suction and cushion)	102 mm	CYCLE 45 s		NET DOSAGE (without suction and cushion)	55 mm		
RESIDENCE TIME	3.2 minutes			RESIDENCE TIME	7.6 minutes		
RELACION	1.9 diameters			RELACION	0.8 diameters		
51.0 % utilization of injection unit				15.7 % utilization of injection unit			
BEST 25% TO 65 %							
MAXIMUM RESIDENCE TIME RECOMMENDED DATA							
PUTTING THE POLYMER NAME IN THE GREEN CELL, THE MAX. RESIDENCE TIME IS OBTAINED FROM THE TABLE				MATERIAL	MINUTES	TEMPERATURE	
ABS				ABS	5 to 6 -- 2 to 3	265 -- 280	
SAN				SAN	6 to 6 -- 2 to 3	265 -- 280	
PS HI				PS HI	5 -- 1 to 2	260 -- 280	
PC				PC	7	320	
ON THIS SPREADSHEET WE CAN CALCULATE THE REAL RESIDENCE TIME OF THE MATERIAL AS A FUNCTION OF SCREW DIAMETER, DOSAGE STROKE, MAXIMUM DOSAGE AVAILABLE, AND CYCLE TIME ON THIS SPREADSHEET WE CAN CALCULATE THE INJECTION UNIT % OF UTILIZATION AND THE DOSAGE/DIAMETER RATIO AS A FUNCTION OF THE SCREW DIAMETER AND DOSAGE STROKE WE CAN COMPARE RESIDENCE TIME CALCULATED WITH DIFFERENT MACHINES AND DIFFERENT SCREW DIAMETERS							
INPUT DATA		1 SCREW DIAMETER 2 MAX. DOSAGE STROKE 3 CYCLE TIME 4 NET DOSAGE STROKE		UNITS millimeters millimeters seconds millimeters			

Figure 22.7

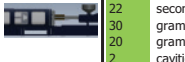
SCIENTIFIC MOLDING CALCULATIONS AND PORTABILITY				Put data in green cells		By José R. Lerma		
DRYING TIME MULTIPLE MACHINES								
DRYER CAPACITY	300	liters						
BULK DENSITY MATERIAL	0.8	kg/liter	300 kg dryer capacity		DRYING TIME RECOMMENDED 4 hours			
WEIGHT CAPACITY DRYER	240	kilograms						
CYCLE TIME	20	seconds						
PART WEIGHT (1 CAVITY)	18	grams						
RUNNER WEIGHT	15	grams						
NUMBER OF CAVITIES	4	cavities						
CONSUMPTION PER HOUR	15.66	kg	15.66	kg	19.2	kg	13.1	kg
SHOOTS PER HOUR	180	cycles/hour	180	cycles/hour	120	cycles/hour	163.6	cycles/hour
REAL DRYING TIME	15.3256705	hours			12.5	hours	15.625	hours
MATERIAL	BULK DENSITY	MACHINE 1		MACHINE 2		MACHINE 3		TOTAL
PETG	0.8	CONSUMPTION	15.66	Kg h	19.2	Kg h	13.1	48.0
								Kg h
MATERIAL	BULK DENSITY	TOTAL EFFECTIVE DRYING TIME		5.0		HOURS		
ABS	0.63							
ABS/PC	0.65							
PUTTING THE POLYMER NAME IN THE GREEN CELL, THE BULK DENSITY IS OBTAINED FROM THE TABLE								
PUT DATA IN GREEN CELLS								
ON THIS SPREADSHEET WE CAN CALCULATE THE DRYING CAPACITY OF THE DRYING STATION AS A FUNCTION OF THE MACHINE'S CONSUMPTION OUTPUT WE CAN SEE IF THE RECOMMENDED DRYING TIME HAS BEEN ACHIEVED								
INPUT DATA		1 CAPACITY IN LITERS 2 CAPACITY IN KG 3 DRYING TIME RECOMMENDED 4 CAUDAL 5 CYCLE TIME 6 WEIGHT PER CAVITY 7 RUNNER WEIGHT 8 NUMBER OF CAVITIES 9 BULK DENSITY		UNITS liters kg hours l/minute s g u kg/l				

Figure 22.8

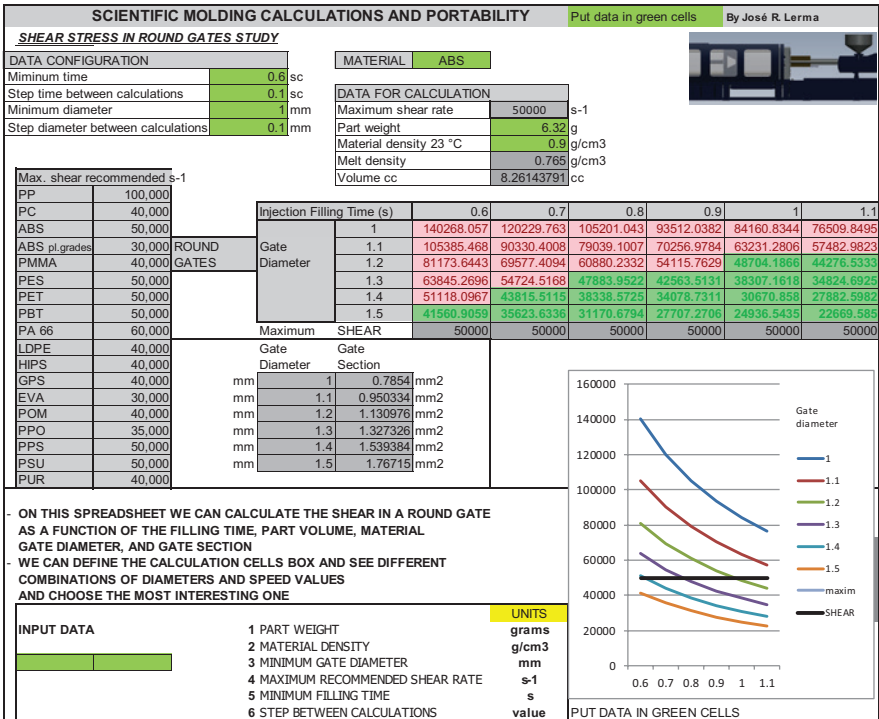


Figure 22.9

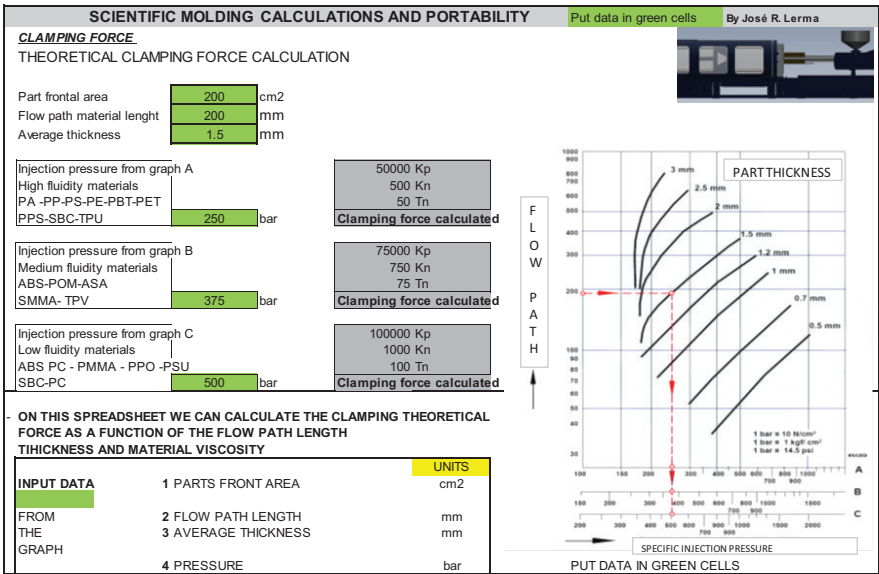


Figure 22.10

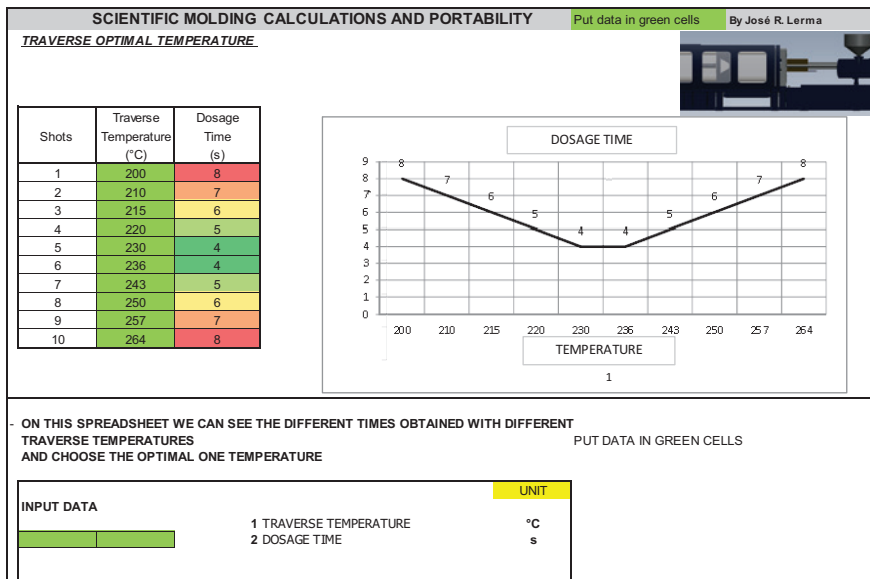


Figure 22.11

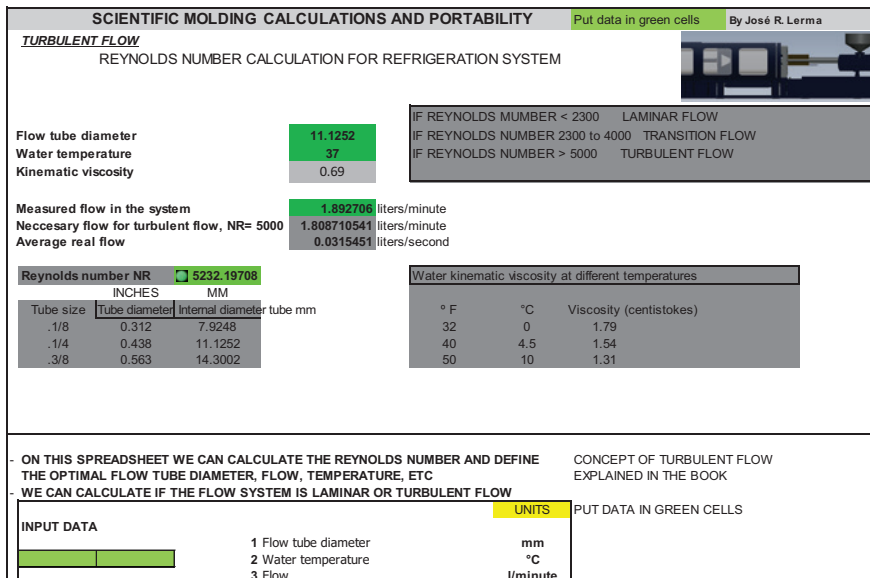


Figure 22.12

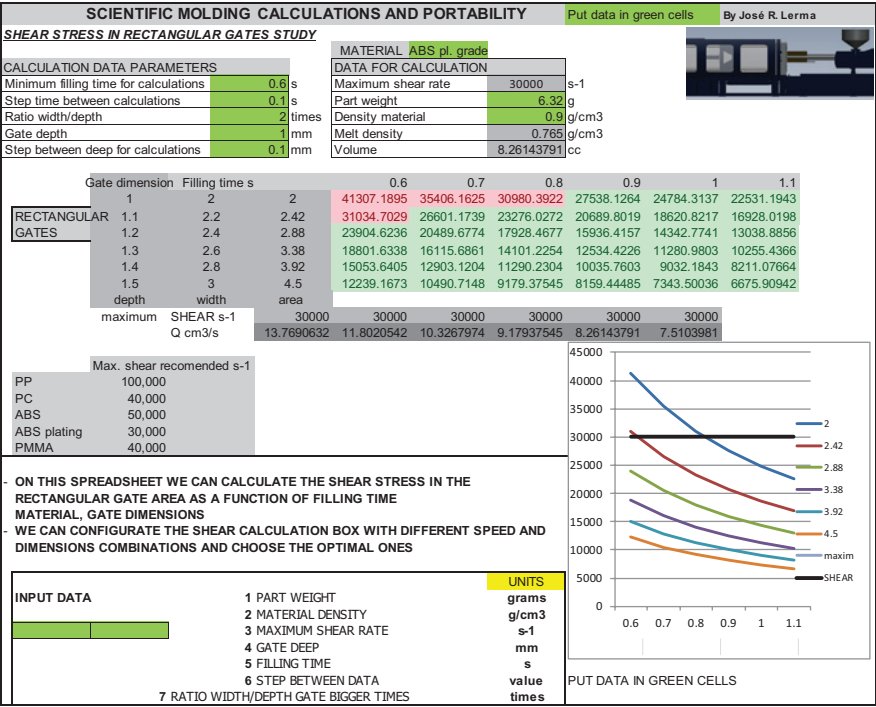


Figure 22.13

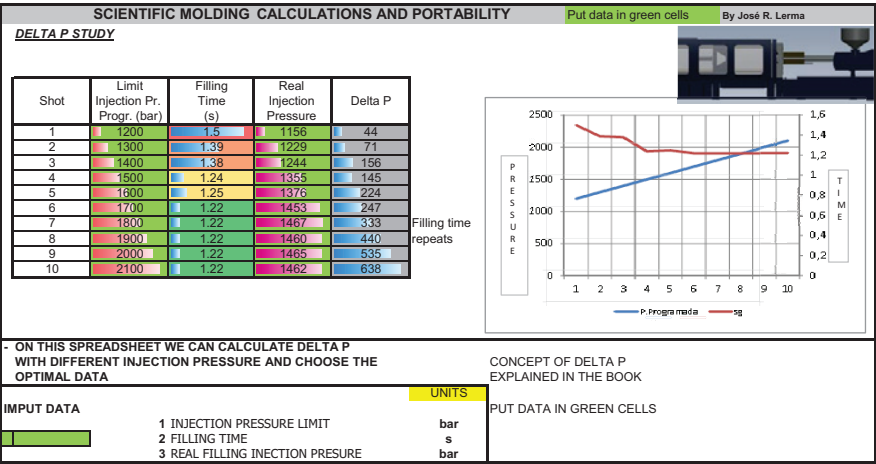


Figure 22.14

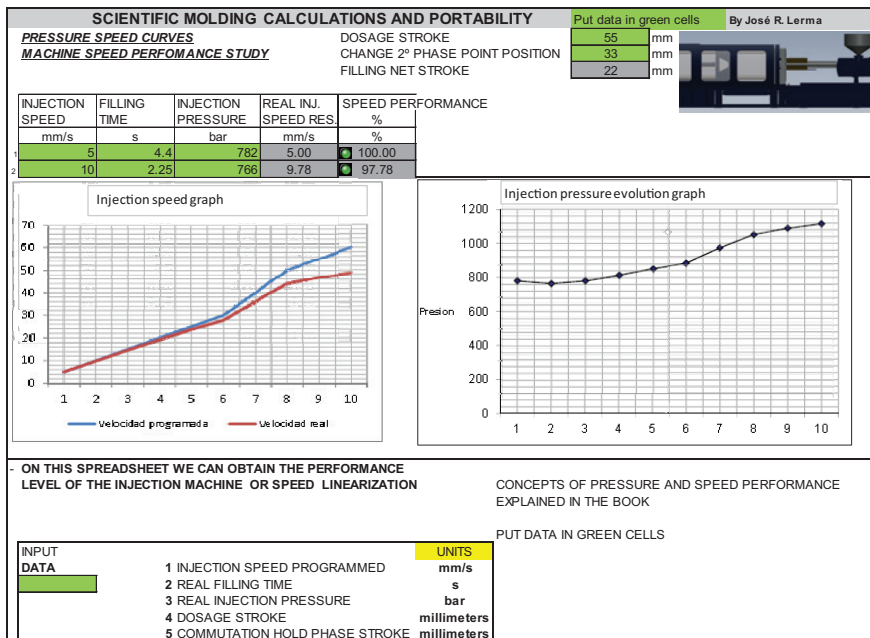


Figure 22.15

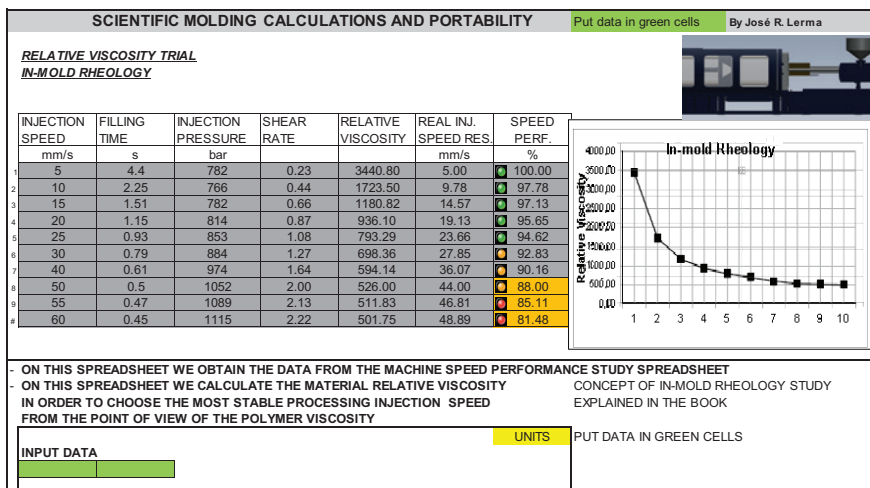


Figure 22.16

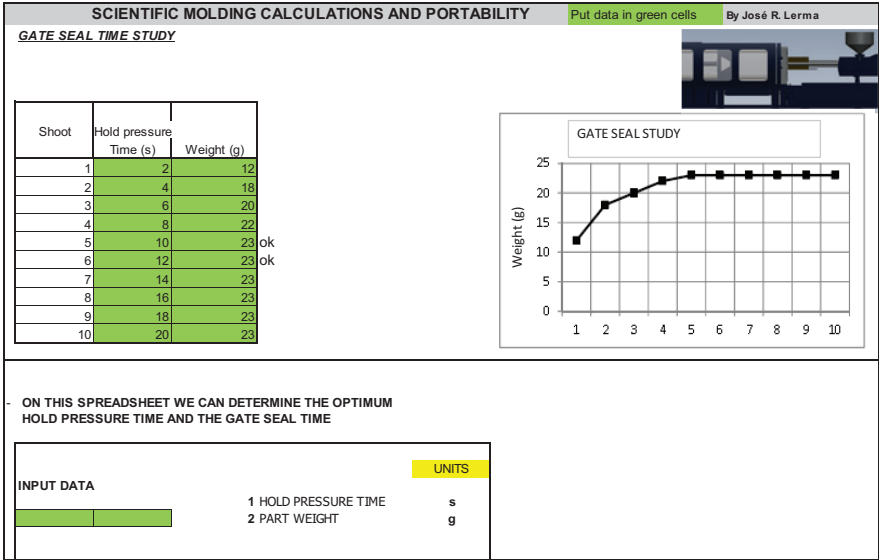


Figure 22.17

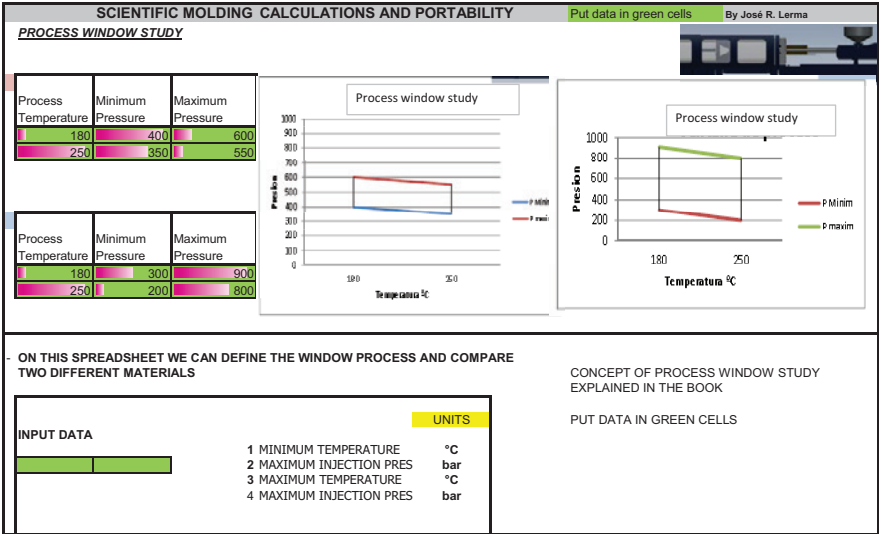


Figure 22.18

SCIENTIFIC MOLDING CALCULATIONS AND PORTABILITY				Put data in green cells	By José R. Lerma
CAVITY BALANCE STUDY					
	Filling speed high (mm/s)	Filling speed medium (mm/s)	Filling speed low (mm/s)		
Speed	6	3	2		
Injection time	0.1	0.2	0.4		
Average weight grams/cavity	Filling speed high (mm/s)	Filling speed medium (mm/s)	Filling speed slow (mm/s)		
1	1.27	1.31	1.30		
2	1.27	1.30	1.30		
Max. weight	1.32	1.32	1.31		
Min. weight	1.27	1.3	1.3		
Range	0.05	0.02	0.01		
In balance %	3.8	1.5	0.8		
ON THIS SPREADSHEET WE CAN ANALYZE THE BALANCING LEVEL OF CAVITIES AT THREE DIFFERENT SPEEDS AND, THEREFORE, THE INFLUENCE OF SPEED ON THE BALANCE CAVITY FILLING: CONCEPT OF CAVITY BALANCE STUDY EXPLAINED IN THE BOOK PUT DATA IN GREEN CELLS					
INPUT DATA		UNITS			
1 LOW SPEED		mm			
2 MEDIUM SPEED		mm			
3 HIGH SPEED		mm			
4 LOW TIME		s			
5 MEDIUM TIME		s			
6 HIGH TIME		s			

Figure 22.19

SCIENTIFIC MOLDING CALCULATIONS AND PORTABILITY				Put data in green cells	By José R. Lerma
SCREW TIP HERMETICITY STUDY					
Shot	Shot weight				
1	119.4	g			
2	119.6	g			
3	119	g			
Median	118.50				
Range	9.60				
Variance	8.03	%			
Maximum acceptable	< 3%				
ON THIS SPREADSHEET WE CAN ANALYZE THE EFFECTIVE HERMETICITY OF THE SCREW TIP NON-RETURN VALVE CONCEPT OF SCREW TIP HERMETICITY STUDY EXPLAINED IN THE BOOK PUT DATA IN GREEN CELLS					
INPUT DATA		UNITS			
1 Shot weight		g			

Figure 22.20

SCIENTIFIC MOLDING CALCULATIONS AND PORTABILITY				Put data in green cells	By José R. Lerma
DROP PRESSURE STUDY					
DATE		MAXIMUM MACHINE INJECTION PRESS	1700	bar	
PURGE EJECTION PRESSURE		145 BAR			
SPRUE AND RUNNER SYSTEM INJECTION PRESURE		800 BAR			
GATE INJECTION PRESSURE		990 BAR			
CAVITY FILLING INJECTION PRESSURE		1670 BAR			
DROP PRESSURE VALUE					
NOZZLE	145	8.5			
SPRUE AND RUNNER	655	38.5			
GATE	190	11.2			
CAVITY	680	40.0			
TOTAL PRESSURE AVAILABLE CAVITY	710	41.8			
DIFFERENTIAL PRESSURE MARGIN		30	1.8		
ON THIS SPREADSHEET WE CAN CALCULATE THE % OF DROPPING INJECTION PRESSURE IN EVERY STEP OF THE FLOW PATH AND SEE WHERE WE HAVE THE MAX. DROP. WE CAN DO ACTIONS FOR IMPROVING THE DROP PRESSURE IF NECESSARY CONCEPT OF DROP PRESSURE STUDY EXPLAINED IN THE BOOK PUT DATA IN GREEN CELLS					
INPUT DATA		UNITS			
1 DIFFERENT INJECTION PRESSURES		bars			

Drop Injection Pressure Distribution

Figure 22.21

Part 5

Failure Analysis

Process Under Control, Failure Analysis

23.1 Points to Consider

23.1.1 Clamping Unit

Mold life and production quality can be affected by the state of the platens and how they perform closing. Flashes, damaged parting lines, and external defects may be the cause of clamping problems.

Platens have to hold the mold when the closing force and injection pressure are applied. They are displaced when the guides are worn and can move during the closing lock (usually upward). We can control this movement supporting a micrometer in an area of the machine not influenced by this movement.

If we use the full closing force of the machine in a small mold, parting lines should be damaged and the platens deflect around the mold and “wrap” it. We must be very careful with small molds installed on machines with large platens.

To avoid these problems, we must follow this rule: no mold in the machine should be placed if it does not cover at least the average distance between the bars.

There is also another rule of thumb: molds should not be placed if they do not cover at least a quarter of the surface of the free platen between columns.

23.1.2 Barrels

Barrels can be worn due to temperature profiles reduced in some areas. They do not wear evenly (wear happens usually in the front area). However, we must not think that the barrel is in good conditions only because we lack adequate means to measure wear completely.

23.1.3 Screws

Much of the heat supplied to melt the material comes from the shear generated in the screw during dosage. In the case of polyamides, it can reach 80%. Semi-crystalline plastics require more energy to melt the crystals. In contrast, amorphous plastics such as polycarbonate require long transition zones to prevent degradation.

So-called barrier screws separate the molten mass from the semi-molten or solid mass to prevent degradation and to concentrate shear on the molten mass. (See in Chapter 13 how the screw works.)

Screw features:

- Compression ratio RK
- L/D ratio
- Length in diameters of the metering zone

- Length in diameters of the transition area
- Length in diameters of the mixing zone

A certain tolerance between screw and barrel (0.01 mm spindle) is generally accepted. If the wear is greater, the raw material will back down on the screw and will exceed shear, the dosage time will change, degradation will occur, etc.

23.1.4 Nozzles

We have to use the right nozzle for each mold and each material. The nozzle diameter should be 10% smaller than the small diameter of the sprue. We should use the appropriate nozzle for each mold and record the type, diameter, etc. to avoid variations from one production to another.

The interior design of the nozzle can bring improvements in the process (diameters, progressive transitions, taper, etc.).

23.1.5 Refrigeration System, Temperature Control in the Mold and the Machine

The system must have enough power to supply water at the right temperature at all times. The temperature difference between the inlet and the outlet of each refrigerated area from the mold should not exceed 3–5 °C.

With regard to the control of flow and pressure, we must obtain a turbulent flow to draw maximum heat transferred from the mold.

Cooling circuits remove most of the heat from the mold, but significant amounts are transferred to the platens and ambient air. A cooling system over the machine can help, isolating panes plaques between molds and platens too.

23.1.6 Water Connection System in Molds

Almost all injectors agree on the importance of refrigeration in the process. That is why we should not make the connection system a task of a specialist plumbing engineer.

We have to avoid that, for every mold change and set up made by different teams of technicians, the refrigeration circuit connections (in, out, and loopings) are reinvented. We need to register and document the connections, inputs, outputs, etc., so that anyone can follow the information and repeat the connections in the simplest way possible. Do it dummy-proof!

Many injection workshops and plants work every day with a great variety of molds. This means that, depending on the combination of molds and machines, requesting performance to the cooling system may vary each day. Sometimes, the system capacity is insufficient to fill all the circuits, to pressurize them properly and ensure that the necessary flow circulates inside. So we have to monitor the cooling system with flow meters, pressure gauges, and other devices.

This is one of the most common issues or “gremlins” in the injection workshops when the refrigeration system has not been well designed and calculated.

23.1.7 Dryers and Dehumidifiers

Some devices may indicate the air temperature, its input and output, and react accordingly. Sometimes, inside the hoppers, the expected FIFO (first in first out) flow does not occur due to the existence of areas with retentions or an incorrect output angle. Inside a passage, the material can slip quickly from the top of the hopper to the bottom.

We must also adjust the drying capacity of the device to the needs of the molds in operation. In some cases, plants are working properly and suddenly, after some changes of mold, there are problems with molds connected to the same dryer.

We should never connect a dryer to a mold that consumes its material more rapidly than the dryer can work. This is another common issue or “gremlin” that “lives” in the injection workshops.

Also, we will have to change the silica or zeolites every 18 months, maximum.



Figure 23.1 Dehumidifier for drying polymers properly; source: Wittmann-Battenfeld

23.1.8 Grinders

The pellets size is very important. To obtain a homogeneous melt, it is necessary that the pellets have a similar size and be homogeneous. We also need to control the blades, racks, and other items. In certain processes, the grinding mills should circulate at low speed (about 25 rpm) to avoid impacts and dust in the pellets.

The ground material can be re-used again in the process, controlling the quantities and avoiding any contamination. The recommended percentage may not be exceeded (10–20% maximum).

The original virgin material, once processed, always loses some of the additives pack as well as the molecular weight because of the process of transformation. These losses are inevitable. The percentage of regrind material may affect the final properties of the final manufactured parts.



Figure 23.2 Grinder for parts and runners; source: Wittmann-Battenfeld

23.1.9 Hot Runner

These supply systems of molten material should not cause pressure drops in the system that exceed 275–300 bar. If we have a hot channel that provides a pressure drop of 400 bar or more and if we need only 150 bar to fill the part, the machine cannot control the cavity filling in a precise way.

Accordingly, the pressure must be analyzed along the flow path of the material.

23.1.10 Thermoregulators

These devices are used to heat the mold. They must be sized properly depending on the mold temperature and steel volumes (the size of the molds to be tempered).

The heating capacity and the power of the pump must be dimensioned according to the output required to establish stable temperatures of the molds.



Figure 23.3 Thermoregulators for mold cooling systems; source: Wittmann-Battenfeld

23.1.11 Appearance Criteria

A definition of “quality” could be “compliance with customer’s criteria”. We must ask whether the client’s criteria are clear enough. It is necessary that we have physical samples of the allowable range limits accepted by the customer.

The so-called “aspect meter”, very used in some workshops, is very subjective and it can cause great losses of money.

23.1.12 Resin Handling

During the injection molding processing, open bags and containers should be covered. We cannot clean the bins, sacks, machines, etc. with jets and air guns. Environmental dirt travels through the air faster than we think. In some production plants, the dirt from bags is drawn before putting them in the injection room.

Another factor must be taken into account: the difference in temperature among the storage areas of raw materials and injection machine rooms. In some circum-

stances, this temperature difference, combined with moisture, may cause condensation of the pellets. To avoid it, we will deposit the bags in injection rooms for a while in advance.

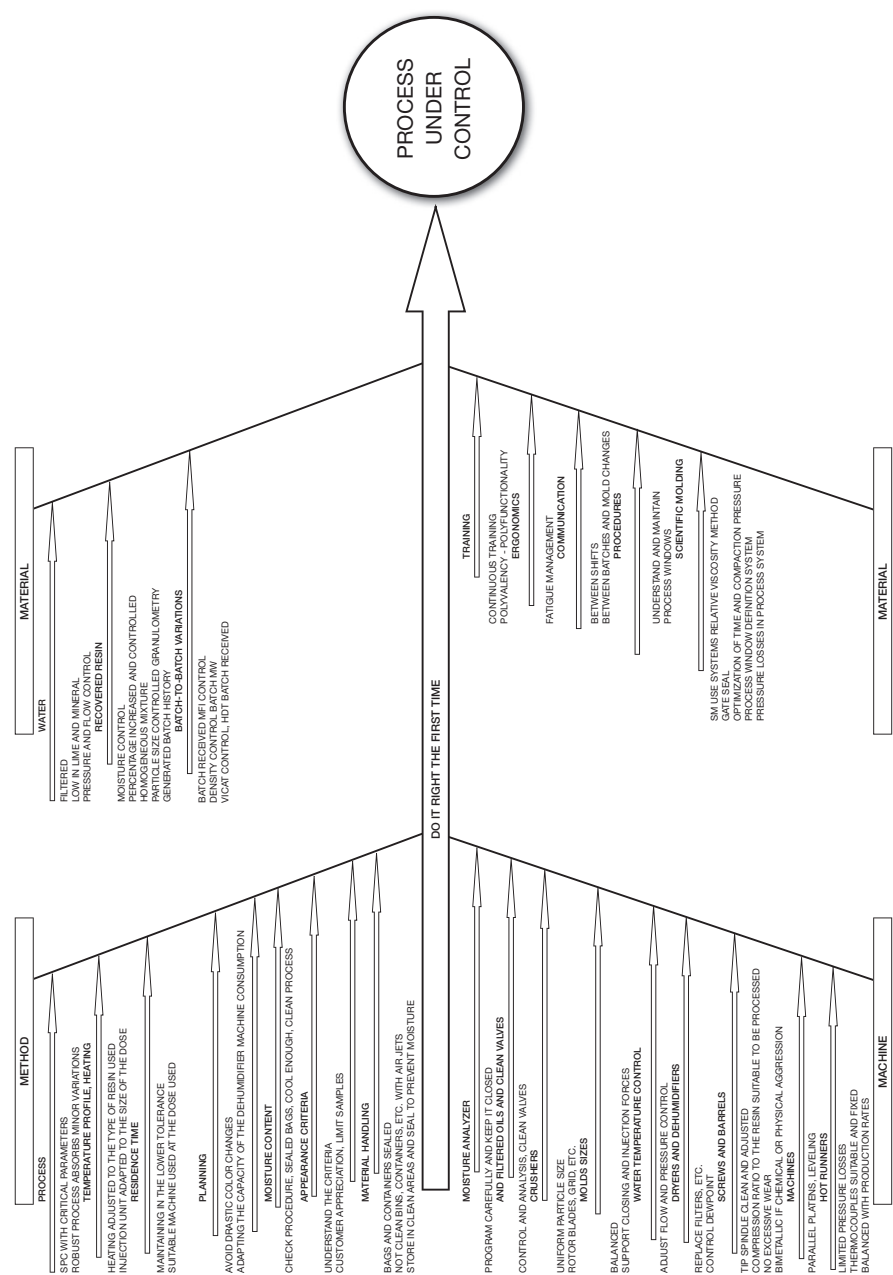


Figure 23.4 Ishikawa diagram analysis

23.2 Failure Analysis, Checks, and Optimizations

23.2.1 Preliminary Investigation of Failures

QUESTIONS TO ASK What has changed since the failure?

When did the failure start?

How often does it happen?

Is it a random failure?

Is it ever produced in the same place?

Is the failure in a new part?

Does it come from an injection process?

Does it come from tests?

Does it come from assembly lines or subsequent processes?

Does the failure appear in a part after its normal use?

If it is a new piece from production, tests, or mounting

Has there been any change?

Are tests too severe?

Have molding conditions been changed?

Has there been any change in assembly or subsequent processes?

Other parameters

New material or new batch?

How many failures (% or ppm)?

Failures/cavities ratio

Other mold? Changes in cavities?

Part from usual source

What are the conditions for failure?

Historical?

Environment?

How long has the part been used?

Possible consequence of some other failure?

ANSWERS

Often nobody wants to be guilty

Most frequent answers:

Nothing has changed

We are under the same conditions

We do the same process

No

Only partial answers are obtained.

All inputs to build a hypothesis are important

If possible, have good parts as reference

23.2.2 Process Optimization

Some Steps to Follow

1. Define the dimensions of the gate (depth, width, length) depending on the type of material.
2. Define the dimensions of the distribution channels depending on the type of material, starting with the channel that fills the gate.
3. Set the dimensions of all levels of distribution channels.
4. Define the sprue big diameter (O).
5. Define the machine nozzle diameter.
6. Determine the use of round or trapezoidal channels depending on the type of gate.
7. Determine the correct number of venting channels depending on the length of the parting line.
8. Determine the depth of venting channels for the parting line and the runners.

23.2.2.1 Radii

1. Check that there are right radii in the corners or sharp edges, using a pen tilted 45 degrees. Press down with the pen and make a line. If you get a single line, the radius is correct. If instead you obtain two parallel lines, the angle is not radiated enough.
2. The radius should amount to 50% of the thickness at the point where the walls of the same thickness meet (e.g., 2.5 mm thickness, 1.25 mm radius).
3. Inside radii: 50% of the thickness; outer radii: 150% of the nominal thickness.

23.2.2.2 Cold Slug

The sprue and the half-fixed mold of the injection side act as nozzle heat sinks. They act very fast and the heat produced by electrical heaters does not compensate the heat evacuation. Therefore, the melted polymer in the nozzle cools and freezes and the flow through the nozzle tip gets clogged.

Possible actions: improvement of temperature control through heaters; increase sprue; improvement of the thermocouples' thermal control in this area.

23.2.2.3 Steps for Analysis of Problems Derived from Plastics Injection Molding Process

- Make a diagnosis and detailed analysis.
- Check that there are no more defects present (often they may be hidden).
- Check that there are no basic causes (e.g., water refrigeration closed, etc.).
- Compare the outputs with the documented information.
- Determine the related outputs.
- Eliminate those items not related to the problem.
- Return the process according to the documented standards.
- Change one parameter at a time.
- Wait for the effects of the changes made.
- Check the relevant parameters.
- Check the mold, machine, and material if the cause does not appear.
- Record the actions taken, and their causes and effects.
- Ensure that the information can be understood and followed by others.

TROUBLESHOOTER QUESTIONS

What has changed since the failure? Is the material drying in time?

When has the failure started? Is the mold set correctly?

How often does it happen? Do the connection and the cooling system work OK?

Is it a random failure? Is the failure produced always in the same cavities?

Is it always in the same place? Are process recommendations being followed?

CALCULATION

TO CHECK

DATA			
	Customer		
	Address		
	Contact		
	Phone		
	E-mail		
Material			
Batch	Masterbach, Additives		%
Problem description			

DATA			
PART			
Name		Average thickness	
Function		Minimum thickness	
Use environment		Thickness part in the gate position	
Weight		Weight of all cavities	
		Runner	
MOLD			
Number of cavities			
Hot runner			
Shut-off nozzles			
Gate dimensions			
Gate type			

SHEAR STRESS GATE

PROCESS			
MATERIAL			
Drying temperature			
Drying time			
Dryer or dehumidifier			
Dew point			
Direct transport to hopper, manual, automatic			
MACHINE			
Screw diameter			
rpm used		Max. rpm	
Injection unit stroke max. dose			
Stroke dose used		Permanence time	
		% Injection unit use	
		Diameters used	
Nozzle diameter and conditions		Max. diameter possible?	
		Control and heating OK	
TN			
Machine			
Screw type		Venting	
		Standard	
PROCESS			
Stable cushion			Value
Max. rpm			
Back pressure			
Programmed melt temperature			
Real melt temperature			

Free ejection purge			
Ejection purge aspect			
Stable dosage time			Value
Stable filling time			Value
Hold pressure time			
Hold pressure			Profile
Injection speed			
Real filling pressure needed			
Filling speed profile			
Profile injection speed or filling? Where?			
Switching point		Correct 90/95%	
Progressive filling			
Limited pressure process?			
Cooling time		Cycle temperature	
MOLD			
Hot runner system			
Hot runner gate diameter			
Water refrigeration			
Circuits diameter			
Bridge conexions? Restrictions?			
Input/output temperature difference			
Quick plugs with no return?			
Venting		Cavity	Runners
Gate dimensions			
Runners shape		Shape	Dimen- sions
Ejection			
Sprue		Diameters	
Hor runner flow diameter			
Sharp edges radii			
PERIPHERALS			
Dryers air return temperature			
Mold temperature controls			

23.2.3 Trials Injection Molding Parameters Template

[illegible]

Typical Problems in Plastics Injection

These are some of the typical problems that we can find in plastics injection molding facilities.

24.1 Lack of Drying or Dehumidification

Source: DuPont

MATERIAL	Process symptoms	Workpiece symptoms	Effects on mechanical properties
ABS	Bubbles in purge	Bursts, streaks Tendency to flashes	Decrease Impact and tensile strength
PA	Drop nozzle material Bubbles in purge	Streaks in the flow direction	Decrease Resistance to impact and tensile strength
PC	Bubbles in purge	Streaks Flashes	Decrease Impact and tensile strength
PET-PBT	No symptoms	Non-visible streaks Increasing flashes	Decrease Resistance to impact and tensile strength
PMMA	Bubbles in purge	Streaks	Decrease Impact
POM	Bubbles in purge	Possible streaks	No effects
TPC EE	No symptoms	Slight increase in the tendency to flashes	Decrease Resistance to impact and tensile strength

Some plastics absorb humidity from the atmosphere. This absorption depends on the type of plastic.

Even the moisture caused by condensation on the surface may cause problems in parts made with engineering materials sensitive to humidity.

The loss of surface quality and loss of mechanical properties are the most common problems that may arise. The presence of moisture is not readily visible or detectable in the pellets; however, moisture levels in them may exceed desirable limits.



Figure 24.1 Dehumidifier for dry polymers; source: Wittmann-Battenfeld

24.1.1 Materials Drying

Most plastics allow a maximum moisture level in the pellets to be well processed. This depends on the water sensitivity of each material.

Several factors can influence the behavior of plastic: the moisture content of the material received from the manufacturer, the type and quality of packaging, the storage period from the batch production, or the conditions to which the material has been exposed during storage and transport.

PA, for example, is usually packed in vacuum bags with aluminum foil to enhance the moisture barrier. If the storage conditions are correct and the humidity of the pellets is adequate, the material can be used directly, without drying first. However, most of the time it should be dried before proceeding to the injection process.

Polyester materials (PBT, PET, etc.) are quite more sensitive to humidity. We need to dehumidify them to ensure impact and other mechanical properties.

These resins, after drying, are able to absorb quickly moisture from their surroundings. It is necessary to handle carefully opened bags and containers as well as the vacuum transport systems. In unfavorable climatic conditions, PET and PBT may take only 10 minutes to exceed the recommended humidity limit (0.02%). We have to close the bags and containers used and place a lid on the hopper during the whole processing.

24.1.2 How to Properly Dehumidify

It is important to follow a proper drying process if we want to get quality parts. This is the first step of the process and can damage the remaining steps.

Simple forced air dryers take air from the working environment, heat it, and introduce it into the dryer. Such dryers are not suitable for water-sensitive materials, such as polyesters or polyurethanes. In these cases dry air dehumidifiers should be used. These systems dry the ambient air prior to the drying of the pellets. Thus, the process is carried out steadily, without environment humidity influences.

These devices, while maintaining the correct temperature, ensure proper dew point ($\leq -30\text{ }^{\circ}\text{C}$). Dew point is the temperature at which moisture in air reaches 100% relative humidity and begins to condense water. When the air is dry, the moisture cannot condense until the air temperature drops below freezing point. When the dew point in a dehumidifier is $-40\text{ }^{\circ}\text{C}$, this means that the air being used to dry contains a quantity of water equal to the air cooled at $-40\text{ }^{\circ}\text{C}$.

When dehumidifier silos are used, it is important to know the bulk density of the pellets to ensure that they remain in the dehumidifier at least for the time required.

A dehumidification during an excessive time or at an excessive temperature can damage the plastic and some additives irreparably. Part of the pack of additives may be damaged by overheating and by excessive drying time. See Section 24.8 at the end of this chapter.

24.2 Filling System

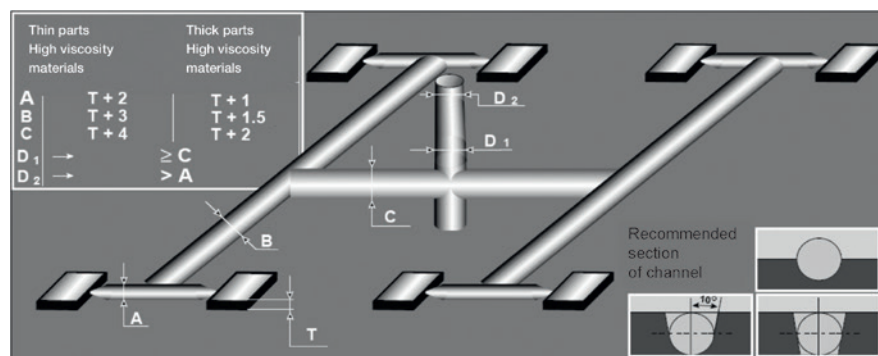


Figure 24.2 Calculations for runners design; source: DuPont

A well-designed part may malfunction due to various factors such as an inadequate size or an incorrect positioning of the gate.

24.2.1 Effects on the Quality of the Parts

If the gates and the runners system are too narrow, the holding pressure will not be effective for the time needed, the volume loss cannot be compensated adequately, and sink marks, voids, and other defects will appear.

The dimensional stability of the process will be highly variable and shrinkage as well as the tendency to warp will be much higher. The inner vacuoles and sink marks adversely affect the mechanical properties: they act as energy concentrators and reduce, for example, impact strength and stretch breaking.

In the case of polymers with fiber reinforcement, a narrow entry will also damage the fiber, reducing its length, and part of the reinforcement will be lost.

High injection pressures and long fill times may indicate that the gates are too narrow. This can also be recognized if with different injection speeds we obtain similar real filling times.

If the gate is too narrow, surface defects can appear due to excessive shear stress. This excess shear can harm some additives (impact modifiers, pigments, flame retardants, etc.). Small gates often cause defects such as jets, bursts, shines, gloss, halos, and marbling effects near the gate. They can also produce deposits of remains of the pack of additives in the mold.

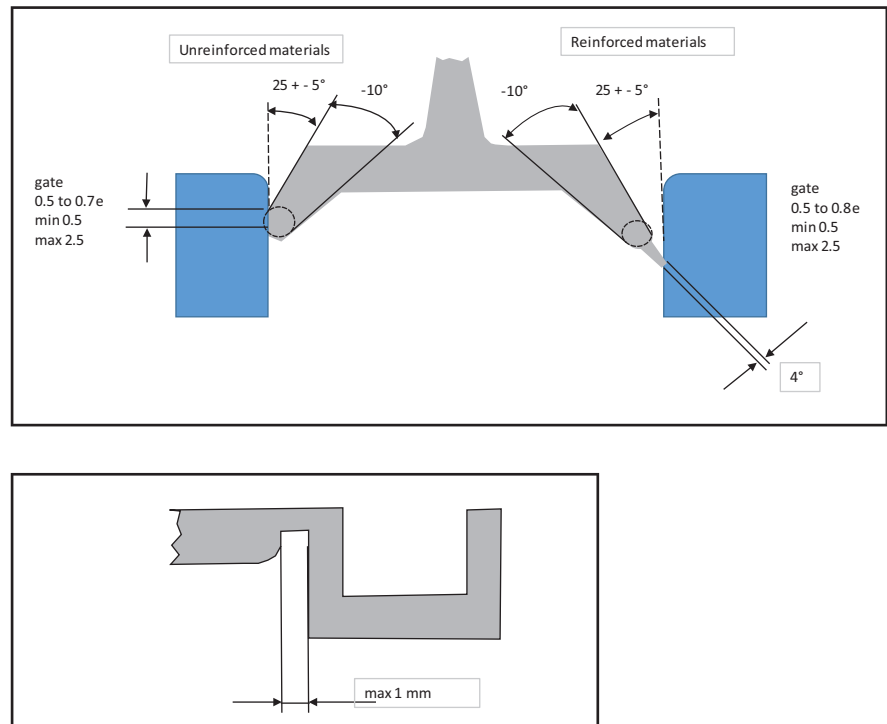


Figure 24.3 Gates design recommendations

24.2.2 Runners System Design

When designing a filling system, we first must consider the section or thickness of the part's wall to be manufactured. The diameter of the runners should never be smaller than the section of the part.

Starting from the gate, the diameter of each channel should be sized to maintain constant shear. The gate or sprue should be designed to catch the cold slug from the nozzle and prevent it from reaching the cavity.

In engineering materials without fiber reinforcement, the gate section usually amounts to 50% of the part thickness. This percentage depends on the type of material and its viscosity and shear sensitivity; it can reach 75 or 100% of the section of the part.

The length or land of the gate is also crucial. It should always be less than 1 mm to prevent premature cooling and surface defects.

In short:

- Always foresee an entrapment for catching the cold slug.
- Make the runners diameter greater than the part section.
- The thickness of the gate must equal at least 50% of the thickness of the part.
- The length or land of the gate must not exceed 1 mm.
- The small diameter of the sprue must be greater than the channel connected to the gate.

24.3 Proper Position of the Gate

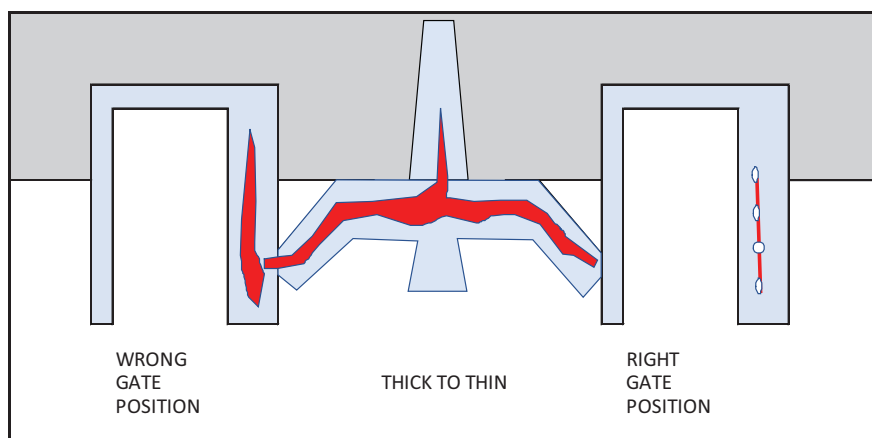


Figure 24.4 Gate position

The position of the gate is crucial for the filling, the filling profile, and the effectiveness of the holding pressure, which also affects the mechanical and strength properties of the parts.

24.3.1 Consequences of a Non-correct Gate Location

The properties of a part, in addition to its design, can be damaged by improper location of the gate. Symptoms may include: weld lines, jetting, voids, sink marks, higher injection pressure, trapped air, gloss near the gate, etc.

These effects are not reduced or improved by changing the parameters. The voids and vacuoles are unavoidable if the entry is located at the narrowest section of the part. This makes the narrowest section to crystallize before, because of its lower section, and prevents the flow from reaching the most remote and thicker areas, which must be volume-compensated for the change in specific volume (see Chapter 2).

On top of aesthetic defects and loss of mechanical properties, shrinkage will be increased in the thickest area. Differential contractions may cause warping.

If there are not enough gates or they are not properly positioned, flow distances can be too long and injection pressures can be too high. All of this worsens the process window and its variability, so it will be difficult to obtain dimensions with close tolerances and have a consistent process.

24.3.2 Recommendations for Correct Gate Location

1. Always try to gate in the thicker section of the piece (thick to thin).
2. If there are two or more cavities, the parts must be gated symmetrically in relation to the runner.
3. Axially symmetrical parts (gears, wheels, discs, etc.) should preferably be filled with three platen molds from the center. In these cases, we can improve the concentricity providing an odd gate number, ensuring that the filling volume through each gate will be similar.
4. Parts with integrated hinges must be entered so that the filling weld line does not match the hinge. Flow delays or stoppages during filling should be avoided near the hinge.
5. In the case of tubular parts, the melt flow must first complete the circular section at one end and then advance through the length of the tube to prevent an asymmetric filling of the flow front.
6. When there are metal or plastic inserts in the mold, it is important that the flow surrounds the insert evenly to prevent misalignment.
7. The gate must be located so that even small flow stoppages will not occur during filling.

24.4 Hold Pressure Time Too Short

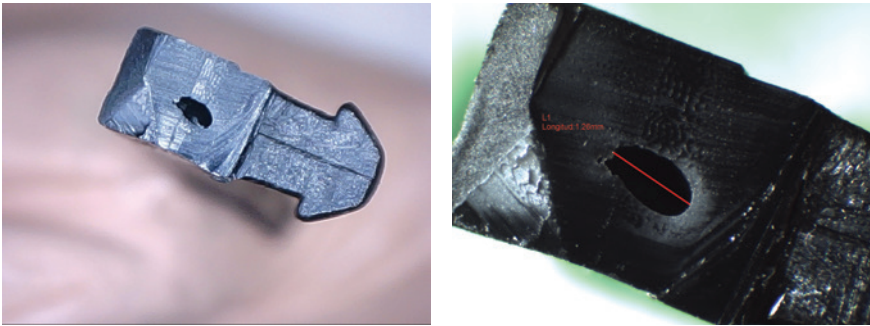


Figure 24.5 Hold pressure time too short: effects

24.4.1 Hold Pressure Stage

Once the cavity is filled, the molecules of the material (semi-crystalline) begin to crystallize and molecules are packed against each other. This process begins in the outer zones of the piece and ends in the nucleus or in the center of the wall thickness. The volume shrinkage this causes can be, for POM, up to 14%. This reduction in volume must be compensated by injecting more molten material into the cavity during hold pressure stage.

In the case of amorphous materials, it is also necessary to compensate this loss of volume although it is smaller. This is necessary also with the TPE polymers family, especially with TPU.

If the holding pressure is applied for a short time, the volume loss cannot be compensated and voids, pores, etc. are produced, which will have an adverse effect on the injected parts and their properties.

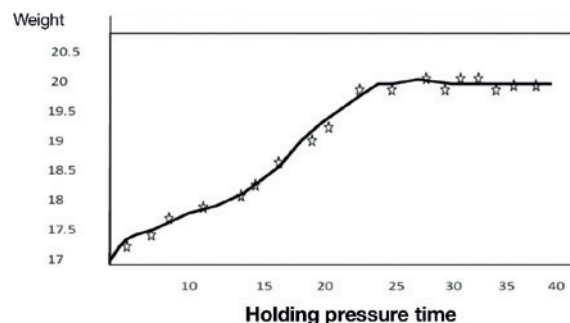


Figure 24.6 Determination of optimum holding pressure time, depending on the evolution of the weights of different parts and holding pressure times

24.4.2 Hold Pressure Time Too Short

Parts made with short hold pressure times have excessive shrinkage, warpage, sink marks, vacuoles, and, in some cases, loss of mechanical properties and poor dimensional stability.

One way to recognize and see the effects of inadequate hold pressure time is to cut the part in the area with greater thickness and check for vacuoles. We can determine the ideal holding pressure time by weighing injected parts and observing the evolution of the weights.

24.5 Inadequate Melt Temperature

The melt temperature determines the quality of parts. Semi-crystalline materials generally have a lower tolerance than amorphous ones, although the latter can also be very sensitive to these temperatures.

24.5.1 Incorrect Melt Temperature

Too high temperatures cause degradation of the polymer and the destruction of molecular chains. Additives such as plasticizers, colorants, or modifiers can also be decomposed and degraded. As a result, defects on the surface, unpleasant odors, loss of additives necessary for the use of the manufactured part, etc. are detected.

When the temperature is too low, the structure does not reach the required homogeneity. This effect drastically reduces properties such as impact resistance and, in most cases, internal stresses and variations in physical properties are produced.

24.5.2 Signs of Incorrect Melt Temperature

If the melt temperature is too high, a fast drop in the viscosity of the material and the appearance of flashes are often related to excessive heat. These signs also indicate a molecular degradation.

In the case of POM, the decomposition causes bubbles that can be observed during purging, and the formation of mold deposits and the smell of formaldehyde are detected. The physical properties of POM are strongly affected.

PA suffers a discoloration and loses its mechanical properties. Decomposition may be analyzed in the laboratory.

PBT and PET react strongly to overheating, reducing their toughness. The parts made become brittle. Discoloration may indicate a significant degree of degradation.

In PMMA, PC, and other transparent materials, the symptoms are usually brownish streaks or black spots.

ABS is degraded with a change to a darker hue and a characteristic odor.

SAN tends to go yellowish when it is thermally degraded.

24.5.3 Correct Melt Temperature

The data sheet often indicates the optimum temperature range for each material. Generally, the temperature set in the heating bands is unreliable because friction, screw rotation, back pressure, and other factors influence the resulting real melt temperature.

24.5.3.1 Melt Temperature Measurement

1. Pre-heat the pyrometer thermocouple.
2. Collect the purge in an insulating container.
3. Move the pyrometer thermocouple during the temperature reading.

24.5.3.2 30/30 Melt Temperature Measuring Method

1. Set in the injection machine the desired melt temperature.
2. Preheat the thermocouple 30 °C above the temperature set in the front part of the barrel.
3. Eject the melt material from the plastic injection unit.
4. Insert the thermocouple into the purged material and wait 30 seconds to measure the real melt temperature of the purge.



If the thermocouple in contact with the melt is moved continuously, we avoid the formation of an insulating “skin” that would affect the melt temperature reading data.

24.6 Correct Mold Temperature

When we inject thermoplastic materials, it is very important to get the mold surface temperature recommended by the manufacturer, especially with semi-crystalline materials such as POM, PA, PPA, PBT, PPS, etc.

Mold design is important because it ensures a correct stability and right temperature.

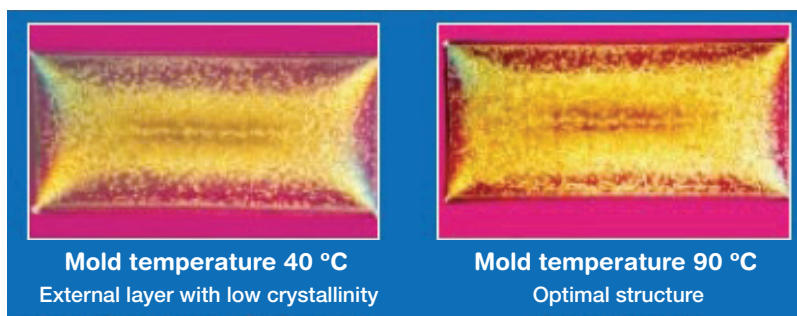


Figure 24.7 Structural changes with different mold temperatures; source: DuPont



Figure 24.8 Mold temperature thermoregulator;
source: Wittmann-Battenfeld

24.6.1 Incorrect Mold Temperature

The most common symptom is a poor surface appearance of the part, often caused by a low mold temperature.

A lack of crystallinity is another symptom that appears with mold temperatures below the one recommended. By not allowing time for good crystallization to occur, plastic parts have poor mechanical properties. For proper crystallization, cooling the melt in the mold must be slow, so that in time it will generate the crystalline structure. Rapid cooling with a cold mold will prevent the generation of this type of desired structure.

Shrinkage and post-shrinkage of semi-crystalline materials are strongly dependent on the temperature of the mold and the wall thickness of the part. Part dimensional changes at high use temperatures are often due to the fact that these workpieces have been processed with too low mold temperatures.

When working with low mold temperatures, low molding shrinkage and subsequent high post-shrinkage are obtained. This post-shrinkage occurs out of the mold, hours after injection, generating deformations and warpage.

If long mold start-up times are needed to obtain correct parts, perhaps this is because it takes too much time to reach thermal balance.

24.6.2 Recommendations to Properly Adjust the Mold Temperature

Molds are increasingly complex. So creating optimum mold temperature control conditions is increasingly difficult. Except in simple parts, the mold temperature control becomes a matter of compromise.

When designing the mold, the control of the part temperature must be taken into account.

When a big mold is designed for small parts, it is important to have good thermal transmission. The dimensions of the cooling channels and water intakes should be large enough.

The use of coupling connectors that might result in restrictions is not recommended.

Good results are obtained using pressurized water as a heating and control element. We must also use hoses and coupling connectors capable of withstanding the desired work temperatures and pressures.

The power of the heating device and the booster pump must be properly sized to heat the mold size and to reach the desired temperature.

Do not forget the norms and safety equipment (gloves, goggles, etc.).

- Use a thermal insulation platen between the mold and machine platens.
- Use separate temperature controls in the two half molds, injection and extraction.
- Refrigerate the base platens of the molds to act as a thermal barrier, preventing the transmission of heat to the clamping platens.
- Check that the temperature difference between the inlet and outlet of the independent circuits does not exceed 5 °C.
- Control the process with mold temperature sensors.

The thermal balance of the mold is obtained some time after the start of production. This thermal balance depends on several factors. The surface temperature of the cavity in contact with the plastic can be measured by thermocouples located 2 mm from the surface or through a pyrometer measurement thermocouple.

The manufacture of parts of accurate dimensions or high optical quality parts must be molded with high mold temperatures, getting less back post-shrinkage, better surface qualities, and more uniformity and repeatability of the process.

24.7 Residues on Mold Surface

This phenomenon may occur with all thermoplastics. Due to the higher performance requested of polymers, these are increasingly incorporating additives (flame retardants, antistatics, UV protection, friction, heat stability, hydrolysis stability, etc.). These additives, when decomposing, may cause deposits in the mold cavities.

There are other causes associated with this defect. The most common are:

- Thermal decomposition
- Excessive shear
- Absence of proper venting channels

24.7.1 Types of Deposits

Each type of additive generates a specific residue. Flame retardants can react at high temperatures, forming surface residues. Impact modifiers may be affected by excess temperature and also by excessive shear.

The pigments and dyes in materials that require high temperatures can reduce the thermal stability of the material, causing residual deposits (polymer and degraded pigments adhered to the surfaces of the mold).

If any part of the mold (cores, sliders, ejector pins, etc.) overheats, modifiers, stabilizers, and other additives may adhere to the surface and leave deposits on it. In such cases, a better balance of the mold temperature or using special stabilizers can help.

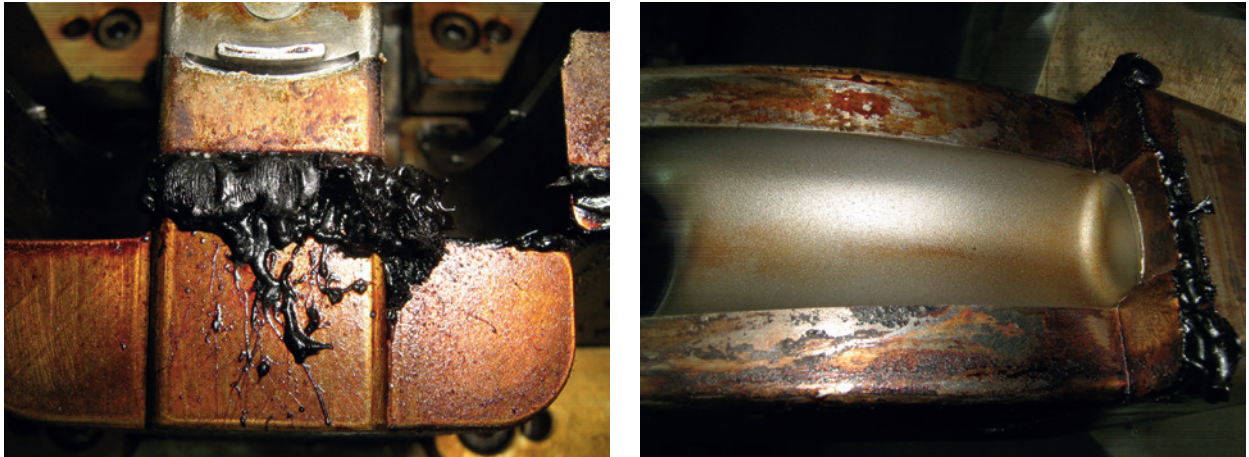


Figure 24.9 Examples of mold deposits

24.7.2 Mold Care

If residues cannot be avoided, care should be taken with the mold. If the deposit can be easily cleaned, cavities and venting channels must be cleaned frequently (for example, at the end of each shift).

When a thick layer is formed, cleaning is more difficult. Having deposits with very different chemical compositions, different solvents for cleaning and removing deposits must be tested. Besides solvents, conventional or household cleaning products can be tested (oven cleaner sprays, soft drinks with caffeine, etc.).



Recommendations to prevent deposits

- Avoid excessive residence time.
- Design large gates and channels.
- Good venting channels and venting outlets from the mold reduce the formation of residues.
- Avoid overheating cores or specific areas of the mold.
- Check the cooling system.

Sometimes it is possible to apply a special treatment for preventing adhesion of deposits on the surface of the cavity. Titanium nitride occasionally helps to reduce the ratio of accumulation of deposits.

24.8 Excessive Material Drying

As we have discussed in the first part of this chapter, some plastic materials absorb humidity. Humidity should be removed from the pellets through proper dehumidification. If this is not done, the mechanical, aesthetic, and other properties are depleted.

Sometimes the opposite effect occurs: an excessive dehumidification or drying (overdrying) also produces adverse effects on the original properties of the material. Plastics are blends of polymer and additives. An excessive time spent at high temperatures (such as the ones for drying) can damage irreversibly some substances of this pack of additives.

Overdrying sometimes occurs when production stops or when drying capacity and the injection machines' consumption are not balanced, and an excessive operating time of drying is produced. Overdrying causes that materials such as PA become yellowish and lose flexibility and impact.

PBT and PET polyesters also lose some mechanical properties in these situations. ABS, PMMA, PC, POM, and PPO become yellowish too. Often colored materials fade: white ones turn gray and red ones turn orange. This process is due to the degradation of pigments and additives.

In some of these materials, the occurrence of flashes at the same process conditions (a change in material viscosity) indicates overheating. In contrast, other materials, such as some PA, become more viscous and filling the cavities is more complicated.

Fortunately, modern available dehumidifier systems have consumption control systems. If an injection machine stops or slows down, the system adapts the drying conditions to the new situation and returns to the initial conditions when necessary.

As important as a good dehumidification it is to avoid overdrying the material.

Defects in Injection Molded Parts

25.1 Defects in Parts Manufactured by Thermoplastics Injection Molding

During the manufacturing process of parts by injection molding there may be different types of quality defects. The most common are:

- Sink marks
- Streaks
- Weld lines
- Corona effect
- Gloss
- Jetting
- Markings
- Black spots
- Inhomogeneous mass

25.1.1 Sink Marks or Uncompensated Shrinkage



Figure 25.1 Sink marks

These sink marks are basically caused by:

- Too slow solidification
- Too short holding pressure or hold pressure time
- Too low holding pressure or an absence of pressure transfer
- Unfavorable thicknesses design
- Overheating located in specific area
- Gates/runners not correctly dimensioned

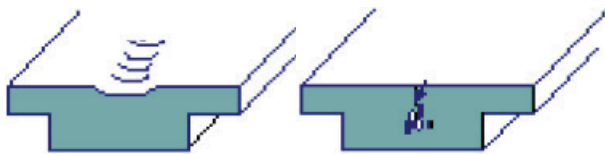
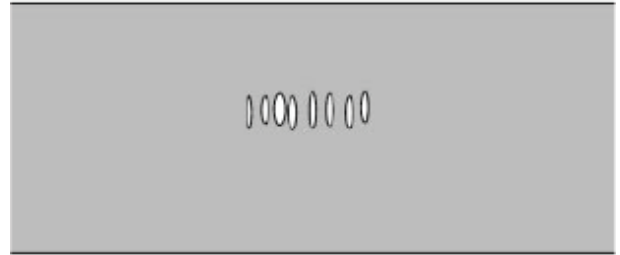


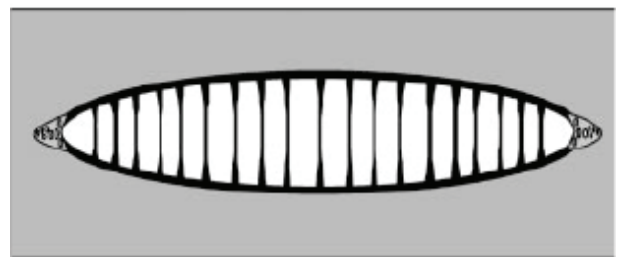
Figure 25.2 The sink marks may appear on the outside of the pieces or be hidden inside the section of the piece in the form of vacuoles



(a)



(b)



(c)

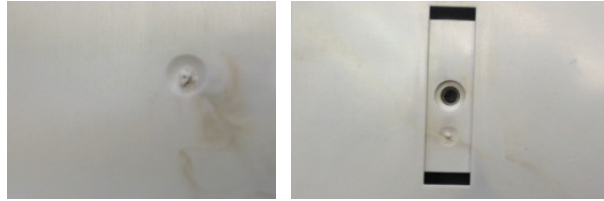
Figure 25.3 Evolution from vacuole to craze under stress: A vacuole becomes a crack or craze in a piece under stress

Verifications—To Check:

- Cushion
- Screw tip or non-return valve hermeticity
- Hold pressure time
- Hold pressure level
- Mold temperature
- Melt temperature
- Thicknesses and dimensions design
- Gate and runners dimension and location
- Areas with high temperature in the mold (sliders, ejectors, etc.)

25.1.2 Streaks

25.1.2.1 Streaks Caused by Burns



This thermal degradation is caused by excessive temperatures and/or residence times; gases are generated by the decomposition of the polymer or additive pack. Brown or silver streaks can be seen in the workpiece surface.

When the molecular structure is thermally degraded, the molecular chain can decrease, and silver streaks appear. The change in the macromolecules causes a brownish discoloration.

The heat required for thermal degradation of the material may come from the injection unit setting, from an excessive shear during dosing (back pressure) by a high peripheral speed (rpm), from an excessive shear on sharp edges, from sudden changes of direction, etc.

Verifications—To Check:

- Check if the melt temperature is near the upper limit recommended or even above.
- See if the streak appears behind narrow sections of passage of material.
- Check if the defect can be reduced by decreasing the injection speed.
- Check if the reduction in the melt temperature has a positive effect on the defect.
- Check if the degradation streak is affected by a high residence time caused by interruptions, excessive cycle, or inadequate machine size.
- Check for a considerable amount of regrind material or dust from the regrind process.
- Check there are no retentions inside the hot runners.
- Check that the nozzle is working properly and there are no retentions. Pay attention to shut-off hydraulic nozzles.
- Check that time and temperature of pre-drying material are not excessively high.
- Check that the shear originated during the dosing by screw rotation is not excessive (keep within the recommended limits for the material).

25.1.2.2 Streaks Caused by Moisture

They appear on the part surface with the shape of comet trails. The surface surrounding the silver streaks is porous and rough. This can be seen under a microscope.

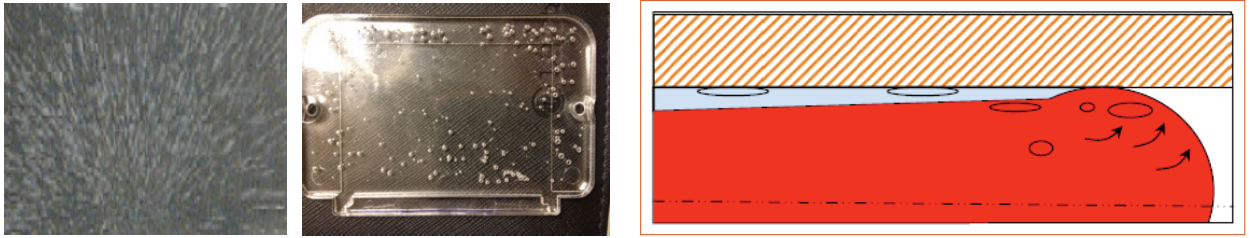


Figure 25.4 Melt flow and gas bubbles during the cavity filling; source: Ascamm

Residual humidity in the melt causes gas evaporation of water inside. These gas bubbles tend to come out to the surface by the advancing flow effect from inside to outside. Trapped bubbles burst at the surface with the application of pressure, creating the visible effect of the streak.

Verifications—To Check:

- Hygroscopic materials such as PA, PBT, ABS, PC, PMMA, TPU, and others need a thorough pre-processing dehumidification. Check the polymer manufacturer's recommendations.
- When material is ejected, the purge bubbles may appear and release steam if the material is not sufficiently dehumidified (inconsistency of purging).
- The flow front has crater-like structures.

25.1.2.3 Streaks Caused by Trapped Air

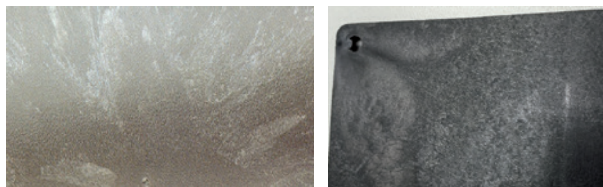
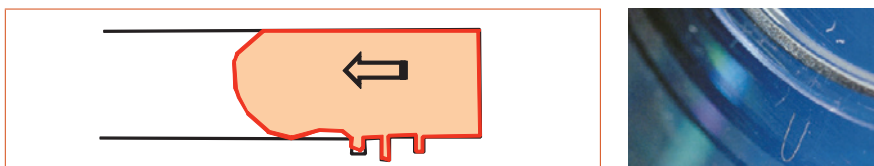


Figure 25.5 Examples of streaks caused by trapped air; source: Ascamm

They appear as matte, silver, or white streaks near the last filling zone. They also appear in areas with ribs, thickness variations, letters, reliefs, etc. The air concentrated in the ribs and grooves can be surpassed by the flow front and be trapped in the melt.

The air unable to escape during filling goes to the surface and becomes compressed in the direction of flow during the hold pressure stage.



Verifications—To Check:

- Make sure that the suction is not the cause of the problem.
- Perform tests decreasing the injection speed to minimize the problem.
- See if ejection purge shows bubbles or explosions and if the flow front has craters.
- Verify the back pressure. If the back pressure is low, the air is not completely removed from the pellets during dosing.
- Verify possible wear in the screw barrel of the plasticizing unit.

25.1.3 Weld Lines

When several flow fronts face each other, the flow front edges that are rounded come in contact and are crushed against each other. If temperature and pressure are not high enough, the corners in contact with the cavity will not bind on the entire surface and microcracks appear. Fluids do not mix homogeneously. At this time it is very important that the aeration or venting of the mold has been effective.



Figure 25.6 Weld lines

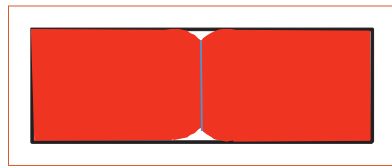
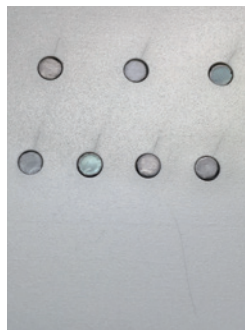


Figure 25.7 Weld lines between two flow fronts can cause air entrapments

Verifications—To Check:

The flow fronts must coincide quickly and with a higher temperature to reduce the incidence of the defect. To achieve this, the following conditions could be tested and checked:

- Material with higher melt flow
- Increased mold temperature
- Increased melt temperature
- Increased injection speed
- Proper venting in critical areas
- Increased hold pressure
- Gates dimensions
- Gates location

Sometimes, we can adapt overflow areas in the welding lines position to promote that the weld line be placed out of the critical zone of the part. However, we must re-work and cut this area later.

25.1.4 Grooves, Vibrations, and Corona Effects

Very fine grooves formed by concentric rings, like those of a vinyl record, can be seen on the surface of the part. Their appearance is due to the formation of a solid layer behind the flow front, which is cooled very rapidly. The cooling of the peripheral layer also causes cooling of part of the flow front. When this happens, a new layer from the melt flow passes through the cold flow front, creating a new groove or line.



Verifications—To Check:

These actions help to increase the speed of advance of the flow:

- Increase the injection speed
- Increase the maximum injection pressure (no limited process)
- Increase the melt temperature
- Avoid small gates and channels
- Use materials with less viscosity (more fluid)

25.1.5 Gloss

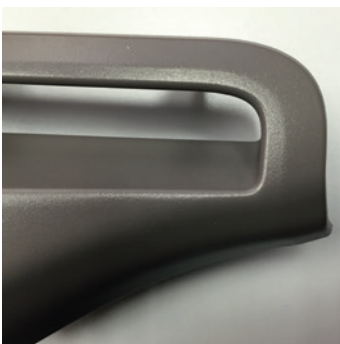


Figure 25.8 Gloss

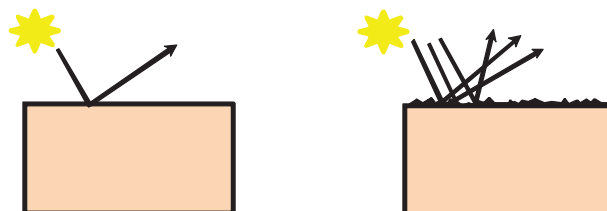


Figure 25.9 Left: high gloss, light reflection, narrow intensity distribution; right: low gloss, light reflection, broad intensity distribution

The brightness of a part is due to the refraction of light on its surface. Gloss differences are due to the different behavior of this surface, caused by various reasons (differences in mold surface, shrinkage differences, cooling differences, different mold temperature, inner vacuoles, orientation of pigments, fillers, etc.).

Verifications—To Check:

- Check the mold temperature (a high temperature causes parts with higher gloss)
- Check the melt temperature (a high temperature causes parts with higher gloss)
- Injection speed: a high injection speed usually increases the part's surface gloss
- Cavity mold surface texturing
- Design of ejection system
- Radiate sharp corners
- Design with uniform thickness
- Provide operational venting channels
- Take into account the different temperatures in molds, runners, ejectors, etc.; these thermal gradients generate differences in surface gloss

25.1.6 Jetting



Jetting is a free melted material jet forcing the melt to zigzag within the cavity. When the melt touches the walls of the mold, it is cooled and cannot melt homogeneously with the rest of material that goes into the cavity.

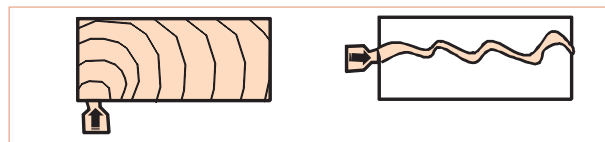


Figure 25.10 Correct and incorrect gate position; it can cause jetting in the molded part

Verifications—To Check:

- Reduce first injection speed to pass through the gate
- Increase melted mass temperature

- Increase gate dimensions
- Increase mold temperature
- Injection speed profiles: slow-fast-slow
- Change the injection point location
- Change the injection gate orientation
- Design elements that break the free jet
- Use more viscous materials

25.1.7 Spots and Markings near the Gate



These markings are originated close to the injection gate area. They are usually caused by small injection gates and/or high injection speeds.

These constrictions in the flow passage from the gate cause extremely strong orientation during injection. The outer layers solidify the molten mass with a very strong orientation.

These layers are extended to their full extent and are split by shear force. Melt flowing through the inside appears on the surface, forming small marks and reflections.

Verifications—To Check:

Actions to reduce the level of molecular orientation and improve the resistance of the solid cold layer:

- Reduce the injection speed (it helps reduce the stress in the cold layer)
- Round shape in the transition from the gate to the cavity (it generates less orientation)
- Increase gate section
- Use materials with different viscosity (usually less viscous)

25.1.8 Black Spots

Caused by thermal degradation, these spots may be due to the following reasons:

25.1.8.1 Process

- Melt temperature
- Excessively long residence time



- Temperature profile in the barrel
- Hot runners

25.1.8.2 Machine

- Wear of the injection unit, screw, barrel
- Dirt on the injection unit, contamination

25.1.8.3 Polymer

- Masterbatch dispersion
- Additives
- Impurities

These black spots are very typical in the degradation of polycarbonate (PC) due to too long machine stops or long material residence time in the injection machine.

Verifications—To Check:

- Reduce melt temperature
- Reduce cycle time and residence time
- Reduce screw peripheral speed
- Reduce injection speed

25.1.9 Inhomogeneous Material

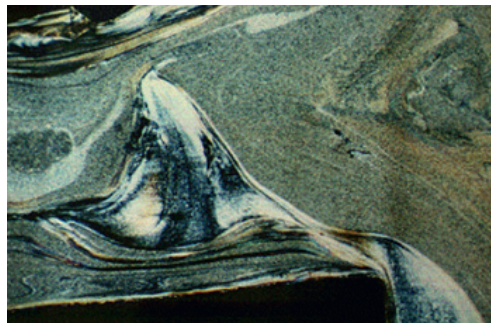


Figure 25.11 Source: Ascamm

The molten mass is not homogeneous. These inhomogeneous areas (usually unmelted polymer) have different densities, shrinkage, and mechanical properties, causing failures.

This defect occurs frequently in semi-crystalline materials, where part of the mass does not reach the melting temperature, causing non-melted zones and therefore not homogeneous.

Verifications—To Check:

- Make sure that the melt temperature is the one recommended by the polymer manufacturer
- Check the real temperature of the melt with a pyrometer

- Apply the back pressure in the dosage required to homogenize the mass
- Use a screw designed for the material

25.1.10 Blushes near the Gate

A blush indicates that the material is freezing prematurely and/or there is an excess of temperature in this area due to the shear, due usually to too small gates. If the defect is near the gate, it can be improved by increasing the depth of the gate. If the defect is farther, it can be improved by reducing the length or land of the gate.

25.1.11 Bubbles

Bubbles are very noticeable in transparent materials. Normally they cause scrap.

- If they are round, they may be due to humidity.
- If they are elongated, they may be due to pressure or vacuum inside.
- If they are in the center of the wall, they are typically due to pressure or vacuum.
- If they are on one side of the wall thickness, they are typically due to humidity.

25.1.12 Cracking

This defect is usually caused by sharp corners. Also, during the part demolding from the cavity, if there is not a right taper design, it may cause microcracks in the parts molded.

25.1.13 Delamination

Parts show layers that can be separated easily. This shearing effect is normally produced in amorphous materials. The highly oriented material layers are frozen and are separated from each other.

Delamination occurs when high injection speeds with small gates and/or cold molds are used.

Reducing the injection speed, increasing the gate dimensions, and increasing the mold temperature in cold molds are actions that reduce this delamination effect.

25.1.14 Splay, Silver Marks

Usually, silver marks are caused by an excessive length of the gate (land). If we observe this defect microscopically and we can see fine granules, perhaps there is an excess of moisture in the pellets. Otherwise, when the surface texture is rough, the material temperature may be excessive.



Figure 25.12 Bubbles in the center of the wall

25.1.15 Warpage

This defect is typically caused by molded-in stress (parts molded with high stress level, high cooling rate, high injection speed, too much pressure, etc). Usually, there is no warpage in parts injected with low hold pressure levels. Overcompactions increase the deformation. Warpage is also caused by differential shrinkage due to reinforcements and also by differences in thickness.

25.1.16 Stress Cracking, ESC

This failure mode is the combination of two effects. The first, stress in the part, the second, a chemical attack made by some substance that may attack the plastic. Both factors are necessary for a failure by ESC.

If the section of a crack or a break is bright, it is probably caused by stress cracking or chemical attack.

This problem occurs sometimes after applying demolding or lubricant agents on the molds. Amorphous materials (ABS, SAN, ASA, PS, PMMA, etc.) are more likely to ESC.

Materials with higher molecular weight and more cross-link or vulcanized improve resistance to ESC. Therefore, impact modified or improved soft touch materials are more resistant to ESC.

25.1.17 Surface Scratching

Penetration effect in the part surface, causing permanent marks or stripes.

The increase in molecular weight increases scratch resistance. The higher the mold temperature, the higher the crystallization and scratch resistance of the piece.

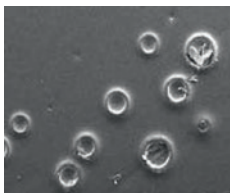
25.2 Defects in Injection Molding and Painted Parts

Source: UMG ABS

25.2.1 Holes and Craters

Appearance of small holes (cratering).

Possible cause: trapped air and/or parts molded with high stress level.



25.2.2 Trapped Air

Air bubbles trapped under the paint layer expand during drying and deform the surface of the paint not yet solidified.

It usually occurs with high evaporation rates of solvent and applications made in environments with high humidity and high temperature, or when paints of remarkable thickness are used.

Possible actions for trapped air:

- Change the environment of the painting process, less humidity and temperature
- Extend the drying time of the solvent to have slower evaporation
- Reduce the viscosity of the paint
- Apply a layer of paint thinner

25.2.3 Part Molded with Stress

Possible cause: part made with stress.

This defect can occur when the substrate has been molded with residual stress and an ESC effect could occur easily. In this case, the substrate is much more easily attacked by the chemistry of the solvent, resulting in cracks or microcracks.

The solvent comes to penetrate these cracks, evaporating uncontrollably during drying.

Possible actions:

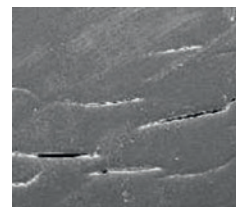
- Use less incompatible solvents with the substrate
- Reduce the amount of solvent applied
- Stabilize parts before painting (depending on the material): perform an annealing to release the residual internal stress, bringing the temperature to the glass transition of the material for a time and slowly cooling
- Inject the molten material without residual stress; for this, it is recommended to:
 - Increase melt and mold temperatures in the injection process
 - Check gate dimensions and runners channels system
 - Use materials with higher melt flow index
 - Check hold pressure stage, time, and pressure

25.2.4 Cracks

These microcracks are caused by an attack by solvents. They usually appear in the acrylic-based paints, near sharp edges, and material gates (i.e., in areas with high shear stress).

Possible cause:

- When the substrate is molded with residual stress, stress cracking may occur; the substrate is much more easily attacked by the chemistry of the solvent, resulting in cracks or microcracks
- The solvent penetrates these cracks, evaporating uncontrollably during drying

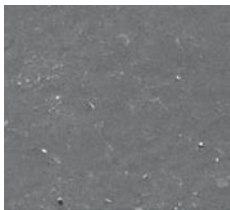


Possible actions:

- Use less incompatible solvents with the substrate
- Reduce the amount of solvent applied
- Stabilize parts before painting (depending on the material): perform an annealing to release the residual internal stress, bringing the temperature to the glass transition
- Inject the molten mass without residual stress; for this, it is recommended to:
 - Increase melt and mold temperatures in the injection process
 - Check gate dimensions and runners channels system
 - Use materials with higher melt flow index
 - Check hold pressure stage, time, and pressure

25.2.5 Irregularities

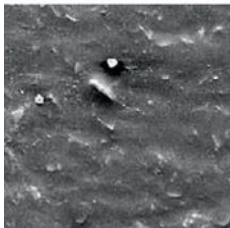
25.2.5.1 Sinkings



Variable gloss and surface microcracks.

Possible cause:

- Solvents penetrate the substrate
- Injection defects such as jetting, flashes, sudden changes of thickness, weld lines with defective venting

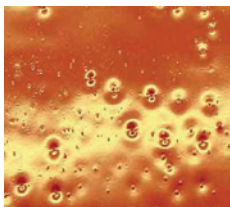


The gate area is also critical for these solvent attacks.

Possible actions:

- Use less aggressive solvents with the substrate
- Modify the amount of solvent applied
- Increase the melt and mold temperature
- Reduce the required pressure and increase flow rate
- Change the type of gate and check its dimensions (depth, land, and width)
- Check effectiveness, location, and dimensions of mold ventilation system

25.2.5.2 Peaks/Crawling



Small marks appear on the painted surface.

Possible cause:

- Possible presence of a contaminant adhered to the substrate

Possible actions:

- Check for contamination with silicones, oils, fats from the mold or molding process, ambient dust or volatile products from other processes
- Manipulate parts with gloves and work in controlled environment
- Degrease parts (e.g., with hexane)

25.2.5.3 Lack of Adhesion

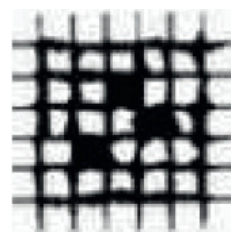
The painting is not well attached to the substrate. (See cross cut test in Section 25.3.)

Possible cause:

- Contaminants such as grease, release agents, humidity, etc. on the surface
- Compatibility between the base substrate and paint
- Surface tension of the part and paint, wettability

Possible actions:

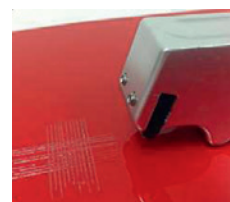
- Degrease parts (e.g., with hexane)
- Use paints with more chemical adhesion to the substrate
- Change the injection conditions to cause a bigger attack of the solvent
- Perform previous treatments such flaming, corona, plasma, to increase the surface tension



25.3 Cross Cut Test

Make six parallel cuts, then make another six perpendicular cross cuts. The distance between blades depends on the layer thickness and the type of test chosen.

ISO 2409		ASTM D 3359-02	
Up to 60 microns	1 mm separation	Up to 50 microns	1 mm separation
From 60 to 120 microns	2 mm separation	From 50 to 120 microns	2 mm separation
From 120 to 250 microns	3 mm separation		



Source: Gardco

Table 25.1 Cross Cut Test

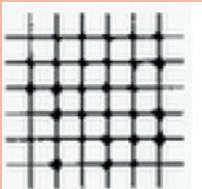
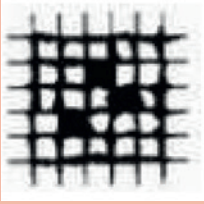
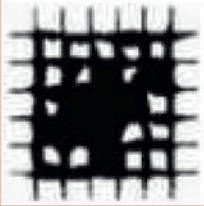
		ISO GRADE	ASTM GRADE
	The edges of the cuts are OK. No square of the grid has been pulled out.	GT 0	5B
	Small paint chips have detached at intersections of the grid. 5% of the section can be detached.	GT 1	4B

Table 25.1 Cross Cut Test (*continuation*)

		ISO GRADE	ASTM GRADE
	The paint has detached along the cut edge and/or the intersections of the grid. 15% of the section can be detached.	GT 2	3B
	Paint has detached partially or widely along the cut edge. Paint has detached completely in individual zones partially or completely detached. 35% of the section can be detached.	GT 3	2B
	The paint has detached along the cut edge in broad strips totally or partially pulled out. 55% of the section can be detached.	GT 4	1B
	Adherence degrees greater than GT 4.	GT 5	0B

General Recommendations

- The resistance of the material against various solvents must be known to determine the solvents that may cause problems during application or degreasing.
- Inadequate solvents could be aggressive and attack sensitive plastics, causing softening and surface tension, lowering the mechanical properties of the product.
- The part surface should be clean and dry, suitable for painting. Clean it to remove any mold release agents, dust, etc.
- Always use fast evaporating solvents.
- The parts must go through an ionized air jet to prevent dust buildup.

25.4 Defects in Chrome Plating on Plastic Parts

Defects in chrome parts can be due to problems related to the molded workpiece or the plating process. Both processes are complex and they have multiple variables.

The most common problems are often related to the presence of bubbles and peaks or to insufficient adhesion between the plastic substrate and the layers of plating process.

25.4.1 Defects

The most common injection molding defects in the case of chrome plastic parts are usually due to:

- Errors in the chrome plating process
- Excessive or insufficient drying of material
- Streaks due to rapid transitions, surface cavity textures, or poor venting
- Contamination due to handling, storage, or transportation
- Internal stresses
- Excessive high pressure level during hold pressure stage; this could reduce the small butadiene particles size
- Gates design and runners channels
- Functional defects of the molds

To help to identify defects caused during the injection process it is interesting to do a progressive cavity filling test (see Chapter 15). In this way one can observe areas where flow accelerations or flow decelerations can be generated, micro-streaks, etc.

25.4.2 Peaks, Spots, Bubbles



Figure 25.13 Peaks, spots, bubbles

25.4.3 Blisters

- | | |
|--|---|
| <ul style="list-style-type: none"> ■ Check drying material (drying conditions recommended by the manufacturer of the polymer) ■ Check use of regrind material, % of regrind material blended with original or virgin material, contamination, dust, etc. ■ Check venting, trapped air | <ul style="list-style-type: none"> ■ Check chrome plating process ■ Check the non-use of demolding agents ■ Check mold, loose particles, damage, grabbing, venting ■ Check manipulation, gloves care, separators, packaging, etc. |
|--|---|

25.4.4 Adhesion



Non-adhesion occurs frequently in areas with high shear, orientation, stress, etc. To discard this effect, we must modify the injection rate and increase the mold temperatures. We should also pay attention to the gate dimensions, distribution channels, sprue dimensions.

- Vary injection speed Reducing tension and stress
- Increase mold temperature
- Increase melt temperature
- Optimize switching point to holding pressure stage
- Reduce holding pressure time
- Reduce holding pressure level (decreasing profile)
- Avoid drastic variations in thickness
- Check reducing the injection speed (slow-fast-slow profile recommended) Reducing effects on gate
- Increase gate section
- Round the transition area gate-part
- Check possible contamination of the material Pollution effects
- Do not use demolding agents
- Check possible heat damage of the material (overheated over melt temperature)
- Check chrome plating process (etching)
- Check handling, packaging, robots, etc.
- Check plate out effect (depositions in mold caused by the additive pack) due to the high stress and high shear
- Excessive shear in screw (high rpm, high residence times)
- Excessive drying time
- Insufficient venting system in the mold

Sometimes this problem appears near ejector pins, slides, or nozzles with movement in the mold.



- Check greasing and cleaning the mold and moving parts.

Other verifications:

- Are manipulations being performed with cotton gloves? Clean ones? This can cause part surface contamination and low surface quality in chrome plating parts.
- Are parts being packaged when they are still hot? Find out whether the pieces, still hot, are packaged with bags or foam. This can cause migrations from foam or bags to the part surface and condensation from the environment.

Analysis of Real Cases

26.1 Broken Support Brackets



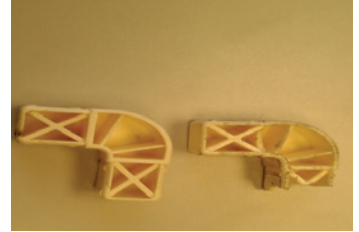
An improper drying, a gate with inadequate dimensions, and an insufficient ventilation of the mold may cause breakage of a technical part when it is used.

A manufacturer of solar energy panels needed support brackets for joining the rectangular metal tubes forming the structural frames. These structures consist of a frame formed by four square-shaped tubes joined by four support brackets (parts). This frame structure holds the solar energy panel on top of it.

TPC-ET was chosen for manufacturing the part; the grade selected has a hardness of 70 Shore D and good toughness and stiffness. The operators responsible for the assembly hit the tubes with hammers so that they fit into the squares, and these are deformed by torsion in the last section (more difficult to assemble). When the squares have been mounted, the tubes are pressed on their ends to deform them and create an anchor that prevents its disassembly. Thus, the structure is defined and gains more strength.

The parts were homologated and began to be manufactured. However, the customer reported that a high percentage of squares of the last batch were broken during the pressing phase, when the metal tubes were crushed against the plastic.

As always, I requested the customer to urgently send us some broken parts as well as others from the defective batch, to analyze possible causes. I also asked the parameters and processing conditions to get an idea of how the material was treated. A few days later, I received a box of parts and I proceeded to analyze them visually.



26.1.1 Drying of Material

TPC-ET is a polyester-based material. It is a hygroscopic material and requires a thorough pre-drying. Before the injection, the humidity should be reduced to 0.1%.

I had a hunch that the residual humidity in the pellets could be causing the problem of fragility (see Chapter 4). Sure enough, when I checked the parts visually, I could see streaks in different areas. These showed that drying was not rigorously performed.

The manufacturer recommended introducing the material into the dehumidifier at 110 °C for 3 hours. Conventional hot-air ovens are not enough to dry polyesters and their derivatives (or many other thermoplastics). Drying with forced air heaters involves heating ambient air and putting it in the hopper where the material is. If this air has high humidity, it introduces moisture into the dryer and, therefore, in the pellets.

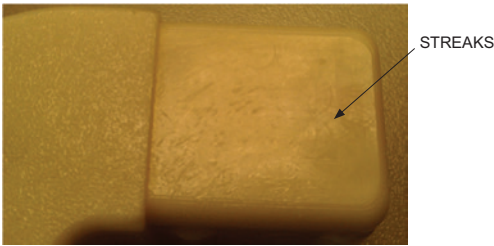
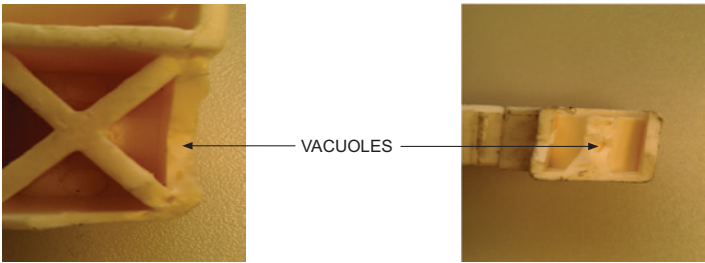


Table 26.1 Maximum Recommended Moisture

Material	Recommended initial humidity (%)
PMMA	0.1
SAN	0.1
ASA	0.1
PS	0.1
ABS	0.1
PBT	< 0.02
POM	0.15
PE	0.3
PP	0.3
PA 66	< 0.1
PA 6	< 0.1
PSU	0.02
ABS PC	0.05
TPU	0.07
PC	0.02
TEEE TPC-ET HYTREL	< 0.1
LCP	< 0.01
PPS	0.05

However, I could see more symptoms of possible causes. In rupture zones, and in some cuts made in the parts, vacuoles were visible to the naked eye: empty areas become like stress concentrators capable of initiating a crack or breakage when the parts were subjected to stress.



These vacuoles are formed by a shrinkage of the material which has not been compensated during the holding pressure phase. During cooling of the material in the mold cavity, a decrease in the specific volume is produced. This decrease should be compensated by providing more material in the holding pressure phase.

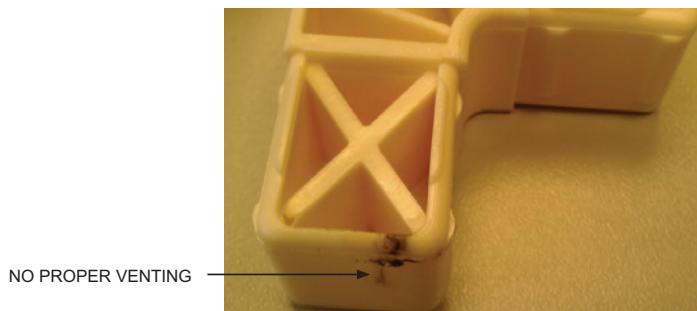
If this compensation does not occur or is insufficient, the shrinkage of the material will be reflected in external sink marks or internal voids. External sink marks can be observed with the naked eye. Internal voids can only be appreciated after sectioning the part. This defect is more visible in thicker areas of the part.

These vacuoles weaken the structure of the part, by making it more fragile.

The way to avoid this defect (see Chapter 25) is to ensure the compensation of the material's volume shrinkage through:

1. A suitable hold pressure time, which controls the evolution of the injected mass weights (with different holding times).
2. Ensuring by correct gate dimensioning the compensation of the volumetric shrinkage of the material. To achieve this, we must ensure that the gate dimensions, runners, etc. are correct. Thus, we optimize the full filling system supply cavity (nozzle, sprue, channels, gate, etc.).

In some parts I could see areas at the end of filling with burns or Diesel effects, caused by the trapped air when it is forced through restricted areas. These burns indicate the absence of venting. However, before reaching burns, we can see other symptoms that indicate this problem, such as surface peaks or points, or matte areas at the end of filling. This all indicates that the gas outlets must be improved.



The recommendations to optimize venting would be:

1. Venting the parting line at least 20 or 30% (channel width: 5 mm; distance between channels: 25 mm)
2. Harnessing the ejector pins to improve ventilation of the mold
3. Ventilating the runner too, both the strip-sprue and in each 90-degree turn
4. Depth of gas outlets: 0.015 mm; length gas vents not more than 1.5 mm

In such cases I recommend doing what is called a filling optimization (nozzle-sprue-runners-gates-venting).

26.1.2 Filling System Review and Optimization

This type of optimization begins with the gate. We must determine the optimal size of the gate, considering what materials are used and the thickness of the part (either the average thickness of the part or the thickness of the wall that attacks and fills the gate).

We must consider each of its dimensions:

Depth It determines how long the entry remains open.

Width It determines the volume of material to pass through.

Length It determines the separation between casting and cavity (should never exceed 1 mm, otherwise it will generate high shear).

Material	Depth	
ABS	60%	The depth of the gate depends on the thickness of the part and the viscosity of the material used. In this case, the TPC ET percentage should be 60%. Since the thickness of the part is 3 mm, the depth is 1.8 mm.
SAN	60%	
ASA	60%	
POM	90%	
PS	75%	
PP	50%	
PE	50%	
PA	50%	
PC	90%	
PA filled	90%	
ABS	60%	

Width factor	×1, ×2, or ×3 depending on the part size and volume
×1: If the piece is smaller than a pack of cigarettes	The width of the gate must measure twice the depth. However, this may be optimized taking into account the size of the part to be produced (can be 1, 2, or 3 times the calculated depth). In this case the factor may be 1. Therefore, the dimensions must be 1.8 mm.
×2: If the piece is more or less the size of a pack of cigarettes	
×3: If the piece is bigger than a pack of cigarettes	

Length	The length of the input must be 0.5 times the depth, but not exceed 1 mm as it can cause excessive shear and defects near the gate. In this case the length should be 0.9 mm.
0.5 times depth	
Max. 1 mm	

By these calculations the final dimensions of the gate are determined: 1.8 mm × 1.8 mm × 0.9 mm. The cross-section of material is $1.8 \times 1.8 = 3.24 \text{ mm}^2$.

Checking parts and watching the remains of the current gates, these are considerably smaller than those calculated. Runner, sprue, and nozzle have correct dimensions. In other cases, we will optimize them.

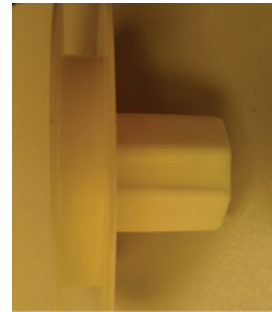
In summary	
Problem	Broken parts during assembly Material: TPC ET
Causes	Humidity Venting Inner vacuoles
Advice	Dehumidify Improve venting Improve gate dimensions

26.2 Pulleys that Do Not Work



An incorrect design (the plastic part was manufactured following the instructions for a piece of metal) and the absence of radii limit the part's strength. In addition, it has been manufactured following a process that degrades the material and makes it lose its properties.

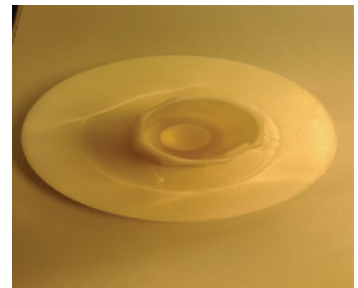
Symptoms of stress cracking generate failures when using the pieces.



I received samples of parts which seem pulleys and a phone number to contact for getting more information. Someone decided to replace a metallic drive pulley with a plastic one made of natural ABS unfilled.

The selection of material, in my opinion, was not correct. But it was the client who chose it, and some pieces broke after few uses. According to the customers, with whom we had a conversation, product users complained about breakage of pulleys.

Since breakages have a bright section, I concluded that the crack could be due to stress cracking (ESC). Such breaks are shiny and not whitish, as it should be normal in an ABS.



Stress cracking (ESC) is due to a combination of two factors: at first, a tension in the material must exist (either due to injection of the part, its assembly, or its use); and, furthermore, a contact with an active chemical medium must exist too. This chemical etching creates small microcracks or crazes, which later degenerate into cracks. In this case, etching may be due to the use of lubricating oils or lubricants greases in the pulley system.

26.2.1 Radii

Additionally, I observed the absence of radii at the intersections of the different walls. The presence of sharp edges results in increased tension, shear, and molecular orientation during filling, in addition to stress concentration at the time of subjecting the parts to effort.

A handy way to see if the radii are present involves passing a ball pen tilted about 45 degrees. If two parallel lines appear, there are no radii. If there is a single line at the top, the radius is correct.

In this case, the radii were insufficient.

Finally, given the fragility of some parts, I decided to check their MFI to compare it with the original. Comparing the MFI of the injected part with the value of the pellets, we can determine the degree of molecular "aggression" applied during the transformation. Differences with values of the order of 40% are quite common in injection processes. Higher values indicate excessive degradation.

In this case the differences were of the order of 100%, indicating an aggressive process. These differences could be also related to inadequate drying, since moisture in the pellets causes the increase of MFI, plus incorrect mass temperatures, excessively high residence times, and sharp corners.

Advice:

- Use lubricant grease or oils that are compatible with the polymer used
- Manufacture molded parts without stress. With this purpose:
 - Use the adequate melt temperature as recommended by the manufacturer
 - Minimize residence time of the material in the injection unit
 - Dry the material properly

26.2.2 Material Selection

If the stresses exceed the strength of ABS, it shall be broken without remedy. If it is possible to know the stresses applied, we can find a material that brings us a safety margin during its use.

In summary	
Problem	Broken parts during use Material: ABS
Causes	Stress cracking No radii Polymer degradation
Advice	Replace chemicals Apply radii Change melt and dry temperatures

26.3 Broken Gears



 The absence of radii, a careless dehumidifying, and the low crystallinity of the material obtained in injected parts causes brittle fractures under stress during use.

I received several parts with visible breaks. I started watching the pieces for possible problems. They were mechanical parts used in gears, with a central housing for a square shaft. I applied a flame to try to identify the type of material and I got a strong scent: it smelled similar to a “burning horn”. When the piece burned, it formed dripping threads. It was made of polyamide (PA).

I also noted bursts and microbubbles in the surface of most parts received. Some had pores or vacuoles in the section break. I also saw the remains of a direct gate. All pieces had a very pronounced weld line in front of the gate.

Possible Causes of Brittleness

The samples indicate that the dehumidifying was not enough. There are traces of humidity everywhere.

The central core, squared, is not radiated on the front side, where it meets the bottom wall of the piece. This generates shear and accumulation of stresses. I

passed the pen on the radii and could clearly see a double line, indicating the absence of radius.

I observed two types of gate: a submarine and other direct by piece. If both work separately and individually, they are not sufficient to fill and package the part.

Advice:

- Dry the raw material (in this case PA) at 80 °C for 12 hours.
- Increase the mold temperature for maximum crystallinity of the polymer (80 °C would be suitable). This would provide more and better mechanical properties.
- Humidify or condition the parts and prepare them before including them in the assembly step. PA parts have to be conditioned to reach their equilibrium of humidity absorption, to achieve the properties of use.
- Radiate cores in the central square of the base, where it meets the wall of the part.
- Increase direct gate in order to compensate the shrinkage that promotes the internal vacuoles.

In summary	
Problem	Broken parts during use Material: PA
Causes	Mold temperature No radii Irregular drying Gate with incorrect dimensions
Advice	Increase mold temperature Apply radii Correct and proper material drying Increase the gate dimension



26.4 Unfilled PC Cover

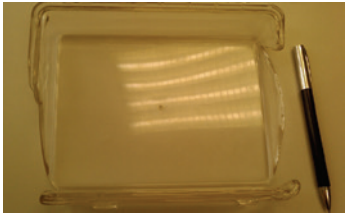


Improper thickness of the wall connected to the gate prevents the proper filling of the transparent PC sheet.

In this case, the problem was in a transparent cover made of polycarbonate (PC). The filling of the cavity was hard and flow lines and corona effect (see Chapter 15) were seen in areas far away from the gate.

After cutting the piece, I noticed that the wall where the gate is located (this is in the center of the part) was too thin (1 mm) in relation to the perimeter side walls (4 mm), rather thick.

The “thick to thin” rule is not observed in this case. Neither has been included a semi-spherical facilitator flow in front of the gate. This simple mechanization



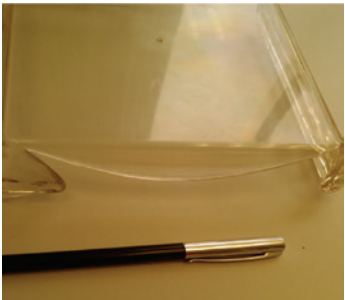
facilitates filling, especially at first, and minimizes friction and shear near the gate.

The gate is too small for the volume and section of the part. If we double the gate section, we quadruple the volume that can pass through it.

It is recommended that the wall connected to the gate should be the thinner wall of the part. Flow restriction prevents the filling and holding pressure of the cavity in the thicker areas.

Advice:

- Review design to increase the thickness of the wall connected to the gate
- Warm the mold (PC can be worked at 90–100 °C)
- Have a facilitator flow in front of the gate
- Increase the gate section for easy filling and packing of the cavity
- Use a more fluid PC



In summary	
Problem	Incomplete parts Material: polycarbonate
Causes	Wall design with incorrect gate No flow facilitator in front of gate Gate with inadequate dimensions
Advice	Increase mold temperature Mechanize facilitator for easy filling Increase the gate section Use more fluid material

26.5 Dimensional Instability in Parts





Cavity filling imbalances cause unacceptable dimensions differences in the parts.

In this case, the difficulties encountered to manufacture consistent dimensions in precision parts make it impossible to carry out the work.

During fabrication of a colored transparent polystyrene (PS) ring, the degree of dispersion of the dimension obtained exceeds the specified tolerance for this product. The tolerances for these products are very low and cannot stabilize the dimensions variation range.

After a meeting with the customer, I visited the injection plant to observe the full injection process. The three plates mold has eight cavities. Such a high number of cavities is not recommended when one wants to make very high precision parts.

I decided to measure the parts and analyze the cavity number groups. I saw a significant spread between the parts obtained from different cavities number.

At this point I wondered:

- Is the switching point correct?
- On many occasions this point is not properly programmed, causing:

1. Overcompaction
2. Partial filling of the part during the hold pressure stage, without speed control

- Is the injection pressure limit being reached?

Often, the filling is limited by the injection pressure limit and we have no control of the speed of filling the cavity.

- Does the flow front advance uniformly?

Normally, injection speed profile curves are set flat or with a constant injection volume during all the filling stroke. This causes the flow to accelerate or decelerate according to the sections of passage of the material, runners, etc. We do not control the flow front speed.

- Is the hold pressure time right?

Normally, this time is set depending on the weight (there are two limits) or depending on the part (dimensions, flashes, grips, etc.), or when the part fails to gain weight. We should not make perfect runners by increasing hold pressure time, cycle, or energy expenditure.

- Do we want to switch to hold pressure stage by hydraulic pressure?

Normally, this system is not too used although it is the most reliable (outside the cavity pressure switching) and is available in almost all current standard machines. We must make better use of available technology in factories.

We make a start from zero, following these steps:

Injection Pressure Limit

Set the pressure value above the real pressure needed to ensure that we do not limit the injection process. There is nothing worse than a pressure-limited process.

Holding Pressure

Set the hold pressure time and hold pressure to zero.

Switching Stroke

Set the switching point close to the dosage point in order to inject a little injection volume in the cavity. We want to fill only a small amount of the part.

With these premises, we can start the progressive filling of the cavities.

During filling, we modify the switching point position to inject a greater quantity of material in each cycle. Suddenly, we find that certain cavities are completely filled while others are not. The eight cavities have not been filled in a balanced way. The probable cause is the small differences in gates and/or runners channels, in addition to the “spiral” effect. Here we identify a cause of the spread of dimensions between cavities.

We cannot obtain narrow dimensional tolerances in an unbalanced mold during filling.

After obtaining the correct switching point position, we proceed to pressurize and pack the cavities. We use the gate seal analysis. First we select a hold pressure time excessively overrun, which ensures that the gate will be closed or sealed and a low hold pressure level.

We increase the pressure values until the pieces are aesthetically and dimensionally correct. At this point we have an excessive holding pressure time, which ensures the gate seal. Then we weigh the injected parts without runner and we gradually reduce the holding pressure time, controlling the weight of each shot.

There will come a moment when the weight will decline. This indicates that the gate was not sealed. So we increase in the previous the step holding pressure time, 1 second or so, and ensure the sealed gate with the shortest hold pressure time possible and, therefore, the optimum time.

Finally, we decrease the pressure injection limit to a value slightly above the necessary real filling pressure. In this way we ensure that it does not interfere with normal filling cavities, and it becomes a security element to any clogged or closed cavity.

With these steps, the dimensions of injected parts are dimensionally repetitive and consistent and will be dimensionally stable although the cavities filled first are bigger. To eliminate this last problem we have to ensure that the dimensions of channels and gates are identical.



Hold pressure

Key points:

1. Do we work with a sealed gate or with an open gate?
2. How much time will be set in hold pressure stage?
3. How much hold pressure will be set?

Points 1 and 2 determine if we work with sealed or open gates.

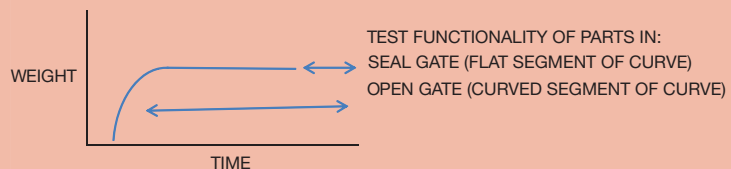
1. Place a hold pressure time much longer than necessary to seal the entrance

2. Start with a low hold pressure and gradually increase until the piece is OK. This pressure is to study the sealing time of the gate. It is not the pressure with which we will work

3. Weigh the part

4. Gradually reduce hold pressure time and weigh the part until we have 0.5 seconds holding pressure

5. Reflect times and weights on a chart



Sealed gate processes are better and more stable.

Advice:

- Match and balance filling between cavities; adjust gates and channels if necessary
- Change the injection process for an optimum hold pressure time with sealed gate
- Adjust any cavity if it is outside the tolerance range

In summary	
Problem	Process with little robust dimensions Dimensional instability
Causes	Cavity unbalanced Unoptimized hold pressure
Advice	Balance filling between cavities Set post-pressure correctly Work with sealed gate

26.6 Insufficient Filling



A change in the polymer used may hinder the filling of the cavity.

In this case, the part was made with a blend of PC-ABS. This blend is a material of high/medium viscosity. The flow path respect to the average thickness of the part was quite unfavorable. The average thickness of the part was 2.5 mm.

Looking at the gates, two submarine gates of small dimensions were connected to the rear walls. These walls were too thin.

In this case there had been a change of material. Previously, the material filled perfectly with this mold. The filling problems began when it was replaced by the new blend.

Given the large difference in viscosity between the two materials, it was necessary to review and modify certain aspects of the mold to properly fill the cavity.

Although the value of the MFI in each case is important, it can lead to certain errors. For example, if we look at a PP and a PC with a melt index of 4 g/10 m, this does not mean that we can fill the same cavity with both materials. In the case of PP, its viscosity may decline by a factor of 100 because of the shear rate, and, in the case of PC, the viscosity can be reduced by only a factor of 5.

Advice:

- Modify distribution channel, increasing the section
- Increase the section of the runner and submarine gate
- Increase the gate section
- Increase rear walls section connected to the gate



In summary	
Problem	Incomplete parts
Causes	Gate and runner channel dimensions not adequate for this kind of material
Advice	Modify runners
	Modify gate
	Modify thickness of walls attached to gate

26.7 Several Problems with Polycarbonate



An incorrect mold design and the neglect of the recommendations applicable to the plastic material cause many problems in parts made of polycarbonate.

26.7.1 A Plastic Chair Full of Problems

26.7.1.1 Concentric Circular, Dark Area around the Gate

This problem is due to the degradation of the dye or color masterbatch. Excessive melt temperature or too long permanence time of the material in the injection unit may cause this problem. An appropriate melt temperature must be used as well as a suitable masterbatch for PC.

26.7.1.2 Weld Lines in the Back Chair Grill

This is an inevitable defect because the flow front of the material has to surround the cores that make the grill. This material's weld lines will be pretty much visible depending on the speed and temperature of the various flow fronts. The weld lines will be less visible the greater the temperature and speed, but they will not disappear. It is also important that these weld lines areas have good venting to prevent air entrapment.

26.7.1.3 Marks in the Cavity Gate

Defect caused by a zone of high temperature and shear. The angle of greater cone diameter of the sprue must have radii and use an injection speed profile that starts with a slow filling.

26.7.1.4 Streaks

Defect caused by humidity of the pellets. By looking under a microscope, moisture is observed throughout the piece. PC must strictly dry at 120 °C 4–8 hours after mixing and blend with the masterbatch of color. The purge of material must be clean and bright, free of bubbles, without air explosions. Do not use suction and ensure the necessary back pressure to avoid trapped air. (See Chapter 25.)

In summary		
Problem	Parts with dark streaks Parts with streaks	Parts with sink marks Parts with weld lines
Causes	Insufficient drying Improper masterbatch	Improper gate design Improper insert reinforcements' design
Advice	Rigorous drying of PC Use masterbatch with carrier PC Radiate gate area	Modify insert reinforcements' design Increase mold temperature to 70–90 °C Improve venting in the joining zones

26.8 Support Breaks



The demolding draft angles, the radii, and the polishing done in the ejection direction of the part facilitate and reduce the ejection stress in the part and in the mold.

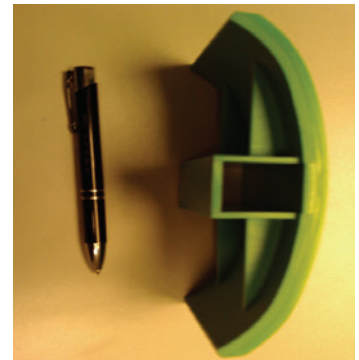
In this case, a problem with a colored POM support had been detected. The parts had significant marks near the gate and breaks in walls and rear ribs.

Checking the pieces I saw some details that should be improved. The design had many sharp corners. In the semi-crystalline materials, sharp corners produce shear during filling and stress concentration. We must always avoid them.

By measuring and checking the draft angles (conicity), I found that they did not exist in the walls and rear ribs. It is necessary to give adequate conicity in each case, to avoid overstressing at the moment of ejection of the pieces. The mold cavity surface was not polished work could be seen; the steel surface finish was from the machining tool.

From the marks on the surface of the piece, small microcraters, it could be inferred that either the material had high viscosity or, most likely, it had been injected when the mold was cold.

For semi-crystalline materials, the mold temperature regulates the cooling rate and hence the final crystallinity and mechanical properties of the part. In these



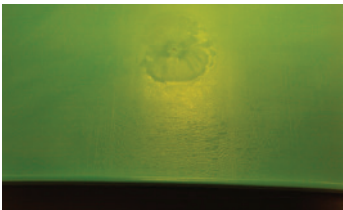
cases we should use the mold temperature recommended by the manufacturer of the polymer (POM: usually 80–100 °C).

The marks around the gate indicate flow restrictions. This defect is produced by a stress in the newly created cold layer. This stress becomes so high that it breaks the cold layer by stretching and material emerges from the molten core again. To avoid this effect it is necessary to increase the gate.

The dimensions are: gate thickness, 3.8 mm; gate section, 1.3 mm.

POM

- Subrunners should be 1.5 times the thickness of the part.
- High speeds produce higher gloss surfaces; slow speeds, more matte.
- If the mold temperature is low, the parts will be more amorphous. If the mold temperature is high, the parts structure will be more semi-crystalline.
- POM does not need large runners but large gates (90% of the part thickness).
When the part burns due to diesel effect, it burns white.

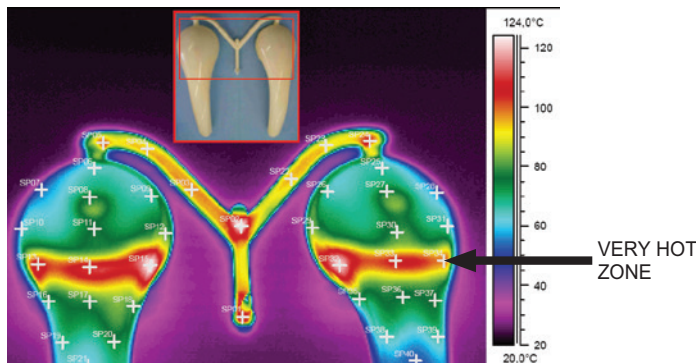


Advice:

- Radiate sharp edges on walls
- Polish walls in the pull direction
- Apply draft angle
- Temper mold at 80 to 100 degrees
- Increase gate section

In summary	
Problem	Breakages in the rear ribs of the part POM-made part Bad aesthetic appearance of part Defects near the gate
Causes	No radii Neither polishing nor draft angles Cold mold temperature Wrong gate dimensions
Advice	Radiate Polish and apply right draft angles for demolding Temper the mold Increase the gate dimensions

26.9 Deformation of ABS Part



An unsuitable design and uneven cooling generate differential shrinkages and deformations.

Parts could not be assembled due to the ovality caused by deformation of the water diffuser's round sealing area. This ovality is produced by a differential shrinkage in the critical diameter. Since a wall of the critical diameter is attached to the body of the part, this body retains shrinkage, generating a resistance to the overall shrinkage. This phenomenon causes a differential shrinkage. But there is more ...

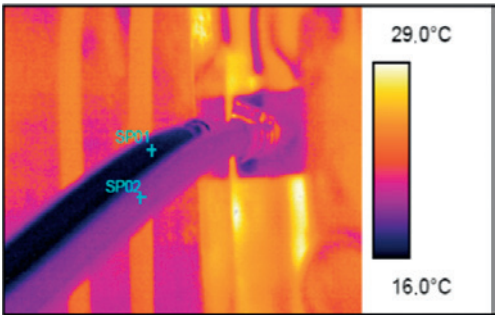
Once a thermographic analysis of parts and mold was made, we could see that a thermal differential of 60 °C was generated in areas with mass accumulation where the mold cooling was not optimal. This inevitably generates differential shrinkage and internal stress that will be frozen, but will be released over time and the subsequent processes where temperature will be applied.

The effectiveness of the cooling system is determined by the smallest diameter of the restrictions. Direct input and output water lines are better than a lot of tubing hoses connections. Temperature differences between the input water line and the output water line (which should be no greater than 3–5 °C) create hot sections in the mold as well as shines and deformations in the parts. In the cooling system, if we double the tube diameter, we quadruple the flow. We must obtain a turbulent flow; it transfers up to four times more heat than laminar flow.

Given the importance of the cooling system connections, this should be done in a way such that it will not be necessary for a qualified plumber to take care of the connections or in every mold setting, or in each production shift, make and “invent” a new connection system. We should document all the connections as well as input, output, flow rates, and temperatures, so that anyone can track the information and carry out the appropriate adjustments. Do it for dummies! This is especially important when there are a lot of cooling channels in big molds.

Advice:

- Revise mold design, cooling system to optimize cooling of critical areas
- Once cooling has been optimized, define standard ovality caused by part design
- Compensate these differences in the mold, modify mold dimensions (provided that these are repeated)



In summary	
Problem	ABS parts deformed Deformations in the sprayer adjustment seal ring Ovality
Causes	Thermal differences in mold Thermal differences in part
Advice	Improve cooling in critical zones Modify mold to adapt real shrinkage Document and identify the cooling systems of molds, in/out water lines' temperature, etc.

26.10 Bimetallic Effect

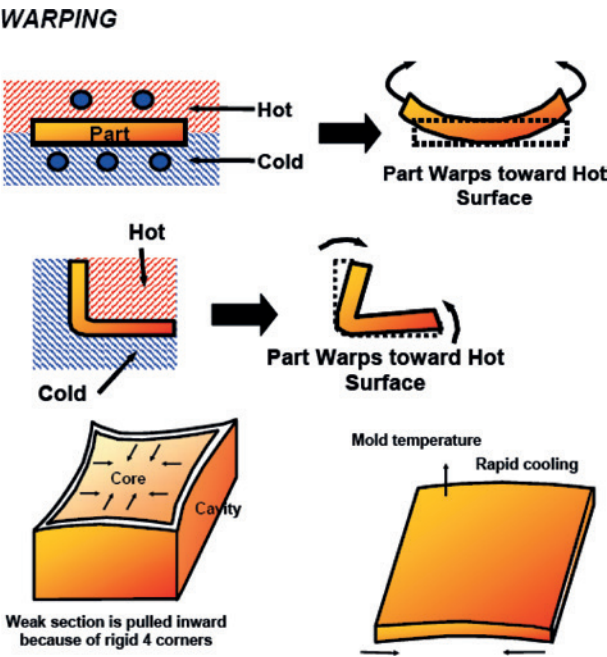


Figure 26.1 Warping; source: DuPont

The differential effect of temperature may help to correct slight deformations caused by differential shrinkage or controlled warping.

Apparently, the new mold designed for a new project did not make it possible to produce the right parts (a chrome lettering for a well-known car model).

These pieces are fixed to the car by an adhesive layer. In this case, the lettering had to be mounted on a metal sheet having a certain radius. The part had to fit perfectly to the radius of the sheet to avoid a permanent stress of the adhesive layer film and prevent the lettering from being unsticked or ripped out.

The parts were flat when leaving the mold, and recovering from shrinkage and post shrinkage. In the worst case, the deformation was the opposite of the desired. The parts were flat because the mold was made with the flat shape.

Faced with this problem, we successfully applied the bimetallic effect, heating more the half-mold on the side that the part must bend more and, thus, obtaining a certain degree of controlled bending. This system produces certain stress levels in the part but in a controlled manner.

The other option would be to make a new mold with the correct radius!

On another occasion, a transparent glass PMMA part had to be assembled in a car instrument panel by snap fit system. Naturally, the glass PMMA part should be adapted perfectly to the housing to prevent annoying sounds inside the cockpit. However, the radius of the PMMA part after post-shrinkage, was not perfectly suited.

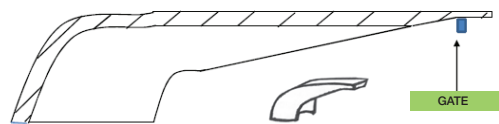
To achieve this, the bimetallic effect was applied by controlling the temperatures of the two mold halves, so that the differential shrinkage brought us parts with the desired radius.

Advice:

- Control differentiated temperatures in both semi-molds to force shrinkage on one side

In summary	
Problem	Required part shape radius is not obtained
Causes	Unfavorable differential shrinkage
Advice	Control temperature in both mold halves Apply bimetallic effect to compensate shrinkage on the desire part side

26.11 Hesitation Effect (Flow Stoppage)



 The differences in thickness can stop the flow at certain times. This stoppage is critical in parts which need a further finishing, since the subsequent filling generates irremediable stresses.

This time, the ABS-made parts did not pass the approved stress tests and the customer had complained about the numerous aesthetic defects. As the defects appeared near the gate, we decided to check and review the filling to locate the cause of failure.

With this purpose:

- We removed the post-pressure (switching it to zero)
- We removed the holding pressure time (switching it to zero)

Thus, we saw if the set switching point was correct. In addition, we made a progressive filling to see the flow path during the cavity filling. We placed the switching point close to the dose and we filled the mold step by step, from the runner to the part, gradually moving the switching point.

When we had 20% of the full part, we noticed that the filling did not grow on a regular basis in the thinnest area next to the gate. The melt material always tended to go for the easiest way.

We continued with the filling, noticing that the flow did not grow on the thin side, but on the thickest part. Finally, with the cavity filled, we noticed that the area next to the gate was still unfilled. At this point the flow had stopped at the thinnest area.

We applied the hold pressure and we achieve the full cavity filling at last.

The flow was stopped during almost all the filling stage. The filling was fully completed only when the hold pressure was applied.

Filling the part in these conditions creates stresses. These stresses appear in subsequent tests, use, and eventually in surface-finishing process (painting, chroming, etc.), in which the surface is attacked in a controlled manner. In this case, residual stresses cause aesthetic defects.

Advice:

- Increase the thickness of the thin zone not to stop the flow
- Increase mold temperature to facilitate the filling
- Use more fluid material
- Increase injection speed filling

In summary	
Problem	Aesthetic defects caused by tensions ABS-made parts with subsequent surface-finishing, painting, chroming, etc.
Causes	Excessive difference in thickness causes the flow front in the thin zone to stop
Advice	Increase of thickness in critical zones Increase of mold temperature Increase of injection speed rate Use material with higher melt index

26.12 Gloss Caused by the Glass Fiber Reinforcement



High aesthetic requirements in glass fiber-reinforced materials: a difficult but possible challenge.

In this case, the goal was to obtain in the molding part a high aesthetic surface quality that avoids a subsequent painting process. We looked and checked on the molding floor, mold, machinery, material, etc. The injection speed was extremely slow for a material with good flowability.

I proposed to increase the injection speed from slow to medium profile, but ... surprise! It caused flashes in the ejectors pins and slides. The set injection speed was too slow and we had discovered why.

In glass fiber materials with aesthetic requirements, the key points are:

- Medium/high injection speed
- High mold temperatures

For example, PBT and PA require mold temperatures of at least 100 °C.

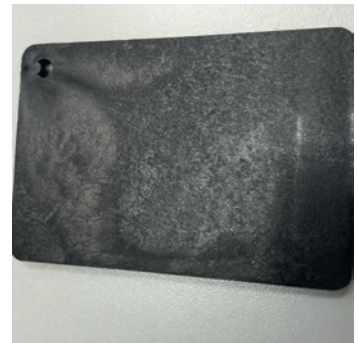
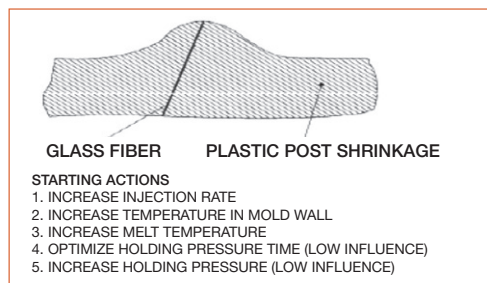


Figure 26.2 Reinforcement fibers visible on surface



A significant mismatch in the mold forced to inject at low speeds, which affected the surface and aesthetic aspect of the parts.

Flashes were caused by not properly dimensioned venting channels, practiced with excessive depth (remember the recommendations for venting). Flashes were due to the depth, and not to the width of the venting channels.



The importance of a good venting system in the mold ... and the runners?

In this case, the customer also rejected the parts due to dull spots that appeared in areas where air was trapped. Before the Diesel effect (or burns in the molds) occurs, the lack of air causes other defects.

Symptoms of poor venting:

- 1st phase: matte surface
- 2nd phase (worsening): appearance of grain, graining, and peaks
- 3rd phase: burns

Depending on the level of ventilation, we can find in the molding shop any of these three phases.

Advice for a proper aeration of molds:

- Venting channels: some mold-makers perform mirror polishing in the venting channel so that they are self-cleaning. The absence of roughness in the channel prevents the adherence of the monomer residues and the volatile substances from the pack of additives are carried by the gases when coming out.
- If the land channel is excessive in its most critical area, the steel can flex and partially shut off the flow of the gases. In addition, volatiles transported by gases leave residues more easily on their way to the atmosphere. The depth of the ventilation channels, not the width, generates flashes on the parts.
- In the parting line, it is recommended to have a gas output venting every 25 mm. 20–30% of the parting line must be ventilated.
- Runners also must be ventilated in each 90-degree turn. The depth of the venting outlet may be higher in this case, since it is not a critical zone for the formation of flashes. Runners ejectors should also be ventilated.

Polymer	Easy flow (mm)	High viscosity /Glass-filled
ABS, SAN, HIPS	0.0508	0.0762
POM	0.0127	0.0381
PMMA	0.0508	0.0762
CA,CAB	0.0254	0.0381
PA 66	0.0127	
PA 66 15% FV	0.0127	0.0381
PC	0.0381	0.0762
PE	0.0254	0.0508
PP	0.0254	0.0508
PPO	0.0254	0.0762
PPS	0.0127	
PSU	0.0254	
PS GP	0.0254	0.0508
PVC	0.0254	0.0508
TPU	0.02	
PBT	0.03	
PET	0.02	
PPA	0.015	

Advice:

Matte areas indicate the first signs of lack of ventilation. A proper venting system, increasing the number of venting channels and dimensions in critical areas, was made, and the venting problems disappeared.

In summary	
Problem	Matte spots Poor aesthetic quality caused by glass fiber outcrop
Causes	Poor mold venting Not optimized cooling
Advice	Increase gas venting Follow venting rules Change injection speed Increase mold temperature Use fiberglass and glass microspheres

26.13 Pressure-Limited Process: Always a Mistake to Avoid



This situation should be avoided always, especially when we want to have a controlled, consistent, and high-quality process.

In this case, the laboratory mechanical tests in order to homologate a lever gave as a result a high percentage of broken parts. Starting mass production was impossible.

When I looked and analyzed the broken parts under the microscope, I noticed the presence of some internal micropores in the broken areas. These pores weaken the structure, since they reduce the homogeneity and act as stress concentrators. They also rarely have rounded shapes, but have edges, which contributes to the formation and initiation of cracks.

What causes this internal micropores? In my opinion, probably a poor hold pressure phase causes this internal shrinkage.

The process engineers told me that “increasing the injection speed did not appear to have an impact on a greater pressurization of the cavity”. They also claimed that “the injection speed did not reduce the filling time nor increase the cavity gate seal time”.

The key was in the injection graphs on the machine computer, when I saw the real injection pressure and speed graph appearing on the screen. The obstacle for process engineers to improve this process was that they had set a pressure-limited process.

We were facing what is called a “pressure-limited” process. This type of process causes problems of lack of control, consistency, and productivity.

Figure 26.3 shows the graph of hydraulic injection pressure.

The injection pressure is in fact a limit pressure, not a process pressure. To meet the set speed, the machine will use the appropriate pressure as a function of the effort required to move the screw at this speed. The machine will use the required pressure according to the desired speed (whenever, of course, it is not limited).

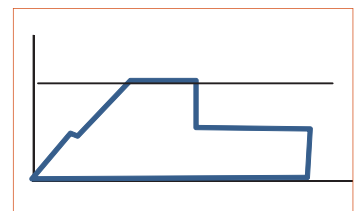


Figure 26.3 Example of limited injection pressure graph

In a pressure-limited process, we prevent the machine to “self-regulate” during injection. The machine will not face any pressure increase caused by a change in viscosity of the material. Neither a speed change will be possible because it involves a higher pressure. As can be seen, the process is limited.

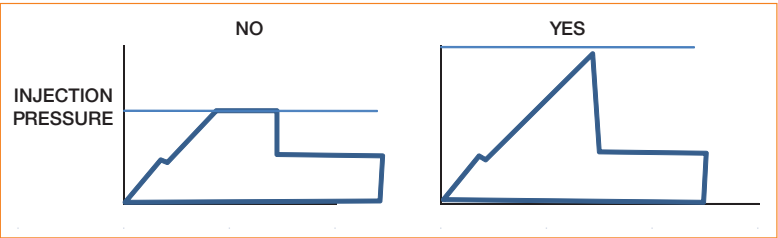


Figure 26.4 Limited and not limited injection pressure: comparative graphs

To avoid this mistake, in the first mold setting operation, we have to define an injection pressure limit higher than that required for filling the cavities. In this way we ensure that we are not limiting the process. Thus, speed increases could not be met by the machine in this case.

When we increased the injection pressure limit and the real injection pressure became “free”, the filling time was significantly reduced, the cavity pressure in the switch point to hold pressure increased, and the efficiency of the hold pressure stage was also much more effective. Thus, the internal pores disappeared and the parts passed the mechanical tests.

In a pressure-limited process, we have no control over the filling speed, neither on the dimensions and properties of the parts.

Moreover, the nozzle of the machine used in this hot runner mold had an inner diameter of 4 mm. Since the hot runner flow tube was about 10 mm, I proposed increasing the diameter of the nozzle to prevent pressure drops in this area. The diameter may be as large as the diameter of the hot runner.

The restriction in the nozzle diameter, smaller than the diameter of the hot runner, generates restrictions which usually force to inject with higher melt temperatures than those used with the correct diameter nozzle and a diameter adapted to the hot runner in flow channels.

Advice:

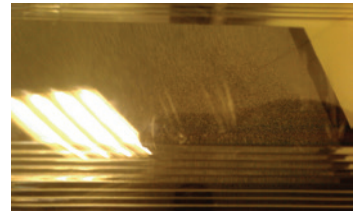
- Increase injection pressure limit and adapt injection speed to the requirements of filling cavities
- Check that the nozzle diameter is equal to the diameter of the hot runner flow tube to avoid restrictions and pressure drops

In summary	
Problem	Parts with pores do not pass mechanical tests
Causes	Poor cavity pressurization due to the limited injection pressure
Advice	Increase the limit of injection pressure to avoid restrictions
	Adapt filling speeds
	Increase the nozzle diameter to be equal to the diameter of the hot runner

26.14 Streaks in Transparent Polycarbonate



Transparent parts are always problematic. If, moreover, they are made of polycarbonate, problems grow.



In this case, streaks detected in a part made of polycarbonate prevented a normal part production.

Streaks are usually due to:

- Insufficient drying or dehumidifying of the material
- Insufficient or no back pressure
- Use of suction
- Inadequate gates
- Inadequate nozzles
- Use of an inadequate machine for a long permanence time or an inadequate screw diameter/dose stroke ratio

26.14.1 Dehumidifying

Polycarbonate requires very precise and proper dehumidification conditions: 120 °C for 8 hours. The temperature/time ratio is very important. Although the temperature is increased, the time cannot be reduced and vice versa.

In the graph in Figure 26.5, we can see that the material dried at 80 °C will never achieve the required level of moisture (0.05%). This rate can only be achieved at 120 °C and for the time indicated.

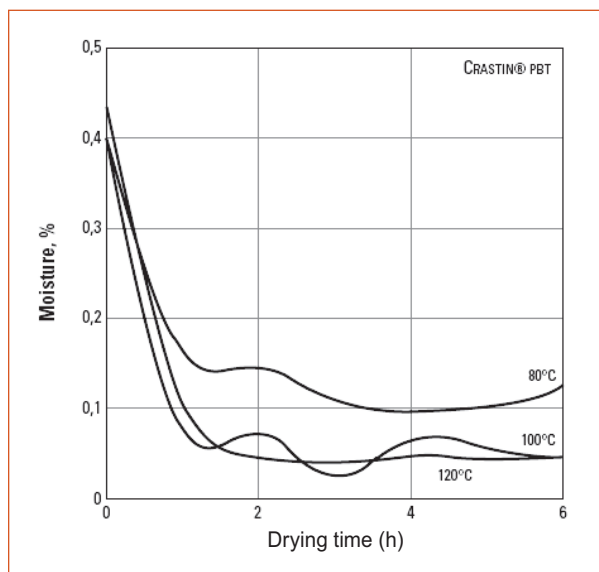


Figure 26.5 Percentage of moisture evolution in PBT with different temperatures and drying time; source: DuPont

Dehumidifiers must be kept in good condition to work properly. Change filter elements, silica, etc. every 18 months maximum.

The dew point temperature is that at which the air condenses the water contained. The lower the dew point temperature, the smaller the amount of water that can be contained in the air. Therefore, it is recommended at least -30°C .

26.14.2 Back Pressure

Back pressure is needed to homogenize the mass, to generate heat energy by shear melting the material, and to prevent air trapped with the pellets at the entrance of the screw from advancing with the molten mass to areas of plasticization and thus finally to the part.

In this case, however, we had to dismiss this cause, since the values used prevented this from happening.

26.14.3 Suction

The suction at the end of the dosage stroke should be discarded in the processes where materials are sensitive to air and moisture. Although the injection unit is supported against the mold, the suction movement introduces air from outside into the molten material in the front of the screw. The molten plastic is highly sensitive to moisture and air, and the device formed by the nozzle and the mold is not airtight.

26.14.4 Gate

After checking the gate, we got the following values:

- Part thickness: 3.2 mm
- Gate depth: 1.5 mm
- Gate length: 38 mm
- Fan gate thickness: 4 mm
- Diameter of hot runners input: 3.8 mm

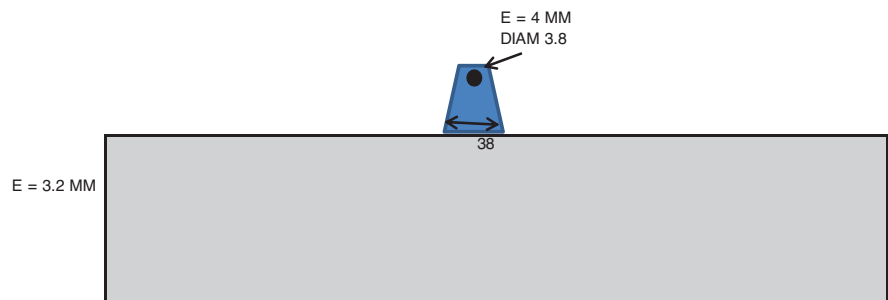


Figure 26.6 Gate dimensions recommended for this part

Polycarbonate is a viscous material and requires a gate section equivalent to 90% of the part thickness. In this case, 90% of 3.2 mm is 2.8 mm instead of 1.5 mm.

The gate length is correct.

Remember that the depth determines and controls the gate sealing time. The width determines the volume to pass through the gate. The length (or land) must not exceed 1 mm.

The diameter of the injection nozzle inlet connected to the gate fan is another factor to check. In this case, the diameter is 3.8 mm and we do not know if behind it, in the hot runner nozzle, there may be any restriction or any area which will generate the dangerous “cold drop”. However, the diameter is 2.8 mm and could be increased to at least 4 mm.

The machine nozzle should be equal to the diameter of the flow tube in the hot runner to avoid unnecessary restrictions and shears.

Finally, we checked the residence time and the rate of use of the injection unit and compared with the screw diameter and the dose stroke used. The results are both correct.

Some defects caused by the gates are usually:

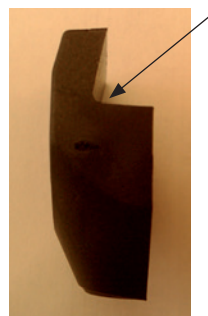
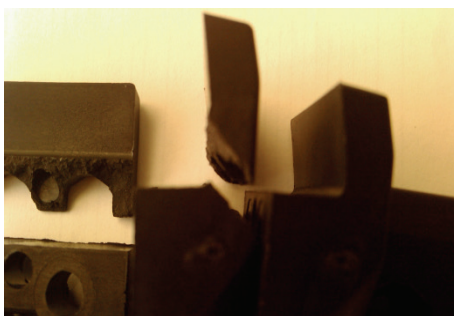
- Blush: the material is freezing prematurely (therefore, we probably have small gates).
- Too high shear in the gate area
- Splay: silver marks, symptom that the land is too big

Advice:

- Modify gate section and inlet diameter of the hot runner nozzle
- Make a more rigorous material dehumidification

In summary	
Problem	Streaks in transparent parts
Causes	Inadequate gate Possible not rigorous drying
Advice	Modify gate (more depth) Rigorous drying in dehumidifier Increase nozzle diameter

26.15 Polyamide Parts Cannot Withstand the Assembly Stress



The parts without adequate gates cannot withstand work stress.

An L-shaped support bracket, made of PA 6 and 30% fiberglass reinforcement, was broken through the 90° vertex angle when subjected to stress.

The mold was a four-cavity mold with cold runner and submarine or tunnel gates. I checked the nozzle, channels, sprues, nozzles, and venting system.

The thickness of the wall connected to the gate was 3.8 mm and the gate section was 1.2 mm. Regarding the optimization gates system, polyamide with fiberglass requires a gate with a diameter equal to 80–90% of the wall thickness. 90% of 3.8 mm part thickness results in a gate diameter of 3.4 mm.



	Depth gate (%)		Subrunners
ABS	60	ABS	2
SAN	60	SAN	1.5
ASA	60	ASA	1.5
POM	90	POM	1.5
PS	75		
PP	50	PP	1
PE	50	PE	1
PA	50	PA	1
PC	90	PC	2.5
PA filled	90%	PA+FV	1.5
ABS PC	90%		
ABS IGNIF	90		

For PA+FV, the runner that feeds the gate must be 1.5 times the thickness of the piece:

$1.5 \times 3.8 \text{ mm}$: the section of the channel is 5.7 mm.

The next runner (in this case the main runner) should be the sum of the above plus 0.6 mm:

$5.7 + 0.6 \text{ mm} = 6.3 \text{ mm}$

The sprue O diameter should be the subchannel plus 1.2 mm:

$6.3 + 1.2 \text{ mm} = 7.5 \text{ mm}$

The diameter of the machine nozzle must be 10% less than the sprue diameter:

$7.5 \text{ mm} - 10\% = 6.75 \text{ mm}$

The key point to properly pressurize the filling system, runners, and the sprue is that the sprue diameter should be the widest in the system. In a balanced filling system, the greater thickness should be the diameter of the sprue; then to the main runner; later, the subrunner, and so on.

To successfully pressurize a main runner of 6 mm, the diameter of the sprue should be 8 mm. If there are no differences between the runners and subrunners section, there will be pressure losses in the runner and the system will not be properly pressurized. Finally, the diameter of the injection unit machine nozzle must be 10% smaller than the diameter of the sprue.

When checking the runners, I could see that the residual traces in the sprue indicated that the nozzle diameter used was 2.5 mm.

The nozzle diameter is a clear restriction for the system. Furthermore, in materials with glass fibers, such restrictions produce a significant reduction in size of the fiberglass reinforcement and therefore of the mechanical properties.

To corroborate this loss of properties, we can conduct an MFI of the virgin pellets and another of the injected parts because this analysis has a direct relationship with the molecular weight, the size of the molecular chains, and the dimensions of the loads or reinforcements. The injection process is always aggressive with the long molecular chains of the plastics. Therefore, it is assumed that after the injection process a loss of molecular weight occurred and thus an increase in the fluidity of the polymer. This difference in polymer flow can indicate the level of damages incurred during the process.

In many cases, a proper configuration of gates, runners and sprue, as well as of the diameter of the machine nozzle, allows the use of lower melt temperatures and cycle time improvements.

As for our problem, the unfavorable fiber orientation with respect to the stress should also be taken into account, since the gate is placed in the most unfavorable direction with respect to the area of greatest stress during the assembling and use of the part (the 90° angle).



26.15.1 Gates

The main gate dimensions are:

- Depth: the gate freeze time is controlled by the depth
- Width: the injection flow is controlled by the width
- Length/land: it is the connection area between runner and cavity. When the land is longer, there may be streaks and flow lines

Depth		
Easy flow	50% E	PP, PE
Medium flow	75% E	ABS, SAN, ASA
Heavy flow	90% E	PC, PO, PPO, PA filled

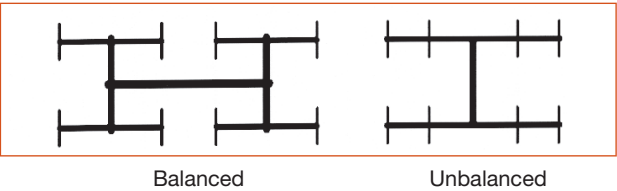
Width	Equivalent to gate depth for small parts Two times the gate depth to medium pieces Three times the gate depth for large pieces
Land	= 0.5 times the gate depth for small parts (0.75 mm max.)

In summary	
Problem	Broken parts when subjected to stress
Causes	Fiber's unfavorable orientation Fiber breakage caused by shear Gate and distribution runners system not optimized
Advice	Modify gates and runners Modify nozzle and sprue diameters

26.16 Unbalanced Runners



 A balanced filling is essential for a homogeneous quality.



A problem with the filling of the different mold cavities reminds us the importance of balanced or compensated filling in a quality injection process.

The material, during the mold filling and pressurization of the cavities, must do a uniform and balanced filling of all the cavities. Thus, dimensionally homogeneous parts may be obtained. It is essential that the flow paths are equal and balanced in all cavities.

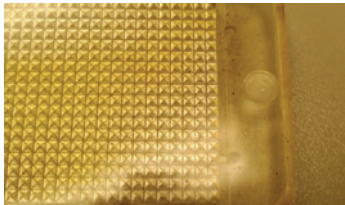
In this case, the distribution channel did not ensure balanced filling. The material filled the most central cavities long before it came to fill the most remote of the central sprue. In addition, the centerpieces were smaller in volume than the rest, worsening the balance.

In this case, the problem is evident, but sometimes imbalances are caused by small differences in gates. To detect them, it is advisable to conduct a progressive filling in the first mold testing, as explained in real case number 5 (Section 26.5).

By observing the flow path of the cavities filling under a specific melt and mold temperature conditions, we can determine whether any gate must be rebalanced for a regular and balanced filling. So, we will have balanced shrinkage and stable and homogeneous dimensions.

In summary	
Problem	Parts with different weights and dimensions
Causes	Unbalanced runners system Improper family mold
Advice	Use mold with balanced runner and filling

26.17 Material Degradation



 Polycarbonate is degraded and charred if the processing recommendations are not followed.

Polycarbonate, like all plastics, is degraded irreversibly when its heat resistance is exceeded. Streaks are the first indication of this degradation. If the situation worsens, brown burned areas will appear, and later, charred spots throughout the piece.

The causes of this degradation of the polycarbonate are usually:

- Excessive mass temperature
- Excessive residence time

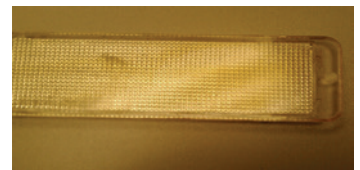
Sometimes it is advisable not to turn off the heaters of the injection unit during rest shifts or during weekends. Keeping a decreasing temperature around 170 °C can help us to boot in good conditions of degradation.

Dehumidifying the Material at 120 °C

Residues in the plasticizing unit caused by degradation and carbonization are difficult to remove, but this can be achieved with some conventional cleaning products. In some cases a PP with fiberglass purge can be performed.

Purge guidelines		
Starting material	Final material	Intermediate material
ABS	PP	
ABS	PSU	HDPE
ABS	PC	Recuperated acrylic
ABS	PBT	HDPE
POM	PC	HDPE
POM	PVC	HDPE
POM	PSU	HDPE
Acrylic	PP	
Acrylic	PA	
ASA	ABS	Recuperated acrylic
ASA	PC	Recuperated acrylic
PE	ASA	Recuperated acrylic
ABS	ASA	Recuperated acrylic
PP	PC	HDPE

In summary	
Problem	Pieces with notorious thermal degradation
Causes	Residence time Excessive melt temperature
Advice	Injection unit cleaning Melt temperature reduction



26.18 TPU: The Unknown Thermoplastic



TPU is a high performance thermoplastic elastomer, but requires a different treatment than other TPEs.

Often, problems related to the TPU parts' manufacture are due to ignorance of the basic rules for the treatment of this material. The design and building of a mold for TPU disregarding specific recommendations for this material can cause serious failures.

26.18.1 What is TPU?

TPU is a block copolymer. Its molecules have a hard segment and a soft segment. The rigid segment is provided by the di-isocyanate and the flexible segment is provided by the polyol. The polyol may be based on ether or ester. The final performance of the manufactured part will depend on the type of base (ether or ester) used.

Ether	Ester
Resistance to hydrolysis	Resistance to abrasion
Resistance to microorganisms	Mechanical properties
Flexibility at low temperatures	Resistance to mineral oils

26.18.1.1 Dehumidification

TPUs are hygroscopic materials that absorb moisture. Their processing requires rigorous dehumidification and proper storage (closed bags, etc.).

Time: 2–3 hours

Moisture: 0.002%

Drying temperature

Shore $\leq$ 90 89–90 °C

Shore $>$ 90 90–120 °C

Machine Recommendations

When screws with long compression areas are used, the material will be deteriorated by shear if the compression mode is suddenly applied. In contrast to other thermoplastic elastomers, TPU does not require shearing during the dosing phase in the plasticizing unit, nor during the filling of the mold and its subsequent hold pressure stage.

An 18/20 ratio L/D on a 20 L/D screw with a seven diameters compression zone would be correct.

Mold Recommendations

- TPU, being an elastomer, has serious difficulties to be demolded, especially with low hardness grades. Sprues with 5–6 degrees of conicity are recommended.
- It is desirable that the mold surfaces are textured with ridges of 25–35 microns.
- Venting must have a depth of 0.02 mm to 0.05 mm.
- The runners preferred shape is a round section, although the trapezoidal section can also be used. The semi-circular or rectangular sections are not recommended.
- Hot runners: hot runners with torpedo not recommended.

- With respect to the gates, TPU presents similar values to polycarbonates (i. e., big gates are required).
- Ejectors must have a slightly larger stroke compared with the ejectors used for rigid materials; thus, the drop is assured. The ejectors with narrow sections, when highly stressed, can pierce or deform the parts.
- Vacuum problems may arise during mold release. To facilitate this operation, we can place runners in the ejectors and even air blowing valves to prevent vacuum.

Process Recommendations

Table 26.2 Mass Temperatures in Plasticization Unit

Shore hardness	Mass temperature [°C]	Nozzle temperature [°C]
60A–80A	170–210	200–210
85A–95A	190–220	205–220
98A–74D	210–230	215–235

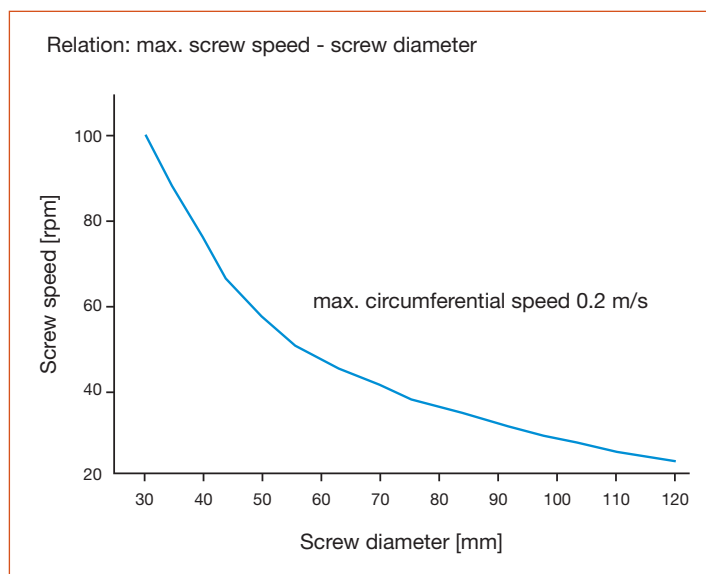


Figure 26.7 Screw max. speed (rpm) according to its diameter; source: BASF Polyurethanes

26.18.1.2 Back Pressure

Values should not be too high to avoid damages. The material is very sensitive to excessive shear.

26.18.1.3 Hold Pressure

Unlike other TPE (thermoplastic elastomers), TPU requires proper hold pressure stage. In the TPU case, we should hold and compensate the loss of specific volume during the cooling and shrinking. The gate must allow this volumetric shrinkage to be compensated, being open long enough.

26.18.1.4 Cooling and Total Time Cycle

The cooling of the material is slow (this is the third significant difference). TPU takes longer than other thermoplastic elastomers to reach the demolding temperature.

Considering the requirements of hold pressure (commented above), the cycle time of a TPU is higher than other thermoplastic elastomers. However, TPUs with nucleating elements and other improvements have been developed and the differences between these and other materials have been reduced.

The most common problems in injection molding parts with TPU parts are usually the following:

The part is not demolded	Treatment of the mold surface (texture: 25 microns) Are air valves or slots in ejectors required?
Runners or sprue remains in the mold	Demolding taper of sprue: 6 degrees Distribution channels with electro erosion finishing
The material does not have consistency	Residual moisture in the material, right dehumidifying
Voids, deformations, sink marks	Hold pressure stage Larger gates
Degradations Gloss, streaks Appearance	Casting with an excessive shear Small gates L/D screw < 20

In summary	
Problem	Some problems with TPU
Causes	Excessive melt temperature, no dehumidification, conicities and surface texture, degradation in screw by shear
Advice	Identify cause and act according on the recommendations

26.19 Bubbles



Figure 26.8 Bubbles



When they appear, it is not easy to determine their cause.

A transparent part made for the automotive sector had internal bubbles. These bubbles, in addition to their aesthetic effect, interfered with light transmission due the internal interferences.

Bubbles, vacuoles, air, gas ... Who is who?

By definition a bubble is “an air globule that forms in liquid and comes to the surface”. In our case, being molten plastic a viscous liquid that freezes, the bubble is trapped inside the parts and cannot come to the surface.

But what are the causes? And, above all, how can we avoid them?

Bubbling does not always have the same root cause; it is due to several causes.

26.19.1 Bubbles Caused by Trapped Air

These bubbles can be caused by a low back pressure, which does not prevent the passage of air between the pellets and the molten plastic in the initial areas of the injection unit. This air moves toward the tip of the screw and therefore the part. In this case, air is often accompanied by streaks because the bubbles trapped between the cold flow skin and the steel mold wall are compressed during the holding pressure stage and explode, generating bursts and streaks on the surface.

These bubbles may also be due to the movement of suction that introduces air into the material dosed to be injected. Also, they are often accompanied by streaks.

The bubbles also may be caused by gases from the melting of the polymer. These bubbles cannot leave the mold due to insufficient ventilation; the polymer surrounds them and thus they remain trapped inside the part. These gases can be produced only by the polymer or aggravated by insufficient dehumidification.

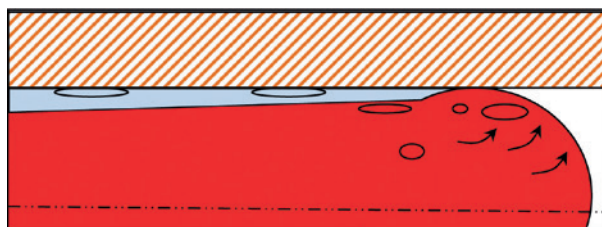


Figure 26.9 Examples of bubbles: when they appear, it is not easy to determine their root cause

Air bubbles travel with the flow, placing themselves on the outside and being trapped in the cold layer, between the material and the cavity.

26.19.2 Bubbles Caused by Vacuum

These bubbles are caused by the uncompensated shrinkage of material. When the volumetric filling of cavities is done, and if the volume loss during cooling is not compensated, a large shrinkage will be produced. This shrinkage may occur deforming the outer walls of the part inward, generating those characteristic sink marks visible outside. This effect can also be produced on the outer walls.

The cold layer may be so consolidated, so consistent, that shrinkage forces cannot cause an inward deformation (especially in rigid materials such as PMMA or PC). In this situation, there is only one alternative, that the shrinkage be released from the inside outward causing visible bubbles in transparent parts, especially in areas of accumulation thicknesses.

Bubbles: how to identify them

Round	They may be caused by moisture.
Elongated	They may be caused by pressure or vacuum.
In the middle of the wall	They are caused by pressure or vacuum.
On one side of the wall thickness	They are caused by moisture.

After identifying the physical cause that produces the appearance of bubbles, removing the problem is much simpler.

Evidently, the eradication of a bubble generated by suction does not have the same treatment as a bubble driven by an excessive thickness whose shrinkage is not being compensated. Sometimes I use a heat air gun, or even a lighter, to determine whether the bubble is produced by air or vacuum. I only have to heat the area of the bubble until the material melts. If the bubble is of trapped and pressurized air, a slight explosion with an unmistakable sound will be produced. If not, this will only melt the material of the part and the problem may be simply due to the presence of vacuum.

In the present case, the bubble did not burst. As it was caused by vacuum, we compensated the shrinkage by increasing the gate.

In summary	
Problem	Bubbles in transparent part
Causes	Thicknesses with uncompensated volume shrinkage
Advice	Identify causes Increase gate to compensate shrinkage

26.20 The Secret of the Night Shift Manager



The required quality was achieved only during the night shift.
What was the secret?

In this case, an urgent message from the afternoon shift quality manager ordered to stop the production of parts in several machines. Problems, aesthetic defects, streaks, and fragility in some parts had been detected. Whatever had happened, it had started in several machines and, like an epidemic, the entire production cell was apparently generating scrap.

However, the next day, in the daily morning production meeting, the production manager reported that the affected production cell worked overnight with good scrap results. The entire production was correct and the parts could be delivered, and, fortunately, the end-user customer was going to receive the ordered parts.

Immediately, the night shift manager became my hero, so, even if I had better plans for that night, I decided to meet him to review and discuss what happened. I wanted to know the changes made in the process to determine the cause of the “epidemic” problem and avoid it in the future.

I was surprised when the night shift manager told me that he had absolutely not changed any parameters or any condition of the production cell.

We reviewed the processes together and compared the records, parameters, etc. and, indeed, changing conditions or parameters had not taken place! We spent hours trying to find the cause that had produced this “epidemic” and had gone away apparently without external intervention.

Then, it was the first time I came face to face with one of the possible “gremlins” that appear in injection molding plants.

26.20.1 Dryers and Dehumidifiers

The drying capacity of our dehumidifying equipment must be adapted to the needs or material consumption of the production molds in operation. If we have a dehumidifier silo with a capacity of 250 kg and the material should stay there for 4 hours, we cannot connect machines that consume more than 60 kg of dry material per hour. In other words, the machinery cannot consume more material per hour than our dehumidifier is able to dehumidify.

In some cases, several machines connected to a dehumidifier can function properly. However, after some changes of mold, when the production mix changes, we start to have problems with almost all parts produced in the machines connected to the same silo dehumidifier.

The key point would be that we cannot connect to a dehumidifier a mold or molds consuming the material faster than the rate of dehumidification.

In this case, the rate of the dehumidifier was overcome during the afternoon shift, causing problems in most machines. During the night shift, only a few machines were launched and drying and consumption capabilities were balanced again. Thus, the material was properly dehumidified during the time required and the parts produced were OK.

We must manage the output in order not to exceed the capacity of the drying system and avoid problems.

Finally, the night shift manager and I prepared the required quality report.

Advice:

- Adapt the consumption rate to the dehumidifiers' output. Manage input/output drying material

In summary	
Problem	Microstreaks and fragility of parts Problem appears and disappears
Causes	Too many machines connected to the same silo dehumidifier No radii
Advice	Improve the capacity of the silo dehumidifier and the consumption of each machine Manage the material input/output ratio in the dryer

Part 6

Reference Material

Reference Data Tables

27.1 Maximum Residence Time

MATERIAL	MAXIMUM RESIDENCE TIME [min]	TEMPERATURE [°C]
ABS	5-6/2-3	265/280
SAN	5-6/2-3	265/280
PS HI	5/1-2	260/280
PC	7	320
PMMA	10/8	260/270
POM	7/20	240/210
PPO	10	280
PS	5	260
PE	-	-
PA 6	20	300
ASA	5	270
PET	4	290
PBT	2/12	290/320

27.2 Usual Mold Temperatures

MATERIAL	MOLD TEMPERATURE [°C]	MATERIAL	MOLD TEMPERATURE [°C]
ABS	60-90	ASA	40-80
SAN	40-80	PET	130-140
PS HI	10-80	PBT	80-100
PC	80-120	ABS/PC	70-100
PP	10-80	PA 66	80-100
PMMA	60-90	TPC-ET	40-60
POM	40-120	PPSU	150
PPO	60-110	PESU	140
PS	10-80	PPS	150
PE	20-50	TPU	15-70
PA 6	60-90	TPE-V	10-80

27.3 Shrinkage

MATERIAL	SHRINKAGE FLOW DIRECTION [%]	SHRINKAGE TRANSVERSAL FLOW [%]
ABS	0.5	0.5
ABS PC	0.6	0.6
ASA	0.3–0.8	
EVA	0.2–0.8	
LCP	0.07–0.5	
PA 6	0.9	
PA 66	1–1.6	
PA 66 GF 35	0.25	0.75–1.1
PBT	1.9	1.9
PBT GF 30	0.3	1.2
PC	0.5	0.7
PC GF 30	0.1	0.4
PC/PBT	0.7	1.1
PE HD	2.4	
PE LD	2.6	
PET	0.2	0.8
PMMA	0.2	0.5
POM	1.7–2.2	1.7–2.2
PP	1.2	1.3
PP T 20	0.93	1.05
PPO	1.2	1.6
PS	0.45–0.6	
SAN	0.5	

27.4 Drying Conditions

MATERIAL	TEMPERATURE [°C]	TIME [h]
ABS	80	4
SAN	70	4
PS HI	70	5
PC	120	4
PP 20% talc	80	
PMMA	90	4
POM	85	3
PPO	80–100	2
PS	70	3
PE	**	**
PA 6/66	80	10
ASA	80	4

MATERIAL	TEMPERATURE [°C]	TIME [h]
PET	135	5
PBT	120/150	4
ABS/PC	110	4
PPO	110	3
TPC-ET	100	3
ABS/PA	90	3
LCP	150	4
PETG	65	6
PPS	140	4
PSU	130	3
PPSU	150	4
TPU	90-100	4
PPS	150	6

** no drying needed

27.5 Maximum Allowed Humidity Data

MATERIAL	STARTING HUMIDITY [%]	PERMISSIBLE MOISTURE [%]	BULK DENSITY [g/cm ³]
ABS	0.4	< 0.2	0.63
ABS/PC	0.6	0.02	0.65
ABS/PA	0.6	< 0.1	0.65
ASA	0.35	< 0.1	0.63
LCP	0.04	0.01	97
PA 6	1	0.1	68
PA 6/30	0.6	0.1	94
PA 66	1	0.1	0.68
PBT	0.5	0.03	0.78
PC	0.1	0.02	0.75
PC OPTICAL	0.1	0.01	0.65
PET	0.2	0.004	0.85
PETG	0.3	0.07	0.8
PMMA	0.3	0.08	71
POM	0.8	0.1	0.85
PP	0.1	0.01	0.54
PP + talc	0.2	0.03	0.7
PPS	0.1	0.01	0.81
PSU	0.3	0.05	0.75
TPU	0.4	0.02	0.72
SAN	0.3	0.2	0.65
SB	0.3	0.05	0.64

27.6 Recommended Depth Venting Channels

POLYMER	EASY FLOW [mm]	HIGH VISCOSITY / GLASS FILLED [mm]
ABS, SAN, HIPS	0.0508	0.0762
POM	0.0127	0.0381
PMMA	0.0508	0.0762
CA,CAB	0.0254	0.0381
PA 66	0.0127	
PA 66 15% FV	0.0127	0.0381
PC	0.0381	0.0762
PE	0.0254	0.0508
PP	0.0254	0.0508
PPO	0.0254	0.0762
PPS	0.0127	
PSU	0.0254	
PS GP	0.0254	0.0508
PVC	0.0254	0.0508
TPU	0.02	
PBT	0.03	
PET	0.02	
PPA	0.015	

27.7 Mold and Melt Temperatures, Shear, and Other Properties

MATERIAL	NAME	MOLD TEMP. [°C]	MELT TEMP. [°C]	MAX. MELT TEMP. [°C]	MAX. SHEAR RATE × 1000 [s ⁻¹]	GLASS TRANS. TEMP. [°C]
ABS	Acrylonitrile Butadiene Styrene	60–90	200–260	280	30	100
EVA	Ethylene Vinyl Acetate Copolymer	20	140–220	220	30	
PS	Polystyrene	20	180–260	280	40	81
HIPS	High Impact Polystyrene	20	200–260	280	40	
LDPE	Low Density Polyethylene	20	180–240	280	40	–80
HDPE	High Density Polyethylene	20	180–240	280	40	–95
PA 6	Polyamide 6	80	230–280	320	60	40
PA 66	Polyamide 6.6	80	270–320	360	60	50
PA 612	Polyamide 6.12	80	230–280	320	60	

MATERIAL	NAME	MOLD TEMP. [°C]	MELT TEMP. [°C]	MAX. MELT TEMP. [°C]	MAX. SHEAR RATE × 1000 [s ⁻¹]	GLASS TRANS. TEMP. [°C]
PBT	Polybutylene Terephthalate	90	220–260	300	50	22
PC	Polycarbonate	80	280–320	320	40	152
PET	Polyethylene Terephthalate	100–130	280–310	340	50	69
PMMA	Polymethylmethacrylate	60–90	240–260	280	40	105
POM	Polyoxymethylene	60–100	190–230	240	40	–38
PPO	Polyphenylene Oxide	80	260–300	300	35	164
PPS	Polyphenylene Sulfide	100–150	310–240	360	50	
PP	Polypropylene	20	200–280	300	100	–18
PSU	Polysulfone	150	330–400	420	50	
TPU	Polyurethane	20	190–220	260	40	
F PVC	Flexible Polyvinyl Chloride	20	140–200	150	20	70
R PVC	Rigid Polyvinyl Chloride	20	140–200	200	20	
SAN	Styrene Acrylonitrile	60–80	220–260	280	40	
ABS/PC	Blend ABS-PC	70–100	240–280	280		
PA 6 30% GF	Polyamide 6 30% Glass Fiber	80–90	270–290			

27.8 Maximum Peripheral Speeds

MATERIAL	SPEED [m/s]	MATERIAL	SPEED [m/s]
PE	0.8	CA	0.45
PP	0.7	PPE/PA NORYL	0.4
PS	0.7	HYTREL	0.4
PA	0.5	ABS/PC	0.2
POM	0.1–0.25	PA 66	0.8
PET	0.3	PA 6	0.3
PBT	0.35	PPSU	0.6
ABS	0.5	ASA	0.3–0.6
SAN	0.55	HIPS	0.5
PC	0.5	PPA	0.2
PMMA	0.35	TPU	0.2

27.9 Density, Melt at Room Temperature

MATERIAL	NAME	MELT DENSITY [g/cm ³]	DENSITY AT 23 °C [g/cm ³]
ABS	Acrylonitrile Butadiene Styrene	0.92	1.05
ABS PC	ABS Polycarbonate	0.95	1.13
PA 6	Polyamide 6	0.96	1.13
PA 66	Polyamide 66	0.96	1.13
PA 66 GF 35	Polyamide 66 35% Glass Fiber	1.15	1.41
PBT	Polybutylene Terephthalate	1.07	1.3
PBT GF 30	Polybutylene Terephthalate 30% Glass Fiber	1.36	1.65
PC	Polycarbonate	1.04	1.2
PC GF 30	Polycarbonate 30% Glass Fiber	1.3	1.44
PC / PBT	Polycarbonate/Polybutylene Terephthalate	1.04	1.22
PE HD	High Density Polyethylene	0.72	0.957
PE LD	Low Density Polyethylene	0.7	0.917
PMMA	Polymethylmethacrylate	1.04	1.19
POM	Polyoxymethylene	1.15	1.42
PP	Polypropylene	0.73	0.905
PP T 20	Polypropylene 20% Talc	0.87	1.04
PP T 40	Polypropylene 40% Talc	0.98	
PP 40% FG	Polypropylene 40% Glass Fiber	0.85	
PS	Polystyrene	0.92	1.05
PVC	Polyvinyl Chloride	1.15	1.43
SAN	Styrene Acrylonitrile	0.99	1.08
PPO	Polyphenylene Oxide	1.06	1.1
EVA	Ethylene Vinyl Acetate Copolymer		0.95
TPE V	TPE		0.92–0.98
TPU	Polyurethane		1.0–1.23
IONOMER	Ionomer		0.94–0.96
PPS	Polyphenylene Sulfide		1.65–1.95
PPSU	Polysulfone		1.29

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Glossary

Anisotropy	The property of being directionally dependent. It can be defined as the difference, when measured along different axes, in a material's physical or mechanical properties. This property can be found in some substances, especially in the crystalline ones.
Aromatic substance	Relating to, or containing one or more molecular ring structures having properties of stability and reactivity characteristic of benzene. Compound related with benzene.
Back pressure on load	Pressure applied to the melted material in front of the screw tip during the dosage stage.
Benzene	Aromatic hydrocarbon C_6H_6 . Each carbon atom occupies the apex of a hexagon.
Birefringence	Property of certain materials to split a light beam into two perpendicularly polarized beams.
Butene	Olefin isomere (C_4H_8).
Calorific value	Amount of heat per 1 kg of substance during combustion.
Capillary rheometer	Instrument for measuring rheological properties of plastics through temperature and deformation stress.
Chemical bond	Cohesive forces bonding atoms in a molecule exerted by pairs of electrons or ions.
Chlorinated hydrocarbon	Volatile compound soluble in fatty tissues and used as solvent.
Closed loop process	Self-regulating process.
Commutation	See <i>Switching point</i> .
Comparative Tracking Index (CTI)	Maximum electrical tension that the material resists before an electric arc is produced.
Compression set	Loss recovery of a specimen when compressed for a time at a given temperature.
Covalent bond	Bond formed when two atoms share electrons to stabilize the union.
Creep	Plastic deformation, also called cold flow.
Crystalline	Material formed by many very small crystals, crystallites
Crystallization	Formation of crystals or spherulites in the semi-crystalline polymer structure.

Delta P	Difference between the programmed injection limit pressure and the real injection pressure.
Dielectric constant	Gap angle between voltage and current flow, the ideal (90°).
Dielectric strength	Electrical resistance at frequencies from 48 Hz to 60 Hz.
Dissipation	Process in which friction is transformed into heat.
Ductility	Ability to assume deformation.
Elastic modulus	Constant relationship between stress and elongation, within the elastic range of a substance.
Exothermic reaction	Chemical reaction in which heat is released.
Free radicals	Reactive molecule with great reaction power because it has an unpaired electron.
Glass transition temperature	Temperature below which molecular motion is greatly restricted.
Gutta-percha	Kind of latex from the Palaquium tropical tree.
Halogen	Element of group 17 (formerly VIIA) of the periodic table (bromine, fluorine, chlorine, iodine, astatine).
HALS	Hindered Amine Light Stabilizers. Protection against UV light.
Heterogeneous	Compound or substance composed by two or more phases.
Hexene	C_6H_{12} .
Holding pressure	Pressure applied to the material after the dynamic filling phase to compensate volume loss.
Hydraulic pressure injection	Hydraulic pressure required for filling the cavities of a mold.
Hydrolysis	Molecular breakdown caused by the water and a consequent loss of properties.
Hydrophilic	Molecular behavior of affinity for water.
Hydrophobic	Molecular behavior of repulsion for water.
Intensification ratio	Relationship between the hydraulic injection pressure and the specific pressure on the material in the screw tip.
Isotropy	Uniformity in all orientations. When the properties are completely independent of direction.
Jetting	Free jet in cavity during filling.
K-ratio	Screw compression ratio or ratio of filet depth in dosage zone/plasticizing zone ratio.

Kinematics	The branch of classical mechanics which describes the motion of points, bodies (objects), and systems of bodies (groups of objects) without consideration of the causes of motion.
L/D ratio	Length/diameter screw ratio.
Melting temperature (T_m)	Melting temperature of the crystallites.
Molecular weight	Sum of the atomic weights of the molecular formula of a compound.
Molecule	The smallest unit with chemical entity.
Monomer	Structural unit from which the macromolecules are formed.
Partage	Parting line of a mold.
Peripheral speed of screw	Screw linear speed during dosage.
Plasticizing capacity	Capacity of the injection machine if acting as an extruder.
Polarity	Grouping of electrical charges within macromolecules.
Polyaddition	Chemical reaction in which functional groups of monomers (or their ends) interact as result of migration of a hydrogen atom.
Polycondensation	Chemical reaction in which water or other low molecular weight substance is secreted during the reaction.
Polydispersity	Ratio between the number average molecular weight and weight average molecular weight.
PVT	Charts graph where pressure, specific volume, and temperature are reflected.
Reference sample	Reference sample approved by the standards.
Refraction	Change of direction by a wave passing a material medium to another.
Residence time	Time during which a material remains in the injection unit.
Reticulation	Association of plastic molecules by chemical bonds to form a three-dimensional framework.
Secondary attraction forces	Intermolecular forces whose scope does not exceed a few nanometers.
Shear	Cutting stress between layers.
Specific pressure injection	Effective pressure applied to the material for filling the cavities of a mold.
Specific volume	Volume/mass ratio. It is the inverse of density.

Sulfide	Combination of sulfur with a chemical element or radical.
Surface tension	Molecular force at the surface of a body.
Switching point	Change point of dynamic pressure or cavity filling at static pressure or hold pressure phase.
Viscoelastic	Behavior of a body that behaves both elastically (Hooke's law) and as viscous (Newtonian law).
Viscosity	Measure of the resistance to gradual deformation by shear stress or tensile stress. Strain rate/applied stress ratio.
Vulcanization	Cross-linking or bonding between molecules.

Disclaimer

The information contained in this manual is accurate to the author's best knowledge of the subject. It is offered only as suggestions and recommendations for the reader's experimentation, and is not intended to replace in any way the tests and trials the reader may need to perform in order to determine the suitability of this information for its particular proposed uses. This information may be subjected to revision due to new knowledge and experience.

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