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Practical Guide for Designers and Manufacturers of Mouldings to Reduce the Risk of Environment Stress Cracking

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ABSTRACT

Environment Stress Cracking (ESC) is one of the main causes of failure of injection moulded plastic components. Failure occurs as a result of the accelerated fracture of polymeric materials due to the combined action of environmental exposure and stress. One of the main reasons for this is that designers often fail to take into account the influence of processing on the ESC susceptibility of the material. In particular, designers fail to appreciate the influence residual stresses may have upon the material properties. This guide outlines the basic steps that should be taken by designers and manufacturers to reduce the risk of ESC in injection moulded components.

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Approved on behalf of Managing Director, NPL by Dr C Lea,
Head of NPL Materials Centre

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1 Introduction

Environment stress cracking (ESC) is the accelerated fracture of polymeric materials as a consequence of the combined action of environmental exposure and stress. It is a problem that has been known about since the early 1950s and still accounts for approximately 30% of all plastic component failures[1]. One of the main reasons for the large number of failures is that designers often fail to take into account the influence of processing on the ESC susceptibility of the material. In particular, designers fail to appreciate the influence residual stresses may have upon the material properties. Residual stresses occur in injection-mouldings as a consequence of constricted flow and differential-shrinkage. The magnitude of these stresses depends on three closely related factors: the material, the mould design and the processing conditions (Figure 1). Each of these factors is critical in avoiding premature failure. A well designed component can easily fail if an unsuitable material is chosen or the material is processed under inappropriate conditions. Likewise, a processor cannot normally eliminate mould design faults during processing. This guide outlines the basic steps that should be taken by designers and manufacturers to reduce the risk of ESC in injection moulded components.

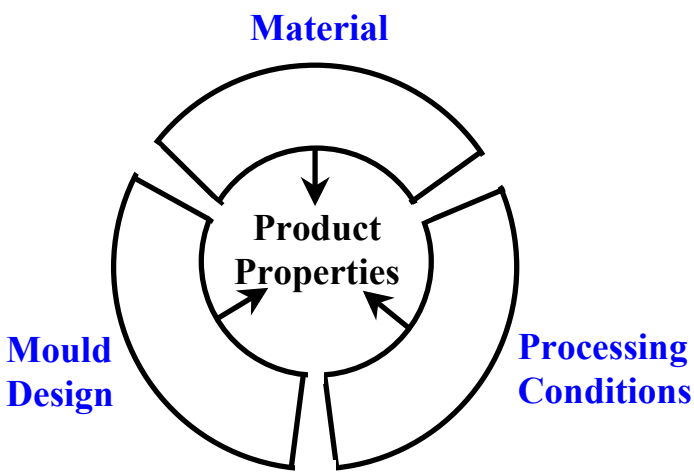

Figure 1 The three main influences on the development of residual stress in mouldings

2 Material Selection

The first step in designing an injection moulded component is to select a suitable material for the service conditions to which it is to be exposed. Many component failures are due to poor assessment of service conditions and a detailed analysis of the service environment is essential to enable a suitable material to be selected. There are many factors that are important in materials selection, e.g. strength, colour, weight etc. This guide will, however, focus on those required to prevent ESC. Too many failures are due to the lack of attention paid to the compatibility of polymers to their

chemical environment. In particular, some degree of accidental exposure should be anticipated in exploring the range of chemicals that may be encounter during service. To assess the ESC susceptibility of a material it is essential to identify:

- chemical exposure (including accidental exposure),
- magnitude of the stresses (including residual stress),
- operating temperatures,
- humidity,
- ultraviolet radiation exposure.

2.1 Material Selection Tools

Once a designer has established the service conditions it is possible to start the selection process. One difficulty is the large number of different polymers grades that are available. Brief descriptions of some of the most commonly used injection moulding polymers are given in Appendix 1 (courtesy of Moldflow[2]). For more detailed information of polymeric grades a wide range of different computer databases are available. One of the most useful is called CAMPUS (Computer Aided Material Pre-selection by Uniform Standards[3]). This can be accessed directly from the Internet (http://www.campusplastics.com) and allows designers to compare the basic mechanical properties of a wide range of different polymer grades. The main advantage of this database over similar systems is that mechanical properties can be easily compared as the data have been obtained using standardised test methods.

The main limitation of the CAMPUS database is that it gives no information on the ESC susceptibility of materials. However, NPL has developed a database[4] using slow strain rate tests[5] to allow designers to assess the ESC susceptibility of polymers in a range of chemical environments (Figure 2). The risk of ESC in a particular polymer/environment combination is given by a single value the "ESC Index". If the risk of ESC is minimal the index is given the value "1". As the risk of ESC increases the index decreases down to zero. This allows designers to easily compare the ESC susceptibility of polymeric materials thereby reducing the risk of failure in service.

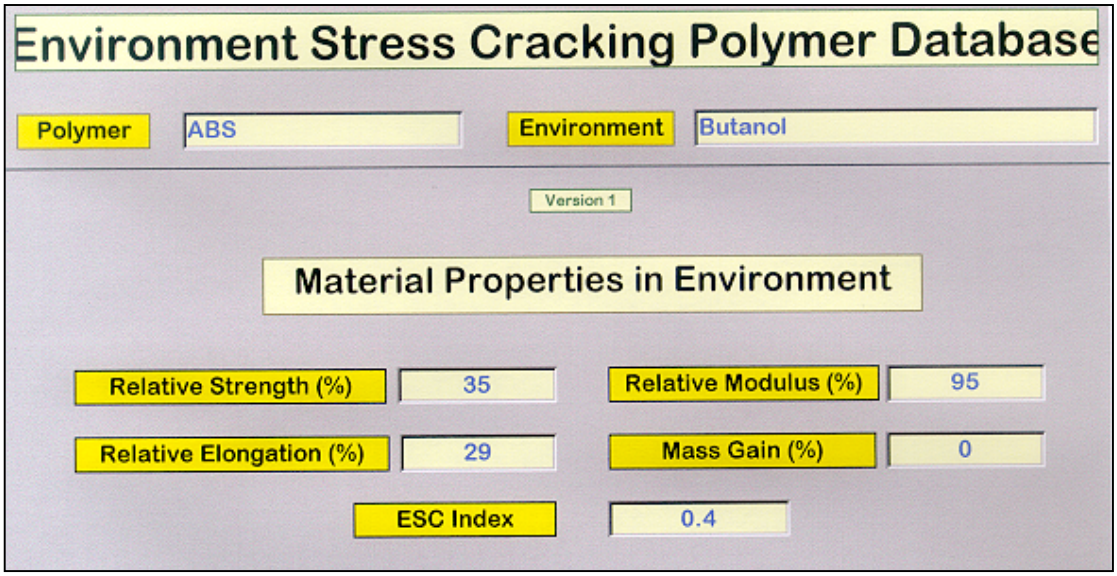

Figure 2 Example of the type of data obtained from the ESC Polymer database

3 Mould Design

Mould design is central to reducing the risk of ESC in injection moulded components. Only if the mould design is correct can the moulder produce a good quality product. It is essential from the start that the designer understands the production and service requirements to prevent problems occurring at a later stage. In particular, a designer should be aware of features within the design that may induce residual stresses and weld-lines, both of which can significantly increase the risk of ESC.

3.1 Residual Stresses

Residual stresses are present in nearly all injection moulded components. The residual stresses present in a moulding are induced during the moulding process as a result of differential shrinkage (see 3.1.1) and constricted flow (see 3.1.3) within the mould. The magnitude of these stresses can be minimised when designing the mould by careful control of wall thicknesses and gate positioning. Failure to do this may lead to the presence of residual stresses in the component that will increase the likelihood of ESC and increase the risk of warping thereby distorting the shape of the moulding.

3.1.1 Wall Thickness

One of the main reasons for the development of residual stresses in moulded components is differential shrinkage through the thickness of the walls in a moulded component. Rapid cooling of a moulding causes the surface to solidify before the core. Subsequent cooling causes the core to shrink. However, shrinkage of the core is constrained by the outer skin that is already solid. As a consequence, tensile residual stresses are formed at the centre of the component with large compressive stresses next to the surface (Figure 3).

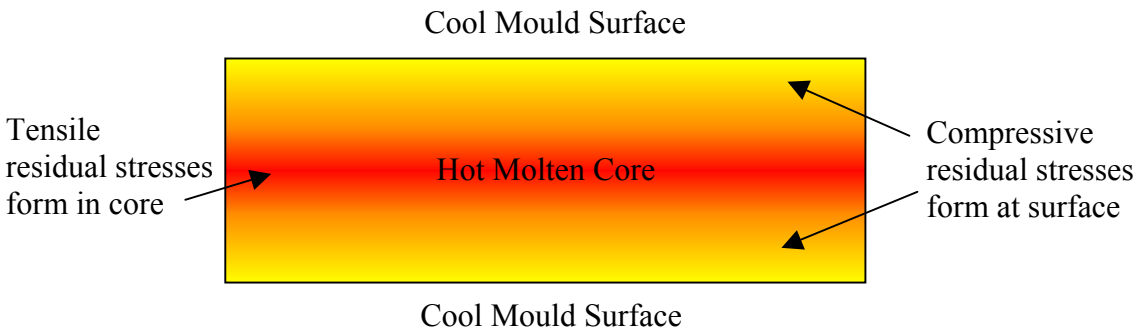

Figure 3 Formation of residual stress across a mould due to differential shrinkage during cooling.

This situation is made considerably worse by abrupt changes in wall thickness. Material in the centre of thick sections will continue to cool long after the thin sections are completely solid causing residual stresses to form along the length of the component. Where a change in wall thickness is unavoidable a gradual transition between one thickness and the other should be used to minimise the build-up of residual stress within the component (Figure 4). An alternative method of avoiding excessive residual stresses is to use a hollow core in the thicker sections. This enables a uniform wall thickness to be maintained within the thicker sections. One technique that can be used to produce hollow mouldings is gas injection moulding[6].

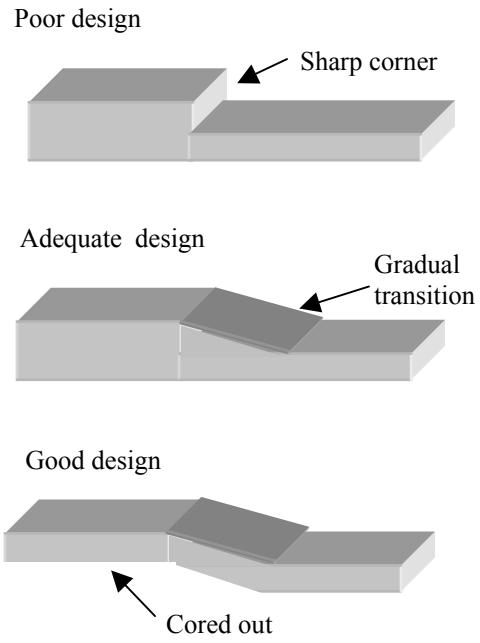

Figure 4 Transition between different wall thicknesses

3.1.2 Cooling Systems

The design of the cooling system for moulded components is extremely important. If one part of the component is cooled more rapidly than another then differential shrinkage will occur. If the component is flexible this will result in warping that will distort the shape of the moulding (Figure 5). However, if the component is restrained from deforming residual stresses will build up instead. A cooling system designed to produce uniform cooling is therefore essential to reduce the risk of ESC in mouldings.

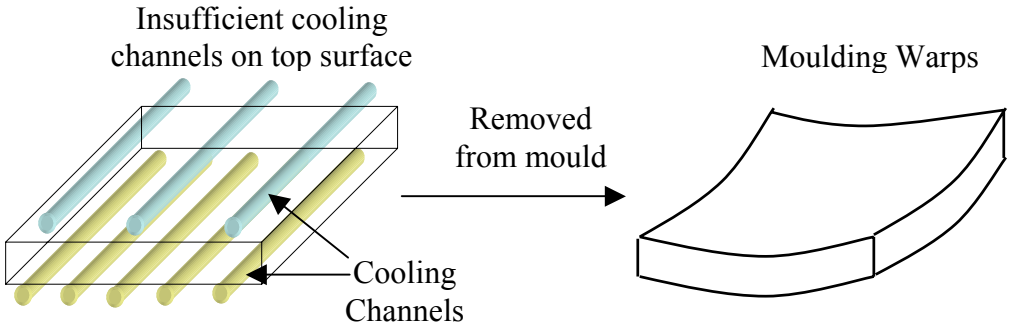

Figure 5 Non-uniform cooling of a polymeric plate will result in differential shrinkage or in the formation of residual stresses.

3.1.3 Constricted Flow

High residual stresses in injection mouldings are also introduced when the polymer melt is constricted. This occurs where the melt is forced to flow from a narrow section into a large mould cavity. As the narrow section constricts the flow into the cavity, higher pressures are required in this narrow section in order to fill the mould. The high pressures cause excessive shearing of the melt which results in the formation of high residual stresses in the narrow sections of the mould. The problem of constricted flow can be resolved by either increasing the cross-sectional area of the narrow section or reducing the volume of the cavity to reduce the flow-rate through the narrow section of the mould.

One common mistake when designing moulds is to position the gates on a narrow section of the mould and force the molten polymer to flow through into a much thicker section. This leads to extremely high residual stresses in the thinner section of the mould. This can be easily corrected by simply repositioning the gate to a location in a thicker section of the mould (Figure 6).

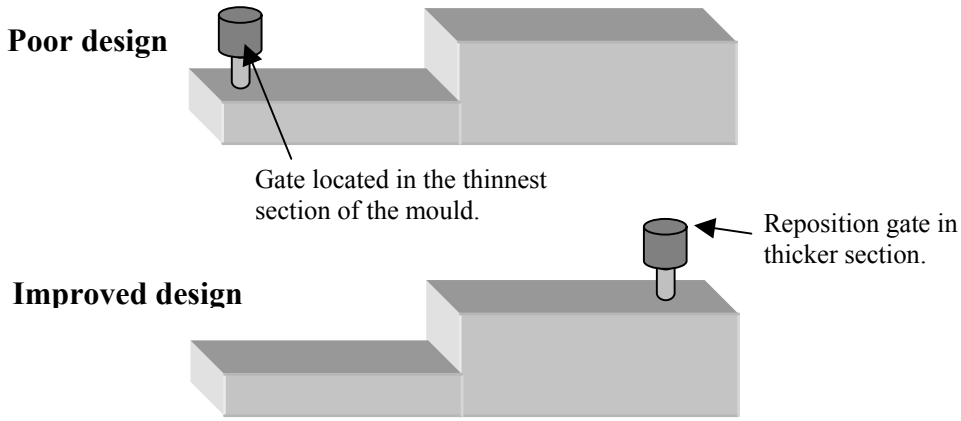

Figure 6 Locate the gate in the thickest section of the mould to reduce residual stresses.

3.2 Weld-lines

One of the major causes of premature failure in injection moulded components are weld-line defects. Weld-lines occur when two melt fronts meet and fuse together within the mould. Such lines are found in multi-gated moulds or where the melt front splits to pass around internal mould inserts. These weld-lines are potential weak spots as the polymer along the weld-line does not fuse together as effectively as in other parts of the mould. It is therefore important in designing a mould to limit the detrimental effect of weld-lines on the mechanical properties of the component. This can be done by positioning the gates so that the weld-lines form at locations unlikely to cause a problem. In particularly, it is extremely important to avoid locating weld-lines in regions that are subjected to high levels of stress, such as moulded-in hinges.

The risk of weld-line failure may be reduced by increased mixing of the two melt fronts to ensure the weld-line fuses together properly. This can be achieved by increasing the temperature and pressure in the mould[7]. Alternatively it can be achieved by designing the mould so that the two melt fronts are moving in the same direction when they converge (Figure 7). This is known as a “meld-line”. Wherever possible meld-lines should be used rather than weld-lines.

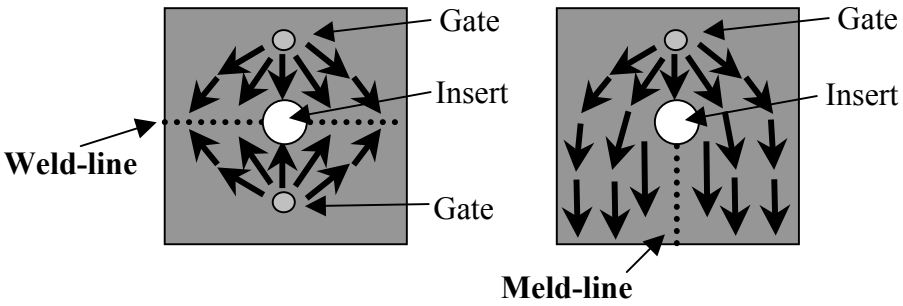

Figure 7 Formation of weld-lines and meld-lines in a moulded part.

3.2.1 Venting

One feature of weld-lines that makes them particularly sensitive to brittle fracture is that air trapped between the two converging melt fronts naturally forms "V" shaped notches that act as stress concentrators (Figure 8). The size of these notches will depend on the amount of air that is trapped in the mould and the amount of venting. It is therefore essential to properly vent the area of the mould in which a weld-line is likely to be situated. Careful positioning of gates may also assist in preventing void formation within the mould, for example cup-shaped components should be gated at the bottom of the cup to prevent air becoming trapped at the bottom of the mould where positioning of vents is not practicable (Figure 9).

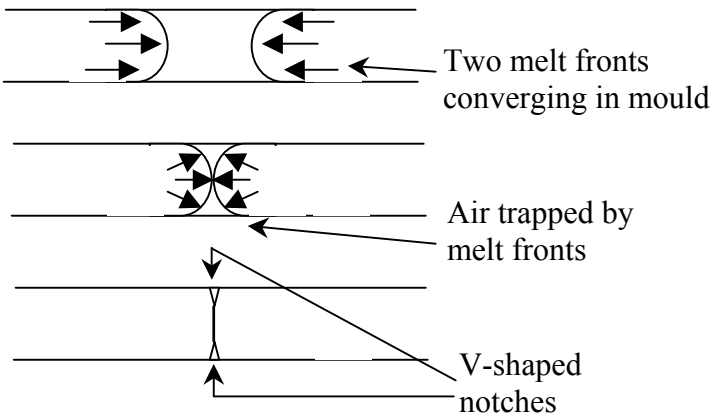

Figure 8 Formation of V-shaped notches in a weld-line due to insufficient venting.

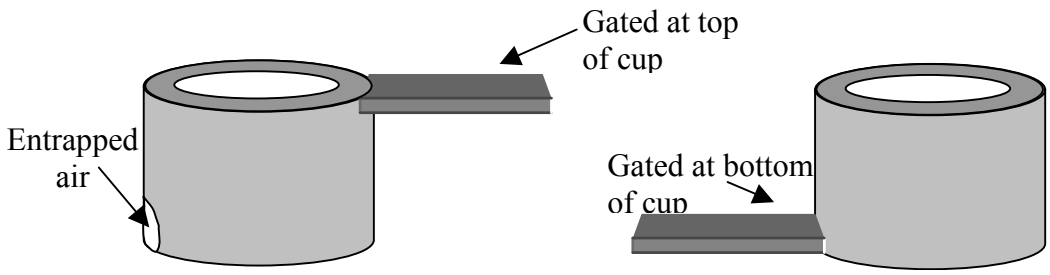

Figure 9 Gate cup-shaped cavities near the bottom to avoid the problem of entrapped gas.

3.3 Recommendations for Mould Design

- Excessive variation in wall thickness should be avoided.
- Thick walled mould cavities should be cored if possible.
- Moulds should be designed to enable the molten polymer to flow smoothly around the mould to prevent constricting the flow.
- Gates should be located, where possible, in the thicker sections of the mould.
- Gates should be positioned to minimise the number of weld-lines formed.
- Avoid locating weld-lines in highly stressed areas of the moulding.
- Where possible position gates to produce meld-lines rather than weld-lines.
- Avoid entrapped air by providing sufficient venting particularly around weld-lines.

4 Processing

Processing is the third of the three main factors that control the life-time performance of injection moulded components. The main variables in the processing of injection moulded components are the melt temperature and the packing pressure.

4.1 Melt Temperature

Choosing the correct melt temperature is vital to the quality of the final product. If the melt temperature is too low the polymer melt will not fuse sufficiently at weld-lines which can lead to a low impact resistance and unpredictable variations in the mechanical properties within the moulding[7]. However, if the melt temperature is increased too much the polymer may degrade, reducing the mechanical properties of the polymer and increasing the risk of failure.

An indication of the correct melt temperature can be obtained from data-sheets obtained from the material supplier. It is, however, inadvisable to assume the temperature of the melt is the same as that set on the barrel. Apart from the temperature rising due to the heater bands the temperature also rises due to friction from the screw. It is therefore important to measure the temperature of the melt using a probe.

In addition to the melt temperature, the dwell time may also influence the polymer melt. This is the length of time the melt is held in the injection unit. If the dwell time is too long it can cause the polymer melt to degrade even if the polymer is at the correct temperature. Likewise, if the dwell time is to short the melt may not have sufficient time to completely fuse together at the weld-lines.

4.2 Packing Pressure

As a mould is being filled the polymer will begin to solidify. Solidification of the polymer will result in shrinkage of the component. If no further polymer is injected into the mould this shrinkage will lead to voids forming, within the component that will act as stress concentrators for ESC. To prevent voids forming a packing pressure must be maintained during the cooling process to ensure further polymer is injected into the mould. If this packing pressure is not maintained for a sufficiently long period of time the components may show excessive shrinkage, warping or voiding. Voiding often occurs at the centre of the thicker sections and may not always be visible during inspection. It is therefore important, if voiding is suspected, to inspect the centre of thick sections. This can be done by taking microtomed sections through the thickness of the moulding and viewing the sections under a transmitting-light microscope to observe the formation of voids.

A problem that can occur if the packing pressure is too high is that large tensile residual stresses form at the surface of the component[8]. These are particularly dangerous as they will be directly exposed to chemical contamination and therefore significantly increase the risk of ESC in the component. These residual stresses form when there is a significant mismatch in the pressures at which the skin and the core solidify. This mismatch in pressure occurs because the skin of the component will solidify as the mould is initially filling at relatively low pressures whereas the core does not solidify until the packing pressure has been applied. The pressurising of the core during its solidification results in a denser core forming. Once the thin sections in

the mould have frozen, the release of pressure allows the core to recover thus straining the skin. The tensile stresses at the surface can be extremely large, completely outweighing the normal compressive surface stresses that are produced due to differential cooling.

Guidelines on the correct pressure and packing-time to use are sometimes provided by the material suppliers[3]. It is, however, important to understand that these are not exact values and may not take into account the influence of additives, such as nucleating agents and pigments, on the properties of the polymer.

The simplest method[9] to determine the length of time to maintain the packing pressure is to vary the packing time and weigh the components produced on laboratory scales (Figure 10). If the packing time is too short the components will be underweight and if it is too long they will be overweight. Overweigh specimens can often be identified by the presence of flashing, excess polymer that forms around the edge of the moulding. The optimum packing-time is the shortest packing-time that is required to produce a component of the correct weight. However, it should be noted that, if the gate freezes, application of further pressure is of little use.

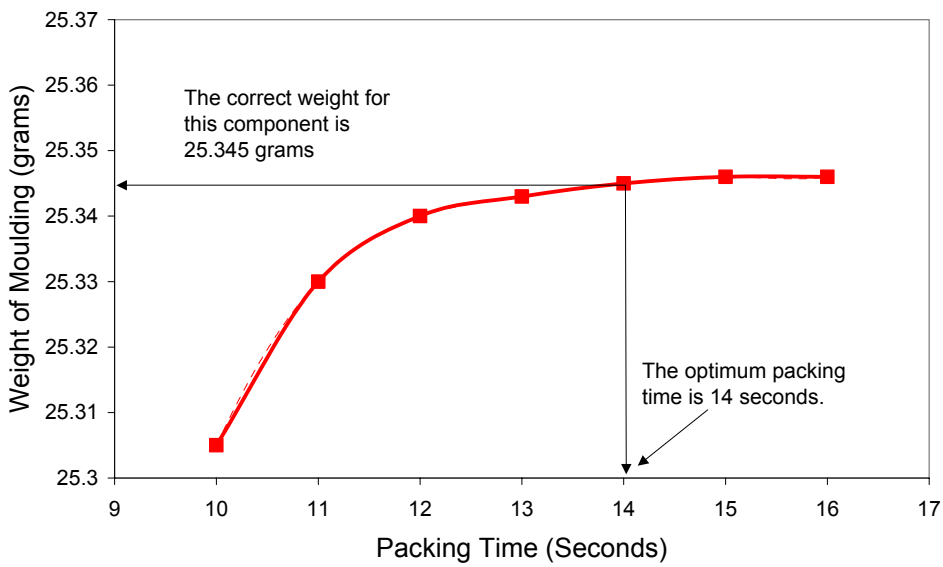

Figure 10 Technique for determining the optimum packing-time for a moulding.

4.3 Pressure-Volume-Temperature (PVT) Measurements

Changes in volume as a function of pressure and temperature can be measured for different polymers using "PVT" equipment[10]. Such data can be used to estimate the shrinkage of different polymer grades. PVT data are also valuable as input data to commercial software packages such as Moldflow which require these data to be able to predict shrinkage and warpage of parts.

4.4 Monitoring Product Quality

One of the simplest and quickest techniques of monitoring the quality of mouldings during production is to use the chemical probe technique[11,12]. This technique involves applying a stress-cracking solvent to the moulded plastic component and measuring

the length of time required before cracks or crazes occur. A well-processed moulding with relatively low residual stress will show few signs of damage. However, a poorly processed specimen with high levels of stresses will show significant cracking after it has been exposed to the chemical solvent. Although this technique has been extensively used to examine the quality of ABS mouldings[13], recent work has shown that it can be applied to a wider range of polymeric materials[11]. The technique can also be used to assess the quality of flow-line defects such as weld-lines[14].

The chemical probe technique involves establishing reference ESC data by conducting ESC tests with annealed specimens (i.e. no residual stress) under applied stress. This gives the relationship between stress and time to craze for specific polymer/environment combinations (Figure 11). When a component with unknown residual stresses is exposed to the environment for a specific period of time, the existence or otherwise of crazing will indicate whether the surface tensile residual stress in the component is above or below the reference value applied in the ESC tests. This exercise is then repeated for environments of varying aggressivity in a progressive manner to estimate the magnitude of the surface residual stress in the component. A list[15] of possible stress-cracking solvents for different polymers is shown in Table 1. The aggressivity of each of these solvents can be varied to obtain different ESC potentials by diluting them with non-aggressive fluids. Although some effort is involved in establishing the reference data, once this is done the test can be conducted within 10 to 15 minutes. This provides a quick and simple technique for assessing the tensile residual stresses near the surface of mouldings. The main limitation of this technique is that it cannot detect the presence of residual stresses below the surface. If this is required a more complex technique, such as layer removal must be used[12].

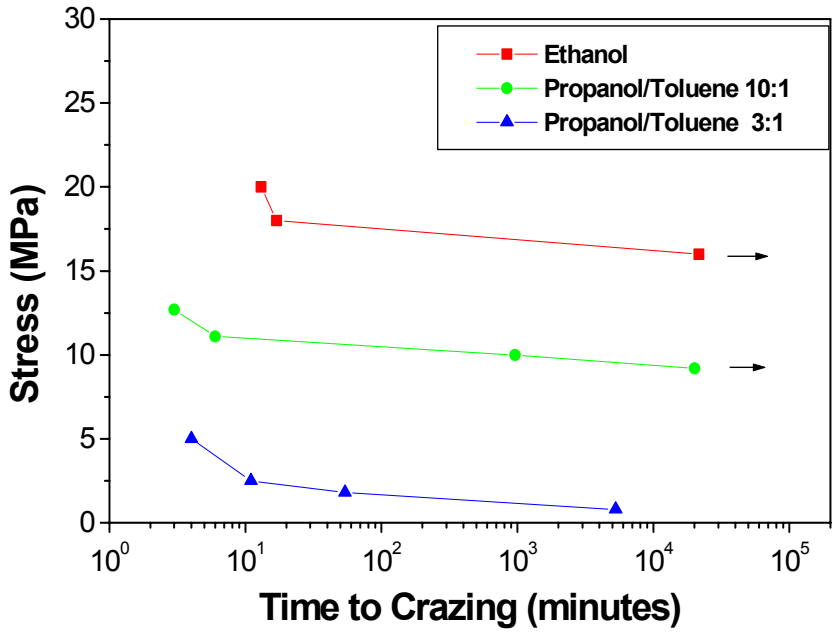

Figure 11 ESC reference data obtained for polycarbonate under constant load.

Table 1 Solvents used in the chemical probe for the examination of different polymers[15].

Material	Test Solvent
ABS	Acetic acid
PC/ABS Blends*	Ethyl Acetate/Methanol (1:3)
Polystyrene	n-heptane
SAN	Toluene + 2-propanol (1:5)
Polyethylene, Polypropylene	Strong surfactants (10 to 15% water solution)
Nylon 6 and 66	Zinc chloride solution (50°C)
POM	Sulphuric acid (50°C)
Polycarbonate	Toluene + 2-propanol
PPE	Methyl alcohol + trichloroethylene (2:1) *or* tributylphosphate
Polysulphone	Ethylene glycol monoethylether
Poly vinyl chloride	Methyl alcohol
Poly (methylmethacrylate)	Ethyl alcohol

* Courtesy of Bayer

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ABS

Generic Class: ABS (Acrylonitrile-Butadiene-Styrene)

Applications: Automotive (instrument and interior trim panels, glove compartment doors, wheel covers, mirror housing, etc), refrigerators, small appliance housings and power tools applications (hair dryers, blenders, food processors, lawnmowers, etc), telephone housings, typewriter housings, typewriter keys, and recreational vehicles such as golf carts and jet skis.

Injection Moulding Processing Conditions:

Drying: ABS resins are hygroscopic and drying is required prior to processing. Suggested drying conditions are 80-90°C for a minimum of 2 hours. Resin moisture content should be less than 0.1%.

Suggested melt temperature:	210-280 ^{o}C (Aim: 245°C).
Mould temperature:	25-60°C (Mould temperatures control the gloss properties; lower mould temperatures produce lower gloss levels).
Injection pressure:	~50-100 MPa.
Injection speed:	Moderate - high.

Chemical and Physical Properties: ABS is produced by a combination of three monomers: acrylonitrile, butadiene, and styrene. Each of the monomers impart different properties: hardness, chemical and heat resistance from acrylonitrile; processibility, gloss, and strength from styrene; and toughness and impact resistance from butadiene. Morphologically, ABS is an amorphous resin.

The polymerisation of the three monomers produces a terpolymer which has two phases - a continuous phase of styrene-acrylonitrile (SAN) and a dispersed phase of polybutadiene rubber. The properties of ABS are affected by the ratios of the monomers and molecular structure of the two phases. This allows a good deal of flexibility in product design and consequently, there are hundreds of grades available in the market. Commercially available grades offer different characteristics such as medium to high impact, low to high surface gloss, and high heat distortion. ABS offers superior processibility, appearance, low creep and excellent dimensional stability, and high impact strength.

Environments likely to cause ESC include:
Methylethylketone; 1,2 Dichloroethane; 1,1,1 Trichloroethane; Aniline; Acetic Acid; Acetone; Amyl Acetate; Methanol; Propanol/Toluene 3:1; Ethyl Acetate; Propanol/Toluene 10:1; Ethylamine; Methacrylate; Butyl Acetate.

Nylon 66

Generic Class: (Polyamide 66, or Nylon 66, or poly (hemamethylene adipamide)).

Applications: Competes with Nylon 6 for most applications. Nylon 66 is heavily used in the automotive industry, appliance housings, and generally where impact resistance and strength are required.

Injection Moulding Processing Conditions:

Drying: Drying is not required if the material is sealed prior to moulding; however, if the containers are left open, drying in a hot oven at 85°C is recommended. If the moisture content is > 0.2%, vacuum drying at 105°C for 12 hours is recommended.

Melt Temperature: 260-290°C (275-280°C for glass filled grades; melt temperatures above 300°C should be avoided).

Mould Temperature: 80°C (suggested). Mould temperature affects crystallinity level which in turn affects physical properties. In the case of thin walled parts, crystallinity changes with time if mould temperatures of less than 40°C are used. In such cases, annealing may be needed to retain dimensional stability.

Injection Pressure: Generally 75-125 MPa (depends on material and design).
Injection Speed: Fast.
Injection Speed: High (slightly lower for reinforced grades).

Runners and Gates: The gate location is important because of a very fast freeze-off times. Any type of gate may be used; the aperture should not be less than 0.5*t (where "t" is the thickness of the part). When hot runners are used, the size of the gates can be smaller than when cold runners are used, because premature freeze-off is prevented.

Chemical and Physical Properties: Nylon 66 homopolymer is produced by the polymerisation of hemamethylene diamine and adipic acid (a dibasic acid). Among commercially available polyamides, Nylon 66 has one of the highest melting points. It is a semicrystalline-crystalline material. The resins have strength and stiffness which is retained at elevated temperatures. It does absorb moisture after moulding, but the retention is not much as in the case of Nylon 6. Moisture absorption depends on the composition of the material, wall thickness, and environmental conditions. Dimensional stability and properties are all affected by the amount of moisture absorption which must be taken into account for product design.

The viscosity is low and therefore, it flows easily. This allows moulding of thin components. The viscosity is very sensitive to temperature. Shrinkages are of the order of 0.01-0.02 mm/mm (1-2%). Addition of reinforcing glass fibres reduces the shrinkage to 0.2-1%. Differential shrinkage in the flow and cross-flow directions is quite high. Mineral fillers yield more isotropic mouldings. Nylon 66 is resistant to most solvents but not too strong acids or oxidising agents.

Environments likely to cause ESC include: Aniline; Nitric Acid.

PC

General Class: PC (Polycarbonate)

Applications: Electronic and business equipment (computer parts, connectors, etc), appliances (food processors, refrigerator drawers, etc), transportation (head lights, tail lights, instrument panels, etc).

Injection Moulding Processing Conditions:

Drying: PC resins are hygroscopic and pre-drying is important. Recommended drying conditions are 100-120°C for 3 to 4 hours. Moisture content must be less than 0.02% prior to processing.

Melt Temperature:	260-340°C (higher range for low MFR resins and vice-versa).
Mould Temperature:	70-120°C (higher range for low MFR resins and vice-versa).
Fill Pressure:	As high as possible for rapid moulding.
Injection Speed:	Slow injection speeds when small or edge gates are used, high speeds for other types of gates.

Chemical and Physical Properties: Polycarbonate is a polyester of carbonic acid. All general-purpose polycarbonates are based on bisphenol A. The bisphenol A component of the molecule contributes to the high glass transition temperature (150°C). The rotational mobility of the carbonyl group within the molecule contributes to the high ductility and toughness of the resin.

PC is an amorphous engineering resin with exceptionally good impact strength, heat resistance, clarity, sterilisability, flame retardancy, and stain resistance. The notched Izod impact strength of PC is very high and mould shrinkage is low and consistent (.1-.2 mm/mm).

High molecular weight PCs (which translate to low melt flow rate) have higher mechanical properties, but processibility of such resins becomes difficult. The type of PC chosen for a particular application should be based on the desired criteria (for high impact properties, use a low-MFR PC; conversely, for optimal processibility, use a high-MFR PC).

The melt viscosities are typically Newtonian up to shear rates of 1000 1/s and decrease beyond that. The Heat Deflection Temperature Under Load is typically between 130-140°C and the Vicat Softening Point is typically around 155°C.

Environments likely to cause ESC include: Acetone; Diethylether; Amyl Acetate; Chloroform; Methylethylketone; Acetic Acid; Ethylamine; 1,1,1 Trichloroethane; Ethyl Acetate; 1,2 Dichloroethane; Trimethylpentane/Toluene 5:5; Butyl Acetate; Methacrylate; Cyclohexanone; Trimethylpentane/Toluene 7:3.

High Density Polyethylene

Generic Class: PE-HE (High Density Polyethylene)

Applications: Containers in refrigeration units, storage vessels, household goods (kitchenware), seal caps, bases for PET bottles, etc. Major use is in blow-moulding applications (packaging applications).

Injection Moulding Processing Conditions:

Drying:	Not normally necessary if stored properly.
Melt Temperature:	220-260°C (for high molecular weight resins, the suggested melt temperature range is 200-250 ^{o}C).
Mould Temperature:	50-95°C (higher temperatures for wall thickness of up to 6 mm; lower temperature for wall thicknesses greater than 6 mm).

The cooling rate should be uniform to minimise shrinkage variations. For optimum cycle times, the cooling channel diameters should be at least 8 mm and must be within a distance of 1.3 D from the mould surface (where "D" is the diameter of the cooling channel).

Injection Pressure:	70-150 MPa.
Pack Pressure:	Up to 75 MPa (holding time is directly proportional to gate size and part cross-sectional area).
Injection Speed:	Fast injection speeds are recommended; profiled speeds reduce warpage in the case of components with a large surface area.

Runners and Gates: Diameters of runners range from 4-7.5 mm (typically 6 mm). Runner lengths should be as short as possible. All types of gates may be used. Gate lands should not exceed 0.75 mm in length. Ideally suited for hot runner moulds; an insulated hot tip runner is preferred when there are frequent colour changes.

Chemical and Physical Properties: High density polyethylene is produced from polymerisation of ethylene (lower temperature and pressure conditions are used compared to the production of low density polyethylene). The material is free from branching and this is made possible by the use of stereospecific catalysts. Because of molecular regularity, PE-HD has a high level of crystallinity (compared to PE-LD).

Higher levels of crystallinity contribute to higher density, tensile strength, heat distortion temperature, viscosity, and chemical resistance. PE-HD is more resistant to permeability than PE-LD. The impact strength is lower. The properties of PE-HD are controlled by the density, and molecular weight distributions. Injection moulding grades typically have a narrow molecular weight distribution.

When the density is 0.91-0.925 g/cm^{-3}, the material is known as Type 1; Type 2 materials have densities in the range of 0.926-0.94 g/cm^{-3}, and Type 3 materials have densities in the range of 0.94-0.965 g/cm^{-3}.

The material flows easily and the MFR ranges from 0.1-28. Higher molecular weights (lower MFR grades) have better impact resistance.

Being a semicrystalline material, the moulding shrinkages are high (order of 0.015-0.04 mm/mm or 1.5-4%). This is dependent on the degree of orientation and level of crystallinity in the part (which in turn are dependent on processing conditions and part design).

PE is susceptible to environmental stress cracking, which can be minimised by reducing internal stresses by proper design and using the lowest MFR material at a particular density level. PE-HD is soluble in hydrocarbons at temperatures greater than 60°C, but resistance to these materials is greater than that for PE-LD.

Environments likely to cause ESC (HDPE) include: Amyl acetate, Amyl chloride; Chloroform, Cyclohexanone; Toluene.

PMMA

Generic Class: PMMA (Polymethyl methacrylate).

Applications: Automotive (signal light devices, instrument panels, etc), medical (blood cuvettes, etc), industrial (video discs, lighting diffusers, display shelving, etc), consumer (drinking tumblers, stationery accessories, etc).

Injection Moulding Processing Conditions:

Drying:	PMMA is hygroscopic and must be dried prior to moulding. Drying at 90°C for 2-4 hours is recommended.
Melt Temperature:	240-270°C.
Mould Temperature:	35-70°C.
Injection Speed:	Moderate.

Chemical and Physical Properties: Pellets for injection moulding are made either by bulk polymerisation of methyl methacrylate followed by extrusion and pelletisation or by polymerisation in an extruder. Formulations vary by molecular weight and physical properties such as flow rate, heat resistance, and toughness. Higher molecular weight grades are tougher than lower molecular weight grades. High flow formulations are generally preferred for moulding.

Heat deflection temperature under load varies from 75°C for high flow materials to 100°C for low flow (high molecular weight) materials.

PMMA has excellent optical properties and weatherability. The white light transmittance is as high as 92%. Moulded parts can have very low birefringence which makes it ideally suited as a material for video discs.

PMMA exhibits room temperature creep. The initial tensile strength is high but under long term, high stress loading, it exhibits stress craze. Impact strength is good but it does show some notch sensitivity.

Environments likely to cause ESC include: Methacrylate; Ethyl Acetate; Aniline; Chloroform; Methylethylketone; 1,1,1 Trichloroethane; Tolulene; Acetone; Propanol/Toluene 3:1; Propanol/Toluene 10:1; Diethylether; Butyl Acetate; Ethylamine; Methanol; Amylacetate; Cyclohexanone.

POM

Generic Class: POM (Polyacetal or Polyoxymethylene)

Applications: Acetals have a low coefficient of friction and good dimensional stability. This makes it ideal for use in gears and bearings. Due to its high temperature resistance, it is used in plumbing (valve and pump housings), and lawn equipment.

Injection Moulding Processing Conditions:

Drying:	Not usually required but resin should be stored in a dry atmosphere.
Melt Temperature:	190-230°C for homopolymer; 190-210 for copolymer.
Mould Temperature:	80-105°C (higher mould temperatures are preferred for precision moulding which reduce post-moulding shrinkage).
Injection Pressure:	70-120 MPa.
Injection Rate:	Medium - High.

Runners and Gates: Any type of gate may be used. When using tunnel gates, the short type is preferred. Insulated, hot tip runners are preferred for homopolymers; both internally and externally heated hot runners may be used in the case of copolymers.

Chemical and Physical Properties: Acetals are tough, resilient materials and exhibit good creep resistance, dimensional stability, and impact resistance even at low temperatures. Acetal resins are either homopolymers or copolymers. Homopolymers have better tensile strength, fatigue resistance and hardness but are difficult to process. Copolymers have better thermal stability, chemical resistance and processibility. Both homopolymers and copolymers are crystalline and have low moisture absorption.

Copolymers may be used continuously at air temperatures up to 100°C; homopolymers have slightly higher temperature resistance. Many grades of acetal resins are available, tailored to different applications.

High crystallinity levels of acetals lead to relatively high shrinkage levels of 0.02-0.035 mm/mm. Differential shrinkage is observed with reinforced grades.

Environments likely to cause ESC include: Oleic Acid; Hydrochloric acid; Nitric acid.

PP

Generic Class: PP (Polypropylene).

Applications: Automotive (mostly mineral-filled PP is used: dashboard components, ductwork, fans, and some under-hood components), appliances (doorliners for dishwashers, ductwork for dryers, wash racks and lids for clothes washers, refrigerator liners, etc), consumer products (lawn/garden furniture, components of lawn mowers, sprinklers, etc).

Injection Moulding Processing Conditions:

Drying:	Not normally necessary if proper storage is used.
Melt Temperature:	220-275°C (not to exceed 275 ^{o}C).
Mould Temperature:	40-80°C (suggested: 50°C). The crystallinity level is determined by the mould temperature.
Injection Pressure:	Up to 180 MPa.
Packing Pressure:	60-80% of injection pressure (up to 150 MPa).

Injection Speed: Typically, fast injection speeds are used to minimise internal stresses; if surface defects occur, slow speed moulding at a higher temperature is preferred. Machines capable of providing profiled speed is highly recommended.

Runners and Gates: In the case of cold runners, typical diameters range from 4-7 mm. Full round sprues and runners are recommended. All types of gates can be used. Typical pin gate diameters range from 1-1.5 mm, but diameters as low as 0.7 mm may be used. In case of edge gating, the minimum gate depth should behalf the wall thickness and the width should be at least double the thickness. Hot runners can readily be used for moulding PP.

Chemical and Physical Properties: PP is produced by the polymerisation of propylene using stereospecific catalysts. Mainly, isotactic PP is produced (the methyl groups lie on one side of the carbon chain). This linear plastic is semicrystalline because of ordered molecular structure. It is stiffer than PE and has a higher melting point. The PP homopolymer becomes very brittle at temperatures higher than 0°C and for this reason, many commercially available grades are random copolymers with 1-4% ethylene or block copolymers with higher ethylene content. Copolymers have a lower heat distortion temperature (approximately 100 ^{o}C), less clarity, gloss, and rigidity, but greater impact strength. The material becomes tougher as the ratio of ethylene increases. The Vicat softening point is approximately 150°C. Because of high levels of crystallinity, the surface hardness and scratch resistance is higher for these materials.

PP does not have environmental stress cracking problems. PP is usually modified by addition of glass fibres, mineral fillers, or thermoplastic rubbers. The MFR of PP ranges from 1 to 40; lower MFR materials have better impact strength but lower tensile strength. The copolymer is tougher than the homopolymer of the same MFR. The viscosity is more shear and temperature sensitive than PE.

Due to crystallinity, the shrinkage is relatively high (order of 0.019-0.025 mm/mm or 1.8-2.5%). The shrinkage is more uniform than PE-HD (the difference in flow and cross-flow shrinkage is typically less than 0.2%). Addition of 30% glass reduces the shrinkage to approximately 0.7%.

Both homopolymer and copolymer PP offer excellent resistance to moisture and good chemical resistance to acids, alkalis, and solvents. However, it is not resistant to aromatic hydrocarbons such as benzene, and chlorinated hydrocarbons such as carbon tetrachloride. It is not as resistant to oxidation at high temperatures as PE.

Environments likely to cause ESC include: Amyl Chloride; Butyl Acetate; Chloroform, Toluene.

NORYL

General Class: PPE/PPO (Polyphenylene Ether Blends).

Applications: Household appliances (dishwasher, washing machine, etc), electrical applications such as control housings, fibre-optic connectors, etc.

Injection Moulding Processing Conditions:

Drying:	Recommend drying before moulding for approximately 2-4 hours at 100°C. PPOs have low levels of moisture absorption can typically be moulded as received.
Melt Temperature:	240-320°C (higher ranges for resins with higher levels of PPO).
Mould Temperature:	60-105°C.
Injection Pressure:	60-150 MPa.

Runners and Gates: PPO is poly(2,6 dimethyl p-phenylene) oxide. The ether linkages offer easier processibility. Copolymers are referred to as PPEs (Polyphenylene Ethers). Typically, the commercially available PPOs (PPEs) are blended with other thermoplastic materials such as PS (or HIPS), Nylon, etc. These blends are still referred to as PPOs or PPEs.

The blends offer superior processibility compared to pure PPOs. Their viscosities are lower. A range of properties can be obtained depending on the ratios of PPO and PS. Blends with nylons offer improved chemical resistance and perform well at high temperatures. The water absorption is low and the moulded products have excellent dimensional stability.

Blends with PS are amorphous whereas blends with Nylons are crystalline. The addition of glass fibres reduces shrinkage levels to 0.2%. These materials have excellent dielectric properties and a low coefficient of thermal expansion. The viscosity level depends on the ratio of the components in the blend; higher PPO levels increase the viscosity.

Environments likely to cause ESC include: Cyclohexane; Ethyl Acetate; Tolulene; Oleic Acid; Methylethylketone; Methacrylate; Dekalin; Petroleum Spirit; Chloroform; Amylacetate; Acetone; Trimethylpentane/Toluene 7:3; Trimethylpentane/Toluene 5:5; 2,2,4 Trimethylpentane; 2 Ethyl Hexanol.

PS

Generic Class: PS (Polystyrene)

Applications: Packaging, housewares (tableware, trays, etc), electrical (transparent housings, light diffusers, insulating film).

Injection Moulding Processing Conditions:

Drying:	Not usually required unless stored improperly. If drying is needed, the recommended conditions are 2-3 hours at 80°C.
Melt Temperature:	180-280°C (upper limit is 250°C for flame retardant grades).
Mould Temperature:	-7 - 70°C (lower temperatures are typically used for thin wall components); Suggested: 40-50°C.
Injection Pressure:	20-60 MPa.
Injection Speed:	Fast speeds are recommended.

Runners and Gates: All types of conventional gates may be used.

Chemical and Physical Properties: General-purpose PS is produced by the polymerisation of styrene. Most commercial grades are clear, amorphous polymers. PS offers excellent dimensional and thermal stability, optical clarity, and very little tendency to absorb moisture. It has good dielectric properties. It is resistant to water and dilute inorganic acids, but is attacked by strong oxidising acids such as concentrated sulphuric acid, and is swollen by some organic solvents.

Processing shrinkage is typically between 0.4-0.7%.

Environments likely to cause ESC include: Trimethylpentane/Toluene 5:5; Nitric Acid 1M; Diethylether; Dekalin; Cyclohexane; Chloroform; Butyl Acetate; Trimethylpentane/Toluene 7:3; Methacrylate; 1,1,1 Trichloroethane; 1,2 Dichloroethane; Propanol/Toluene 3:1; Tolulene; Sebacic Acid; Ethyl Acetate; Aniline; Acetone; N Hexane; Methylethylketone; Propanol/Toluene 10:1; Petroleum Spirit; Amylacetate; 2 Ethyl Hexanol; 2,2,4 Trimethylpentane; Butanol.

PVC

Generic Class: PVC (Polyvinyl Chloride).

Applications: Water distribution piping, home plumbing, house siding, business machine housings, electronics packaging, medical apparatus, packaging for foodstuffs, etc.

Injection Moulding Processing Conditions:

Drying:	Not usually necessary as PVC absorbs very little water.
Melt Temperature:	185-205 ^{o}C.
Mould Temperature:	30-50 ^{o}C.
Injection Pressure:	Up to 150 MPa.
Packing Pressure:	Up to 100 MPa.
Injection Speed:	Relatively slow, to avoid material degradation.

Runners and Gates: All conventional gate types may be used; pinpoint and submarine gates are used for moulding small components and fan gates are typically used for thick sections. The minimum diameter of pinpoint or submarine gates should be 1 mm and the thickness of fan gates should not be less than 1 mm.

Sprues should be as short as possible; typical runner sizes are 6-10 mm and should have a full round cross-section. Insulated hot runners and certain types of hot sprue bushings may be used with PVC.

Chemical and Physical Properties: Rigid (unplasticised) PVC is one of the most widely used plastic materials. It is produced from sodium chloride and natural gas. The repeat chemical structure is vinyl chloride. Additives are mixed with PVC to make it processible. PVC resins produced by suspension or mass polymerisation techniques are the major types used for melt processing. PVC is substantially an amorphous amorphous material.

Some of the additives used include stabilizers, lubricants, processing aids, pigments, impact modifiers, and fillers. Some features of PVC include low combustibility, toughness (designed to be virtually unbreakable), good weatherability (including good colour and impact retention, and no loss in stiffness), and excellent dimensional stability. PVC is highly resistant to oxidizing and reducing agents, and strong acids. However, unplasticised PVC is not recommended for environmental and continuous use above 60 C. It is not resistant to concentrated oxidizing acids such as sulphuric or nitric acid and is unsuitable for use with aromatic and chlorinated hydrocarbons.

It is very important to process the material at the correct melt temperature; otherwise severe problems from decomposition (which produces hydrochloric acid which in turn accelerates decomposition) could result.

PVC is a relatively stiff flow material and has a narrow processing range. The molecular weight determines the flow characteristics. Higher molecular weight materials are more difficult to process (this could be modified by addition of

lubricants). Typically, however, relatively low molecular weight resins are used in moulding).

Shrinkages are fairly low (0.002 - 0.006 mm/mm or 0.2 - 0.6%)

Environments likely to cause ESC include: Cyclohexane; Sodium Carbonate 0.3M; Methylethylketone; Ethyl Acetate; Sodium Hydroxide 50%; Diethylether; Butyl Acetate; 1,1,1 Trichloroethane.