

The Dimensional Stability of Moulded Parts: A Review of the Technology Base

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ABSTRACT

This review describes the factors that are responsible for the shrinkage of moulded parts which results in either a reduction in the size of the part or local distortion or both. Semicrystalline materials are more susceptible to shrinkage than their amorphous counterparts due to the additional volume changes which occur during crystallization. Shrinkage is predominantly affected by the processing conditions employed although the design of the mould plays an important role. The amount of shrinkage that occurs in a moulded part can be substantially modified by the presence of additives such as glass-fibres or pigments.

The residual stresses generated within the moulding as a result of mould filling and subsequent cooling of the melt provide the driving force for shrinkage. If these stresses are asymmetrical then differential shrinkage can occur causing the part to distort or warp. Unbalanced residual stresses can arise from differences in the flow pattern of the melt during mould filling or from uneven cooling of the melt after this process is complete.

A number of empirical techniques have been developed, predominantly within the moulding industry that can be used with some degree of success to enhance the dimensional stability of moulded parts. However, a more cost effective approach to achieving this goal appears to be to use one of the recently available predictive software packages that have been designed to model the moulding process.

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1 INTRODUCTION

A variety of moulding methods are employed by industry to manufacture articles to within close tolerances of the original design specification for comparatively low costs. In some circumstances the mouldings produced may be unacceptable due to excessive amounts of shrinkage and/or out of plane distortion. Articles manufactured by injection moulding using semicrystalline materials as a feedstock are particularly prone to this problem that becomes more serious with the size and complexity of the mould (1).

Shrinkage in mouldings can to some extent be tolerated by manufacturers unless the parts are cosmetically undesirable or unfit for their application. Cosmetic blemishes such as sink marks or dimples are commonly found on mouldings at the intersections of reinforcing ribs or bosses. Often these blemishes can be masked by texturing the surface of the part or ignored if the part is hidden, perhaps within some more complex assembly. More serious problems occur if shrinkage results in the distortion of threads, holes and snap-fits which can render the part useless.

Similar cosmetic and 'fitness for purpose' arguments apply to warped parts. However it should be noted that cosmetically unacceptable warpage cannot be easily hidden by textured surfaces. Some degree of warpage can be advantageous for certain applications, eg in the manufacture of panels for use in items subject to vibration where they act as sprung-loaded plates retaining the torque on fixing bolts. In other situations when parts need to be welded or glued together part distortion can contribute to the mechanical failure of joints as these joining procedures rely on a good initial fit between the components.

Traditionally the design of moulds for injection moulding machines has been very dependent on the experience of both moulders and toolmakers. This approach is now changing with the advent of software packages that simulate injection moulding and predict some of the properties of the moulded product. These design tools complement the experience of the moulders and toolmakers and reduce lead times to production. The aim of this review is to provide designers who are familiar with CAD/CAM packages with a general description of the factors responsible for causing plastic mouldings to shrink or warp and how they may be controlled.

The factors that are responsible for shrinkage and warpage of injection moulded parts are described in Sections 2 and 3 respectively. Section 4 provides an overview of some empirical methods that have been developed to predict dimensional instability and also discusses the applicability of predictive software. Section 5 describes practical approaches to reducing dimensional instability through careful mould design and changes in material formulation and processing conditions. Standards which are related to shrinkage and warpage of moulded parts are described in Section 6. A brief summary of the principles of injection moulding can be found in Annex 1.

2 SHRINKAGE OF MOULDED PARTS

2.1 DEFINITIONS

Part shrinkage can be described as the difference in size between one or more dimensions of a moulded part and the mould cavity. More specifically, shrinkage through the thickness of the moulding and in directions both parallel and perpendicular to that of the flow can be described in terms of three linear components. These linear shrinkages can be multiplied together to give an overall volumetric shrinkage, or any two components can be used to define an area shrinkage. The relative magnitudes of the linear shrinkages will depend on the type of material and on the processing conditions being used.

2.2 WHY MOULDED PARTS SHRINK

Heating a moulded article will cause it to expand in size. The opposite is true when a melt is cooled to form a solid during the latter stages of the injection moulding cycle. This densification of material results in the dimensions of the moulded part being smaller than those of the cavity in which it was cast. The amount of shrinkage that occurs depends on the type of material used as a feedstock. Shrinkage is more of a problem for semicrystalline materials such as poly(oxymethylene) or polyethylene than for amorphous plastics such as polycarbonate or polystyrene. This additional shrinkage reflects a greater difference in volume between the melt and the solid state due to the presence of crystals in the latter. These permit higher densities to be achieved than with amorphous polymers because of more efficient chain packing.

To compensate for material shrinkage the mould cavity has to be machined such that its dimensions are greater than those specified in the part design. This is often a challenging exercise: Rubin (2) has identified some 30 variables that affect dimensional stability, many of which are interrelated. These include the nature of the material, the geometry of the mould and the processing conditions employed which are discussed at some length in Section 5.

2.2.1 Shrinkage of semicrystalline and filled polymers

Shear stresses developed during mould filling tend to orientate polymer chains in the direction of flow. This preferred alignment can be frozen into the solid as oriented crystals. Crystallization results in a greater length change in directions perpendicular to the flow direction than parallel with it. In practical terms, due to the anisotropy in an edge-gated rectangular plate, the plate will shrink more across its width than along its length. High aspect ratio fibre reinforced plastics experience similar anisotropic shrinkage but for these materials shrinkage along the fibre length is constrained by the fibre (3). Given that fibres tend to align themselves with the flow direction, the shrinkage of an edge-gated rectangular plate made from this type of material will be minimal along its length. Shrinkage of the plate will therefore be limited to a reduction in width.

2.2.2 The influence of mould geometry

Unfortunately the majority of mouldings do not have uniform wall thicknesses and may have holes or protrusions such as bosses or stiffening ribs. All of these features have the potential to complicate mould filling (1) by altering the resistance to flow and locally changing the processing conditions. This can be observed in areas of thin wall cross-section where additional shear of the melt will cause local viscosity changes through shear heating. Thin walled regions can also influence the amount of molecular and reinforcing fibre orientation (4). The temperature gradient through the thickness of the moulding, which has a time dependence, will depend on factors such as wall thickness and both the mould wall and melt temperatures. In turn the temperature gradient influences local levels of crystallinity in semicrystalline materials and the size and distribution of spherulites (3).

2.2.3 The influence of residual stress

Shearing of the melt during injection moulding can generate residual stress which subsequently results in shrinkage (3). During the filling phase shear stresses develop within the melt away from the walls of the part, as shown in Figure 1, causing the polymer chains to distort by elongating them in the direction of flow. If the melt is rapidly cooled then the distorted conformations will be frozen-in giving rise to a region under tensile stress near the cavity walls.

During the initial cooling of the melt, material near to the cavity walls freezes-off leaving still molten material in the core as shown in Figure 2. During the later stages of cooling this core material also shrinks but is constrained by the frozen material at the walls. This generates a region of thermally induced tensile stress in the centre of the mould and zones of compressive stress near to the cavity walls. Relaxation of the residual stresses after ejection may lead to part distortion or shrinkage (5).

2.2.4 The influence of pigments

Unexpected shrinkage problems can occur when pigments are added to the feedstock to change the colour of moulded parts (6). Often parts manufactured from feedstock containing different pigments will have such widely differing shrinkage rates that they will no longer comply with the design tolerances. In a recent survey (7) polyolefins pigmented with either blue or green phthalocyanins were highlighted as being particularly susceptible to shrinkage. It is considered that this may reflect the influence of the pigments on crystallization behaviour. Pigment additives can affect both the size of the crystallites and the rate of crystallization by acting as nucleating agents (6,8) inducing crystallization to occur at higher temperatures than expected. Similar effects are produced by other organic pigment systems used to colour polyolefins such as perylenes or disazo compounds:

The sensitivity of the shrinkage rate to different types of pigment depends on the type of material. Neubert (8) studied the influence of different pigment additives on the linear shrinkage behaviour of fan-gated rectangular plaques manufactured from an unfilled poly(butylene terephthalate) (PBT). A range of pigments were studied including phthalocyanine greens and blues, together with carbon black and quiacridone red at concentrations of either 0.1% or 0.5%. Greater shrinkages occurred in the

pigmented testpieces than for those manufactured from virgin material, although the effects were small and would be unlikely to affect industrial production unless very tight tolerances are required (± 0.1 mm). Typical shrinkage rates were found to be 0.0176 mm/mm for virgin PBT compared with 0.0208 mm/mm for the worst pigmented material that was a PBT containing 0.5% phthalocyanine green.

Broadhead and Koch in a similar study (9) studied the influence of a range of pigments including carbon black, quinacridone red and phthalocyanin blue on the shrinkage behaviour of homopolymers and copolymers of polyethylene and polypropylene. Shrinkage measurements made on thin end-gated rectangular plaques revealed that the polyethylenes were insensitive to the type of pigment used. This was not the case for the polypropylenes which showed greater susceptibility to dimensional changes when coloured with the red and blue pigments. This variation in shrinkage behaviour was observed in a transverse direction to that of the flow which was sufficient to cause production problems for a manufacturing company.

3 WARPAGE OF MOULDED PARTS

3.1 WHY MOULDED PARTS WARP

Warpage occurs because of the relaxation of unbalanced residual stresses that result either from the melt flowing into the cavity during mould filling or to unbalanced cooling or some combination of the two. Typically residual stresses are compressive on the surface of the part and tensile within the core. Variations in shrinkage can reflect differences in the rate at which the part is cooled (thermal warpage) or molecular or fibre orientation induced by the flow of the melt into the cavity (flow warpage). As the amount of differential shrinkage is unique to the combination of mould design, processing conditions and the type of material used it is difficult to predict whether or not a part will warp.

Variations in the amount and type of crystallization behaviour can occur in parts with uniform wall thicknesses during the cooling cycle if the cooling rates are out of balance on opposite sides of the cavity. To achieve balanced cooling requires careful planning as moulds tend to run hotter on the core side than the cavity side. Toe-in of the side walls of box-shaped parts is a typical example of a warpage effect caused by uneven cooling between the core and the cavity (3), figure 3.

The shrinkage of semicrystalline thermoplastics increases with wall thickness due to the reduced rate of cooling (10) as shown in Table 1. In parts that have variable wall thicknesses this can lead to differences in local shrinkage rates and cause warpage.

Differential shrinkage can also be induced by the way in which the melt flows into the cavity during filling because of molecular orientation. In practice isolating molecular orientation as the cause of differential shrinkage is difficult to do unless the filling process is analysed using predictive software. Excessive packing pressures that are used to reduce mould shrinkage can generate highly stressed areas

Material	Shrinkage at wall thickness	
	0.8 mm (mm/mm)	6.4mm (mm/mm)
Polypropylene * (PP)	0.012	0.024
Nylon 6,6 * (PA 6,6)	0.010	0.022
Poly(butylene terephthalate) * (PBT)	0.007	0.022
Polycarbonate (PC)	0.006	0.008
Acrylonitrile-butadiene-styrene (ABS)	0.005	0.008

Table 1: The shrinkage rates of various thermoplastics as a function of wall thickness (1), the * denotes a semicrystalline polymer.

in the region of the gate. Over packing of this nature in centre-gated parts such as lids or containers is thought to be the main factor responsible for 'oil canning' where the part bows in or out in the gate area (3) to relieve the stress.

Warpage has recently been shown to be affected by the presence of mould release agents during manufacture of parts by rotational moulding. Nagy et al in a recent study (11) of the effects of colourants on the properties of a rotational moulded polyethylene boxes showed that the presence of mould release agents containing zinc stearate resulted in significant warpage of the boxes. Their results were subject to a significant scatter which they attributed to the presence of small amounts of material from previously moulded parts that remain attached to the mould surface. This is thought to cause the part to detach itself from the mould surface during cooling thus reducing the rate at which heat is transferred to the cavity which results in differential shrinkage and hence warpage. This problem was significantly reduced by applying a small excess pressure within the moulding to ensure good contact between it and the mould through the cooling cycle. It should be noted that the processing conditions used by Nagy et al (11) were chosen to obtain high cooling rates and therefore measurable amounts of shrinkage and warpage. The observed effects may be of less importance if optimal processing conditions are used.

Additional shrinkage problems can occur if recycled thermoset material is added to virgin feedstock. Smock (12) states that polyurethane facias from cars can be recycled at a concentration of 5% in virgin feedstock, although concentrations of up to 10 - 12% regrind can be used without any significant loss of properties in the product. However in practice it is impractical to mould parts using feedstock containing more than 5% polyurethane from cavities sized to accommodate the shrinkage behaviour of virgin material. This is because the higher concentrations of regrind significantly reduce the part shrinkage due to curing in comparison with that produced by the virgin material.

4 PREDICTING DIMENSIONAL INSTABILITY

Shrinkage data for amorphous plastics is often presented in material suppliers technical data sheets as a single value (expressed in mm/mm or as a percentage) (13,14) which is normally measured in the direction of flow in a dumbbell testpiece. Typically two shrinkage values are quoted for semicrystalline materials to reflect their anisotropy. One value is a measure of shrinkage in the direction of flow while the other is that which occurs perpendicular to it. Such testpieces are typically 4 mm thick (15) and moulded according to the conditions specified in an appropriate materials standard. In practice moulded parts are of variable thickness and are rarely produced using the same or even similar processing conditions as those used to manufacture the test bars. Even when the wall thickness does correspond to that of the test bar there may be more or less shrinkage in 'real' mouldings compared with that of the manufacturer's test bar due to differences in the processing conditions. The supplier's shrinkage data is thus of little use to the moulder other than providing some indication of a material's tendency to shrink.

The shrinkage of amorphous materials with low shrinkage rates of 0.020 mm/mm or less can be reasonably predicted and may be controlled by varying processing parameters such as the packing pressure, the mould or melt temperature or as a last resort the cycle time (16). Shrinkage of crystalline materials with high shrinkage rates of more than 0.025 mm/mm can be controlled to some extent by varying the processing conditions providing the part is symmetrical and centre-gated (16). In situations where it is impractical to centre-gate a symmetrical part there is some benefit to be gained from using multiple gates to approximate centre-gated filling behaviour. However we should note that predicting the shrinkage behaviour of a multiple-gate fill without using software may be difficult. Similarly there is considerable uncertainty in predicting the shrinkage behaviour of an edge or side-gated asymmetrically shaped moulding manufactured from semicrystalline materials.

To help moulders to estimate the dimensional changes of parts due to shrinkage some companies produce nomograms (16) relating wall thickness and gate area to material shrinkage. While these charts are useful in predicting the behaviour of parts with constant wall thickness, they provide only loose guidance for mouldings of variable thickness. Thus the manufacturer and designer often resort to using prototype mould designs that can be modified, if necessary, during refinement of the processing conditions. This approach is both time consuming and expensive in its use of man hours and machine time.

While prototyping will lead to the manufacture of a production mould and a window of processing conditions, the window may not be large enough to accept batch-to-batch variations in the properties of the feedstock. This variation can reflect differences in the water content of the resin, the regrind content and the presence of colouring agents or other additives that can result in mouldings being manufactured that fail to meet the design tolerances. In practice small refinements to the processing window are made by producing small numbers of mouldings for each set of processing conditions.

This is a time-consuming process since not only does the machine have to reach a steady state before samples can be taken but also the resultant mouldings can take a considerable period to stabilize. For some materials such as unfilled semicrystalline polymers, eg acetal, nylon or polyester this period of stabilization can take up to 2 hours. However it is normally much shorter (20-25 minutes) for materials that are less susceptible to shrinkage such as amorphous or highly filled systems (17). Significant cost savings can be made by using a master plot of the measured shrinkage of the moulding against stabilization time (17). These data can then be used to predict whether another moulding manufactured under a different set of conditions will meet the design specification by comparing its shrinkage at a particular time with that of the master plot.

A more cost effective approach to generating mouldings that comply with the design specification tolerances and are also cosmetically acceptable is to use predictive software packages (18,19). These powerful design tools can be used to predict how the mould will fill and to estimate the resultant shrinkage and warpage of the part. Using these systems gives the designer freedom to explore how different gating arrangements and processing conditions will affect the quality of the manufactured part using either different grades or types of plastic. The software is particularly suited to predicting mould filling and the dimensional instability of complex shapes or parts fed by complex gating arrangements.

4.1 EMPIRICAL METHODS FOR REDUCING DIMENSIONAL INSTABILITY

Attempts have been made to provide plastics engineers with guidelines which provide a simple comparison of the tendency of different materials to warp as a function of certain processing conditions (20,21).

Heberlein (20) presented a warpage scale for different materials based on the deflection of testpieces moulded using different gating arrangements and temperature gradients across the mould cavity. This technique can be used to assess the susceptibility of different materials to flow or thermally induced warpage.

Kamanayo et al (22) applied a statistical interpolation model developed for the mining industry (23) to empirically assess the influence of different processing conditions on part shrinkage. This technique provides a short-cut route for optimizing processing variables although it does rely on data obtained from moulding trials. Mamat et al (24) used the same technique to explore the influence of different processing conditions on the shrinkage of both filled and unfilled polypropylene. In this study they demonstrated that the holding pressure was the most influential factor affecting shrinkage followed by the holding time. Less influential processing variables were the temperature of the melt and that of the cavity.

Warpage can be successfully controlled at least for small mouldings by following some empirical guidelines which have been developed by industry over time and are described in Section 5. There is

an element of risk in employing these empirical solutions as there may be limitations to their applicability. Hence there may be instances where their use is inappropriate.

4.2 THE USE OF PREDICTIVE SOFTWARE TO REDUCE DIMENSIONAL INSTABILITY

During the past five years there has been a dramatic increase in the power and storage capacity of computers together with an equally dramatic reduction in cost. This has led to the development of predictive software packages which continue to become increasingly more reliable in their ability to model mould filling and to predict the dimensional stability of mouldings. Typically the capabilities of the software are a reflection of its initial cost. The simplest algorithms describe the filling of a cavity during injection moulding on the basis of the assumption that the temperature of the mould is the same over all the surfaces. Simulations based on this assumption have the potential to identify the positions of weld lines, stress concentrations and injection pressure requirements. Modelling at this level allows the designer to quickly explore what affects different gate locations and gate sizes will have on these features. The calculations will also give some indication of processing parameters such as the fill time. Details of the functions used in the calculations and a description of the assumptions made can be found in references (25 - 27).

Taking a more realistic temperature profile of the mould allows more detailed calculations of mould filling to be carried out by linking the filling module to a cooling analysis programme. The cooling analysis generates a 'real' mould temperature accounting for the position of cooling channels, inserts, heat pins and other mould features in the computation. The results obtained from the filling and cooling analyses permit more reliable estimates of processing parameters such as injection speed, packing pressure, melt temperature and mould temperature to be obtained. Prior to predicting the pattern of freeze-off in the moulded part the packing phase of the moulding cycle is analysed. The information from the filling, packing and cooling analyses is then fed to a fourth module that predicts the magnitude and distribution of residual stresses which reside within the moulding at the moment of ejection and subsequently how the part will warp.

4.2.1 Data requirements

Products marketed by Moldflow (Moldflow) (18) and A.C. Technology (C-Mold) (19) are the market leaders for injection moulding simulation software. These two packages have different requirements for shrinkage data. Moldflow mould end-gated rectangular testpieces that each have a grid moulded into one of the outer surfaces (28). The separation between points on the grid is measured after a period of two weeks after manufacture during which the dimensions of the part stabilise. The coefficients of a function used to fit the shrinkage data are incorporated into a database and are subsequently used to predict shrinkage and warpage. C-Mold follows a different approach and determines the shrinkage based on calculations of residual stress which requires measured values for both the tensile modulus and Poisson's ratio (29). The disadvantage of the Moldflow approach is that the method is empirical and therefore strictly only applicable to the processing conditions used to manufacture the testpieces. A similar uncertainty lies within the C-Mold approach as to which single

value of the temperature dependent tensile modulus should be used, noting that the material progressively stiffens as it cools after being ejected from the mould.

Attempts have been made to model shrinkage using volumetric data obtained as a function of pressure and temperature (PVT) (24). The success of this approach has been limited since the PVT data are unlikely to match the processing conditions used and to account for the variations in conditions that occur throughout the mould. Furthermore, problems can be encountered in attempting to derive accurate linear shrinkage data from volumetric measurements (30).

4.2.2 Modelling the influence of additives

The influence of additives on material properties is to some extent catered for by simulation software, for example rheological data exist for many fibre- and mineral-filled grades of plastic. However there are other additives for which there is little rheological data available, such as pigments, which, although they have little influence over the rheological properties of plastics can affect both their mechanical properties and dimensional stability. Currently available software is unable to predict these effects unless the pigmented material has been specifically characterised.

Fibres play a very important role in the dimensional stability of moulded parts by limiting the shrinkage of the plastic along their length. Zheng et al (31,32) have quantified the influence of several factors that can influence dimensional instability by using a single variate analysis to rank the effects of differential cooling, differential shrinkage and orientation effects due to the presence of fibres on warpage. The results of this study on glass-fibre filled nylon 66 showed that differential shrinkage due to fibre orientation is by far the most influential factor causing twice as much warpage as differential cooling and ten times that of differential shrinkage due to crystallization. The dominant role that fibres have on the dimensional stability of mouldings has been a particular problem for the predictive software packages which have to accurately predict the orientation of fibres throughout the part. This is a very complex issue which has received considerable attention in the literature (33 - 40).

4.2.3 Heat transfer considerations

Predicting heat loss through the mould walls is complex and requires a number of assumptions to be made regarding the nature of the interface between the cavity and the moulded part. The model employed needs to account for freezing of the boundary layers and the potential for shear heating of the melt in the core region. Modelling real mouldings gives rise to additional complications such as variable wall thicknesses, wall intersections and/or the presence of inserts that are necessary to place openings in the moulding.

Many part shapes such as boxes are designed with almost square-cut corners that can have a significant influence over the pattern of flow particularly in melts containing fibres and may cause difficulties in controlling local heating. The reason for the difficulty in controlling the temperature in these regions

is due to the geometry of the two heated surfaces as shown in Figure 3. There is some evidence (41) to suggest that this pattern of behaviour is presently predictable, although more qualitatively than quantitatively.

4.2.4 Predictions of warpage

Current models for calculating residual stress (5, 42) assume that there is no slip between the moulding and the cavity walls during cooling. This assumption is convenient for computational reasons but may not be realistic. Bushko and Stokes (5) have recently demonstrated a strong dependence of the residual stresses calculated for a rectangular plaque on the boundary conditions assumed for the stress calculations.

Predicting the warpage of moulded products is not trivial and is not normally calculated until the part has been ejected from the mould. After ejection any residual stresses in the moulding provide a driving force for distortion. This is a complicated process to model as some material within thicker parts of the moulding may still be molten at the time of ejection. This fluid material may experience significant supercooling before the onset of crystallization. The resultant shrinkage of the core material that occurs during this process will be opposed by the frozen outer layers leading to internal stresses. Modelling part distortion outside the mould (43) must therefore cater for the relaxation of internal stresses that exist at the point of ejection and cater for continuing crystallization and associated shrinkages that in turn generate 'new' stresses. This behaviour is likely to be modified by the presence of existing decaying stresses. This poses some significant numerical problems in modelling the time dependence of the distribution and magnitude of residual stresses and requires the use of finite element methods. Either elastic or viscoelastic analyses can be employed, although the latter is more complex requiring significantly longer computing time and is therefore more expensive to do. Rezayat et al (44) in a comparison of viscoelastic and elastic approaches found only a small improvement in the accuracy of the predictions using the more complex viscoelastic model. This finding may not be general and may only apply to particular mould shapes and for a limited range of materials. Interestingly Rezayat et al (44) suggest that the data available for simulation programmes may be of limited accuracy. For example, the viscosity data derived from capillary rheometers may be an overestimation of the properties of materials containing more than 20% fibres. This overestimate could be due to the fibres breaking up or blocking the rheometer. More reliable results may be obtained from an in-line rheometer that has a larger bore size (45).

As predictions of dimensional behaviour are at the end of the calculation chain they are susceptible to errors propagated through the calculations which arise from over simplification or inaccuracies in the functions used to describe filling, packing and cooling of the cavity. The accuracy of predictive software is also influenced by the accuracy or applicability of the material data. This in turn can reflect limitations in the test methods used to generate it. Some simplifications used in the functions reflect a lack of knowledge while others are necessary to carry out the calculations in an acceptable time using currently available computing power. It is often assumed that the flow of the melt during filling of

the mould is sheet-like which requires the thickness of the wall to be small in comparison with the overall dimensions of the part. This assumption breaks down for very thick walled mouldings where eddies, turbulence and backflow can occur. Simulations for mouldings of this type can be inaccurate even for describing how the mould is filled and can lead to ill-informed decisions being made regarding part design.

4.2.5 Uses and experimental validation of predictive software packages

Comparisons between the predicted dimensional stability of parts and real mouldings have been presented in a number of papers (31,32,46 - 48). However, some care must be exercised in drawing conclusions from published comparisons of real mouldings with software predictions, particularly for older publications. In some cases mismatches between the predicted behaviour of mouldings and those manufactured reflect the limitations of the software, the available computing power and the accuracy of the moulding process control at the time at which the work was done.

Zheng et al (31,32) compared the observed warpage of an automotive radiator end tank (as measured by Sherman and Calder (34)) with that predicted by Moldflow (49). The radiator end tank was manufactured from 33% (by weight) glass-fibre reinforced nylon 66. The predictions made by the software were found to be in good agreement with the observed distortion of the part.

Foss et al (47) compared C-Mold predictions of modulus and fibre orientation with mouldings manufactured from 30% (by weight) glass filled PBT. A good quantitative agreement was obtained between the predicted and measured orientation of the fibres in both the centreline region and near to the plaque surface. Predictions of tensile modulus were slightly less successful, an under prediction of 25% was found in the flow direction and an over prediction of 5 - 15% occurred in a direction perpendicular to it.

Zou and Horney (50) described the application of Moldflows warpage software (49) to the design of a power tool casing manufactured from a nylon containing 30% fibres. Calculations of warpage along a parting line were made which assessed the relative contributions from flow orientation and differential cooling. Various changes to the mould design were explored such as varying the location of the gate to assess their influence on predicted part distortion. While there was no verification of their findings with real mouldings this work does serve to illustrate the power of using predictive software as a design tool.

A number of simplifications need to be made in modelling the warpage of moulded parts. These are necessary to simultaneously model the changing properties of the material whilst it cools in an often complex geometry. They can be achieved by either applying complex material models to simple shapes or simpler material models to complex geometries (51,52). The model chosen and assumptions made regarding the time dependence and uniformity of the mould wall temperatures can mask information concerning the influence of cooling on warpage. Liu and Rietveld (52) have attempted to show this

by modelling thermally induced stresses and warpage in a rectangular plate of injection moulded polystyrene. Using a 2-dimensional viscoelastic phase transformation model they assumed a viscous fluid model for the melt and a standard linear solid for frozen material. Their model successfully described the residual stresses and warpage of the rectangular plate and demonstrated the importance of accounting for the liquid-solid phase transformation and the stress relaxation that occurs within the mould cavity during the cooling cycle.

5 PRACTICAL CONTROL OF DIMENSIONAL INSTABILITY

The strategies that have been developed to either eliminate or reduce shrinkage and warpage of parts can be classified according to:

- changes in design,
- changes in material formulation,
- changes in processing conditions.

The success of these strategies that are often interrelated will depend to some extent on the skills of both the designer and the moulder. Often the solution used on the production line will be a compromise between one that is 'ideal' and one that meets the cost and time constraints that operate at all levels from design to manufacture. Detailed information relating to effective mould design and optimization of processing conditions can be found in a number of textbooks and design guides (53 - 56).

5.1 MOULD DESIGN FEATURES

5.1.1 Wall thicknesses

Subtle changes in the design of parts can, depending on the material (1), result in significant improvements in the dimensional stability of the resultant mouldings. Small changes in the wall thickness of the part can be used to ensure even filling of the mould by locally enhancing or retarding the flow front. This manipulation of the flow of the melt can be used to eliminate or reduce the size of weld or meld lines, eliminate air pockets, and to control the rate at which the melt solidifies.

Changes in wall thickness can be used to ensure adequate flow to complex parts of the moulding or to ensure that the flow paths within the mould are balanced. Gates should be positioned so that material flows from thicker wall cross-sections of the part to progressively thinner walled regions (10). Flowing from thin to thick walled sections can cause problems such as incomplete filling, sink marks and high internal stress (1). The transition from thick to thin should be gradual as a sharp changes can result in turbulent flow that can cause surface blemishes that act as stress concentrations. Thick walled sections should be avoided (10). Where it is necessary to produce thick parts material can be cored out to produce hollow cross-sections. This strategy not only preserves the mechanical integrity of the part but also enhances profitability through savings in material and cycle time.

5.1.2 Corners, fillets and radii

While almost square-edged corners are often incorporated into designs for aesthetic reasons they may represent a structural weakness and should be avoided in moulded plastic parts. Fillets and radii placed on corners offer many mechanical advantages by reducing stress concentrations and internal stress and help the flow of the melt through the cavity. A radius equal to half the adjacent section wall thickness is desirable to reduce stress concentrations (57).

5.1.3 Selection and positioning of gates

Inappropriate positioning of a gate or a series of gates can lead to distortion of moulded parts, particularly those manufactured from fibre-reinforced plastics (3). Warpage can occur in long-thin rectangular parts if the gate or gates are positioned along one of the long axes of the moulding. This type of gating arrangement will result in radial flow of the melt which will control the orientation of the fibres. This can result in differential shrinkage, due to the constraints imposed on the melt by the fibres, and warpage of the product. The problem can be overcome by using a centrally positioned single gate at one end of the part that will ensure lamellar flow of the melt through the cavity. Although there is likely to be more lateral shrinkage for parts produced with this type of gating arrangement there should be less tendency for it to distort.

Centrally located spoke gates can generate unbalanced radial flow patterns in circular parts leading to warpage. Similar unbalanced radial flow patterns can be produced in edge gated circular discs where the gate is located on the circumference. Problems of this nature can be overcome by using a centrally located diaphragm gate which ensures a uniform radial distribution of fibres and eliminates any tendency for the material to distort. Empirical guidance for the design of gates i.e. sizes and positions can be found in Bryce (58) who also discusses the importance of vents, an important topic often ignored in design guides.

5.1.4 Ribs

The tendency of parts containing large 'flat' areas such as container lids to distort can be avoided by changing the shrinkage behaviour of the part by using variable wall thicknesses or by adding stiffening beams or ribs. These should be positioned in the part such that they are parallel to the flow direction. The thickness of the rib should be no more than 2/3 of the adjoining wall thickness. The shrinkage of thicker walled sections can cause vacuum bubbles or sink marks at the intersection of mating surfaces and may induce flat surfaces to warp in the direction of the stiffener. Often cosmetically undesirable features can be hidden by decorating, contouring or texturing the part surface, although it is often more difficult to mask warped areas.

5.1.5 The design of cooling systems

The design of the cooling system is very important as poor design and operation of the cooling system can lead to the manufacture of warped or highly stressed parts. The cooling channels running through the mould can be connected in series or in parallel with a coolant supply and exit channel as shown

in Figure 4. Serial connections are more commonly used in industry since any variation in the bore of the cooling channels will cause differences in the resistance to flow in a parallel connected system. Turbulent flow of the coolant enhances the rate at which heat can be removed from the melt which reduces the cycle time. For general purpose moulding the rate at which the coolant flows through the mould should be such that there is a temperature difference of 5°C between coolant temperature at the entrance and exit. For precision moulding this gradient should be reduced to 3°C.

Specific cooling devices have been developed for cooling potential hot spots that may exist within the mould, such as at bosses or studs, that consist of baffles, bubblers and thermal pins as shown in Figure 5. Baffles can be flat sheets inserted into the coolant channels that direct the flow of coolant into the area to be cooled. In other applications cone shaped inserts with external spiral or helical channels are used where the coolant emerges at the tip of the cone and flows down the outside, cooling the mould as it does so. Cooling of narrow width mould protrusions can be achieved by using bubblers where the coolant emerges as a fountain. A thermal pin can be simply a cylinder manufactured from a good heat conductor such as copper inserted into the mould or a hollow cylinder that is part filled with a volatile solvent. A dramatic cooling effect can be obtained using hollow cylinder thermal pins since energy from the melt is absorbed by the solvent as a latent heat as it vapourises. Subsequently this energy is transferred to the coolant again as a latent heat as the vapour condenses at the bottom of the thermal pin.

Care must be exercised in ensuring that cooling pipes are symmetrically positioned about the part as differences between the centres of as little as 0.5mm can cause warpage. Guidance regarding the design of cooling systems can be readily found in the notes supplied by materials suppliers and textbooks on mould design (16,29,56)

5.2 CHANGES IN MATERIAL FORMULATION

It is possible to enhance the dimensional stability of moulded parts through subtle changes in the composition of the feedstock i.e by using different grades, fillers or by adding nucleating agents. Unfortunately changing the grade or the type and quantity of additives can have adverse effects on both the mechanical properties and the surface finish of the final mouldings. These deficiencies can be attributed either to changes in the rheological properties of the melt which can affect the way in which the mould fills or to a different level of crystallinity compared with that of the original feedstock. Changing the rate at which the material crystallizes by adding nucleating agents can be used to alter the shrinkage characteristics of mouldings. This can in certain circumstances be helpful in compensating for differences in the nucleation behaviour of different pigments to produce different coloured parts from a single mould.

5.2.1 Fillers

The addition of fillers in the form of fibres such as glass results in anisotropic shrinkage of materials with the greatest shrinkage occurring in a direction perpendicular to that of the flow along which the

fibres align themselves. This anisotropic shrinkage can be reduced by using grades of crystalline materials that contain low aspect ratio fillers such as talc or glass beads (59). These additives improve the dimensional stability of moulded parts compared with those manufactured from fibre reinforced materials, although they do lower both the impact and tensile strength which may be detrimental to the performance of the product.

5.2.2 Nucleating agents

Rapidly cooling a melt of a semicrystalline polymer often results in extensive supercooling, which delays the onset of crystallization. Table 2 shows the maximum degree of crystallinity $x_{c(max)}$, the maximum crystal growth rate $v_{(max)}$ and the melting temperatures t_m of some common semicrystalline plastics. It is apparent from this table that materials such as polypropylene can tolerate more supercooling because it crystallizes less rapidly than a material such as polyethylene (HDPE). The low crystallization rates of polystyrene and polycarbonate explains why these materials are amorphous under normal processing conditions.

Polymer	$x_{c(max)}$	$v_{(max)}$ ($\mu\text{m/s}$)	t_m ($^{\circ}\text{C}$)
High Density Polyethylene	0.80	33	141
Polyamide 66	0.70	20	267
Polyamide 6	0.35	3.3	229
Isotactic Polypropylene	0.63	0.33	183
Polyethylene Terephthalate	0.50	0.12	270
Isotactic Polystyrene	0.32	0.0042	240
Polycarbonate	0.25	0.00017	267

Table 2: The maximum degree of crystallinity $x_{c(max)}$, the maximum crystal growth rate $v_{(max)}$ and the melting temperatures t_m of some commonly used materials (taken from D. W. van Krevelen (60)).

Supercooling can be reduced by adding inorganic materials such as sodium phenylphosphinate, aluminium benzoate or lithium benzoate in concentrations of up to 0.5% which act as nucleating agents thereby inducing crystal growth at higher temperatures than might be expected. These materials can be used to great effect to dope materials that have low crystallization rates. Interestingly many of the commonly used fillers such as talc, silica, carbon black and kaolin are poor nucleators and will not significantly alter crystallization rates.

The spherulites formed in melts containing nucleating agents are smaller than those formed in unseeded melts because of there being more initiation sites available to form crystals. The presence of many small spherulites can be beneficial, improving the optical properties of some materials causing

them to be more glossy and have improved clarity. Similar improvements are seen in certain mechanical properties such as modulus, tensile strength and yield strain. There are however cases where too much crystallinity can be detrimental to product performance, for example, blue screw caps on shampoo bottles manufactured from polypropylene containing phthalocyanine pigments were found to fracture on tightening (61). This failure was attributed to the fact that the pigment was acting as a nucleating agent for the polypropylene. The nucleating agent, by altering the level of crystallinity, increased the amount of shrinkage of the cap causing the fit on the bottle to become too tight. It should be noted that this may not have been the sole reason for the top's failure that may have also been induced or aided by the stress cracking effect of a constituent of the shampoo.

Using nucleating agents generates significant cost savings by reducing the cooling time and therefore the cycle time. For a material such as polypropylene the saving in cycle time can amount to ~30%. Furthermore parts manufactured from materials doped with nucleating agents tend to be more dimensionally stable post-moulding because of the reduced susceptibility to post-moulding crystallization.

5.3 CHANGES IN PROCESSING CONDITIONS

The dimensional stability of moulded parts is very dependent on the processing conditions employed (16, 28, 29) as shown in Figure 6. However in industry the processing conditions are often less than optimal to keep the cycle time as short as possible in the belief that this will maximise profit. Following this cost driven approach can, however, be a false economy if many mouldings are lost through wastage.

Suggested changes in the moulding conditions that may result in the manufacture of parts that are less susceptible to dimensional instability are mainly concerned with filling the mould as quickly as possible. This can be achieved by increasing the injection speed or slightly raising the temperature of the melt to ensure that most of the material in the cavity is molten at the end of the injection phase and will benefit from the packing pressure until freeze-off at the gate. This will help to reduce shrinkage. Increasing the gate size normally permits a larger packing pressure to be applied for a longer period to the mould and helps the material flow into the cavity. Care must be exercised in applying the correct pressure to the mould. If the packing pressure is too low then there will be insufficient material available to compensate for the change in volume and the part will shrink. This effect can manifest itself locally if the mould is filled in such a way that certain regions, i.e. ribs are prevented from 'seeing' the packing pressure due to premature freeze-off of the surrounding areas. If the packing pressure is too large then excess material contained within the mould will cause the last area to freeze-off to be highly stressed. These highly stressed regions that are normally found near the gate are prone to failure in service through attack by fluids such as oil, fuels or organic solvents. In some circumstances the highly stressed, compacted material expands when ejected from the mould to relieve the internal stress thereby causing local distortion of the part.

Increasing the cooling time is an option that if followed will of course extend the overall cycle time and increase production costs. This may prove to be a cost effective strategy to follow if there is a significant reduction in the number of unacceptable products that are manufactured. By extending the cooling time the influence of applying lower cooling rates to the part or the effect of ejecting it at a lower temperature on dimensional stability can be assessed. Lowering the mould temperature can also be used to suppress crystallization that in turn reduces mould shrinkage. This latter option should be carefully considered before use since using the products at higher temperatures than that of the mould can lead to problems in service. Pierick (62) showed that resins moulded at 38°C but exposure to higher temperatures, i.e. 66°C were subject to post moulding shrinkage.

6 STANDARDS RELATING TO SHRINKAGE AND WARPAGE

Most of the currently used standards measure shrinkage in mouldings as some change in the overall dimensions. These standards are useful for quality control, i.e. assessing batch-to-batch variation of a material moulded using a given set of processing conditions. They can also be used to optimize processing conditions for a given material, mould and machine to ensure that the product size is within specification. However this procedure, because of its 'trial and error' approach, is both time consuming and expensive. The data generated are not useful for design purposes as measurements of overall dimensions cannot be used to obtain information concerning areas of local shrinkage that may, for example, occur near a gate. It should also be noted that currently available standards do not cater for fibre reinforced plastics.

6.1 Reversion standards

The reversion standards assess shrinkage of mouldings by comparing dimensions before and after a period of annealing at some elevated temperature. The shrinkage or reversion of the moulding is generally expressed as a percentage. Reversion is associated with a post moulding heat treatment.

ISO 2557 - Plastics - Amorphous thermoplastics - Preparation of test specimens with a specified reversion - Part 1 : Bars (1989)

This standard is used to injection mould testpieces with a specific amount of shrinkage. The method involves moulding many testpieces as rectangular bars or dumbbells over a range of processing conditions. The amount of molecular orientation that can be produced in a dumbbell testpiece is primarily dependent on the temperature of the melt and the injection time. The processing conditions used to manufacture the testpieces are chosen such that only one of these parameters is varied at any one time. Plotting the reversion of the testpieces as a function of the variable enables the processing conditions required to produce mouldings of any required reversion to be manufactured.

ISO 2557 - Plastics - Amorphous thermoplastics - Preparation of test specimens with a specified reversion - Part 2 : Plates (1986)

This standard describes a method for injection moulding film-gated rectangular plates from amorphous thermoplastics where the reversion of testpieces cut in directions parallel and perpendicular to the flow direction is known.

ISO 8328 - Plastics - Amorphous thermoplastic moulding materials - Determination of maximum reversion (1989)

A description of a method for assessing the amount of molecular orientation either in injection moulded thermoplastic dumbbells or rectangular bars cut from plate specimens. The standard only applies to unreinforced materials that have a high degree of uniaxial orientation.

BS 2782 (11) - Method 1102B. Longitudinal reversion of pipes: oven method.

This standard measures the change in length of thermoplastic pipe that has been subjected to a period of annealing at some elevated temperature. Details of the annealing conditions are given in the appropriate thermoplastic pipe standards.

6.2 Other shrinkage standards

ASTM D955 - 89 - Measuring shrinkage from mold dimensions of moulded plastics.

This standard describes a procedure for assessing the variation in shrinkage of mouldings manufactured under specific conditions from different batches of material. The standard covers thermoplastics and thermosets and caters for edge-gated rectangular blocks or discs manufactured by injection, compression or transfer moulding techniques. The shrinkage is determined at various times after moulding (typically at 24 or 48 hours) and expressed as:

$$\text{shrinkage} = \frac{l_f - l_o}{l_o}$$

where l_f refers to the length or diameter of the moulding and l_o is the equivalent dimension of the mould.

ISO/DIS 294-4 - Plastics - Injection moulding of test specimens of thermoplastic materials - Part 4: Determination of moulding shrinkage.

This discussion standard describes a procedure for determining anisotropic shrinkage of rectangular plates manufactured from thermoplastics. The data generated can be used to check the uniformity of manufacture and to explore the influence of different processing variables on shrinkage.

7 THE FUTURE

Companies are experiencing ever increasing pressures to reduce the lead times to production due to competition within the marketplace. Significant time savings can be made by using injection moulding

simulation software packages to reduce the time spent conducting moulding trials and establishing the optimum processing conditions. This software can be used during the design phase of the product and mould to predict the influence of different gating arrangements and processing conditions on, for example, filling behaviour and cycle time. The software can also be used to optimise packing profiles, to design efficient cooling circuits and to predict the dimensional stability of manufactured products. Using software in this way represents a change in design philosophy as such packages have in the past tended to be used only as trouble shooting tools to identify the factors responsible for causing poor quality mouldings. This change in the role that the software plays in design has generated a requirement for improved accuracy of predictions. To achieve this goal requires not only improvements in the algorithms employed but also in the quality and type of materials data that are needed. A discussion of these issues may be found in reference 63, some of which are being addressed in current research programmes at the National Physical Laboratory ⁶⁴.

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ANNEX 1 NOTES ON INJECTION MOULDING

The Machine

Figure 7 shows a schematic representation of a typical injection moulding machine. The machine hopper feeds pelletised plastic into the barrel which is heated by a number of band heaters and contains a reciprocating plasticising screw. The screw is used to compress, melt and transfer material into the mould cavity. The depth of the flights mounted on the screw varies along its length although the outside diameter remains constant. This arrangement effectively divides the barrel into different regions. Material fed by gravity into the feed zone beneath the hopper is both heated and compressed as it progresses along the length of the barrel. The energy required to melt the material comes in part from the band heaters mounted on the outside of the barrel and through viscous heating of the material as it passes through the compression zone. Material contained within the metering zone passes through a heated nozzle which makes contact with the mould via a sprue bush.

The Mould

The mould cavity is formed between a fixed platten and a movable platten which is brought into contact with the former via a hydraulic system. This type of two-part mould can contain a number of mould cavities. During the filling phase of the moulding cycle the nozzle is brought forward to the mould and material is injected into the cavity. Melt flowing into the mould from the nozzle is distributed to each cavity through a system of runners which are attached to a single sprue. The

runners terminate in gates which provide a point of contact between the runner and the cavity. Large or complex cavities can be fed by more than one gate which ensures that mould fills correctly during the injection phase of the moulding cycle.

The Moulding Cycle

The basic operations during injection moulding can be summarized as follows:

- the reciprocating screw moves forwards acting as a plunger injecting molten material into the mould cavity,
- after the mould has filled the screw continues to move slowly forward while applying a packing pressure,
- cooling of the molten material in the cavity eventually results in a progressive solidification of the melt. After freezing off at the gate the screw begins to retract, plasticizing material in preparation for the next shot,
- the mould opens and the part is ejected,
- the mould closes and the operation is repeated.

Detailed descriptions of injection moulded machines and their operations can be found in many textbooks, eg reference (16).

Flow induced residual stress

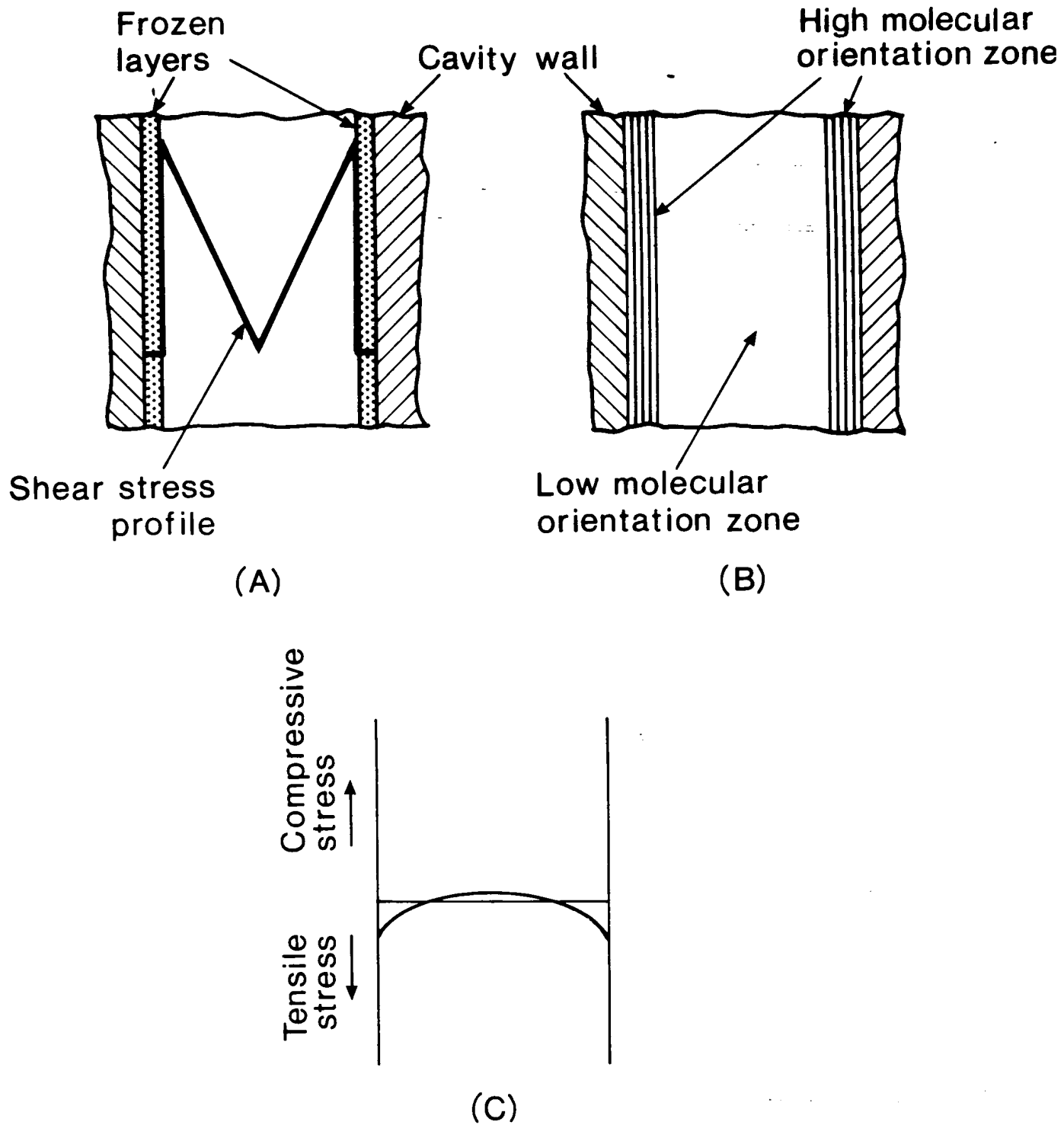


Fig.1 During mould filling the high shear stresses that occur near the walls of the cavity (A) induce the polymer chains to disort and become locally oriented (B). Rapid cooling of the melt at the cavity walls causes the chain distortion to be frozen into the structure generating local tensile stresses (C).

Thermally induced residual stress

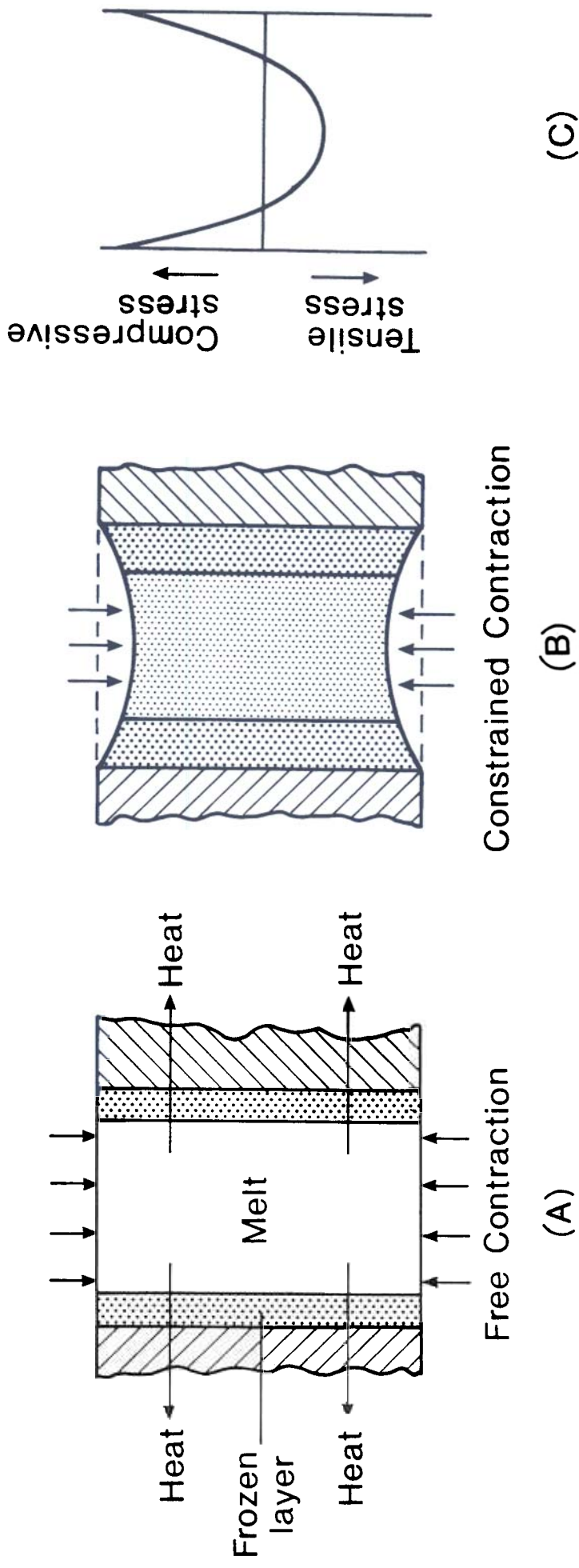


Fig.2 During the initial cooling of the melt the polymer nearest the cavity walls begins to contract. The volume change due to shrinkage is compensated for by a reduction in the packing pressure (A) which acts on the still molten core. During the later stages of cooling the core also contracts but is restrained by the already frozen outer layers (B). This generates both residual tensile and compressive stresses (C).

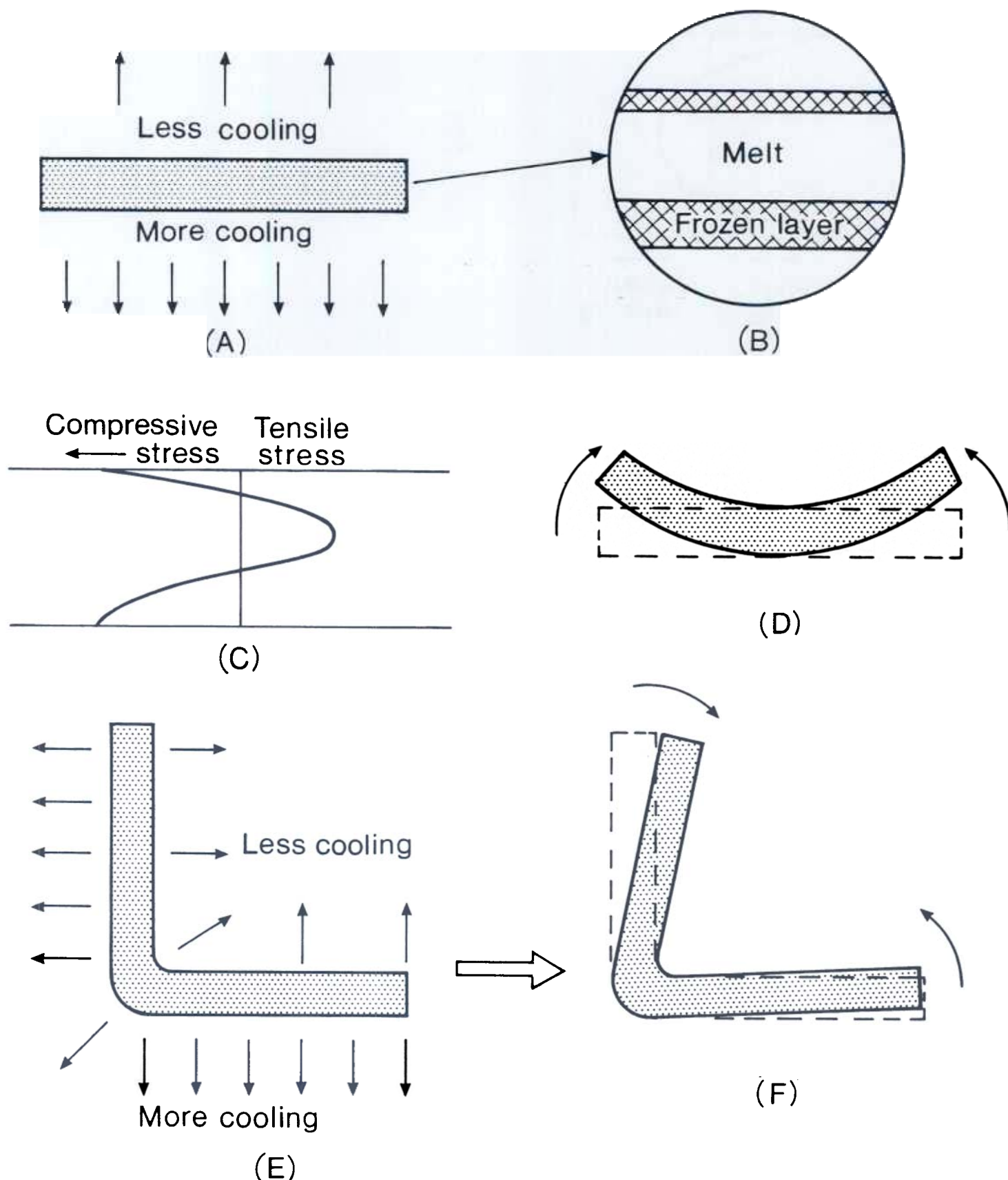
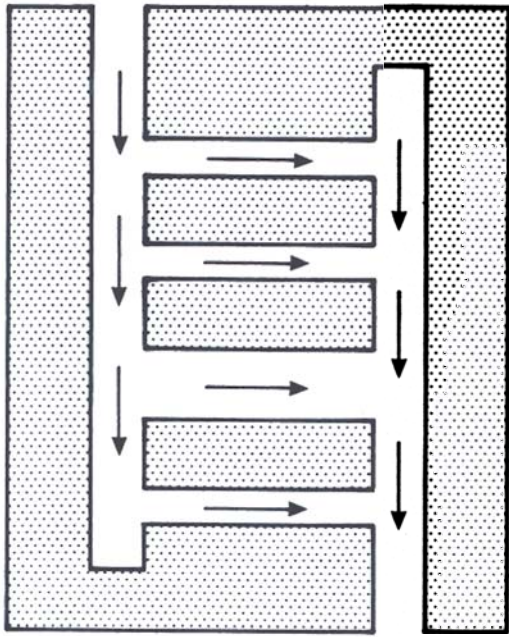
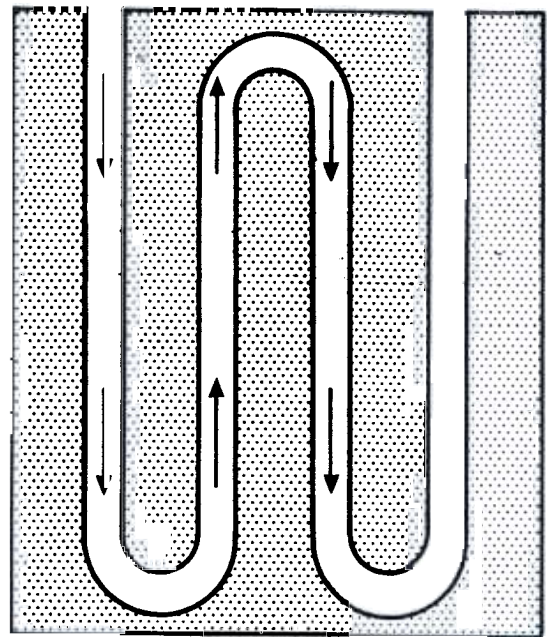


Fig.3 Unbalanced cooling of the cavity (A) leads to asymmetrical frozen layers (B) and hence unbalanced residual stresses (C). The greatest compressive stresses found on the cooler side of the moulding are relieved by the part bending in the opposite direction (D). Unbalanced cooling (E) at wall intersections also generates asymmetrical residual compressive stresses which are relieved by the walls 'toeing in' (F).



A



(B)

Fig.4 Mould cooling channels can be connected in parallel (A) or in series (B).

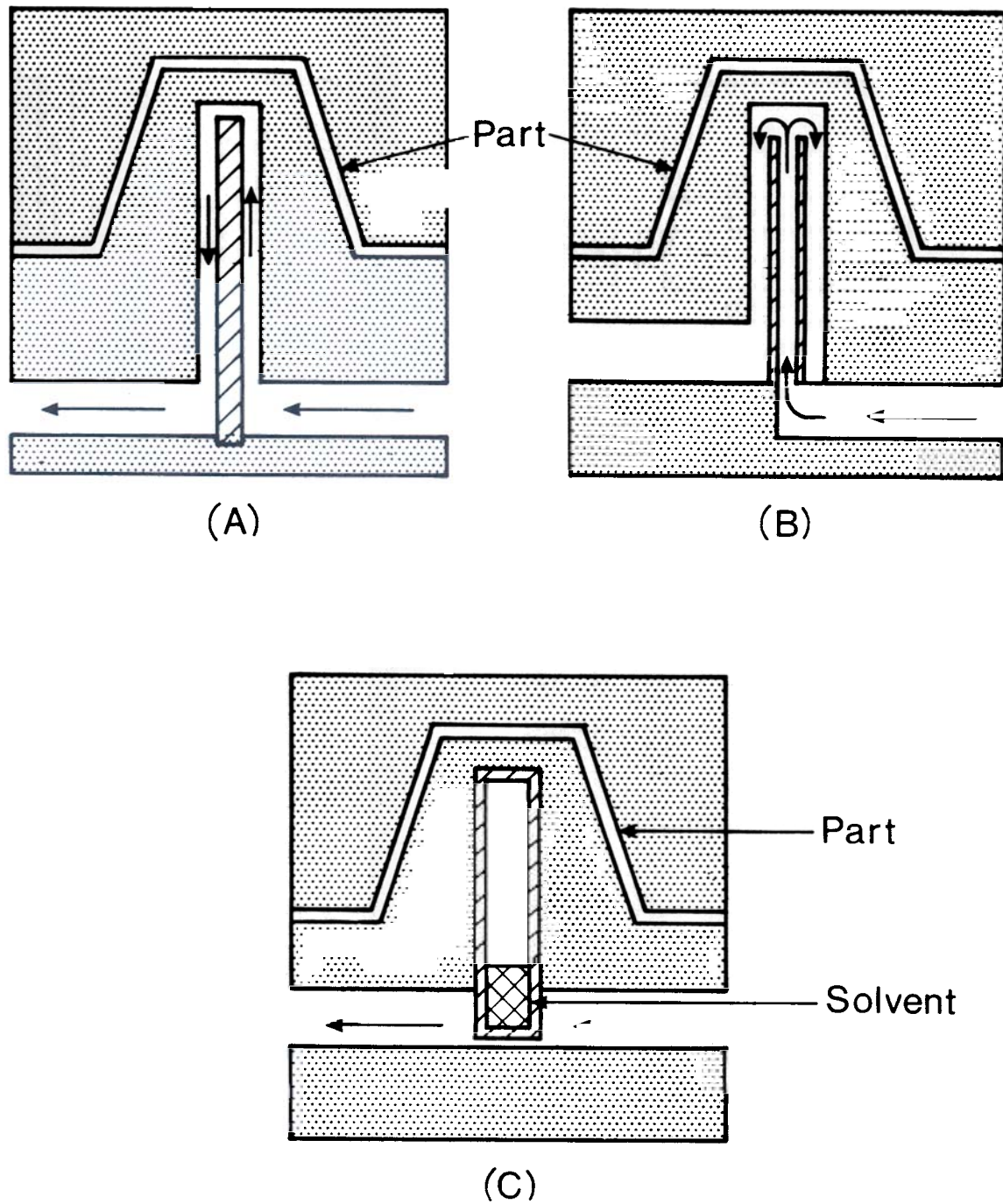
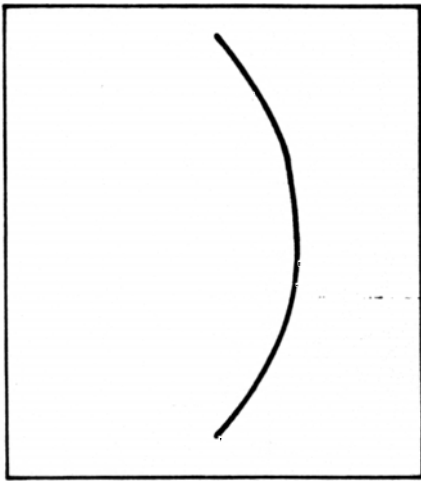
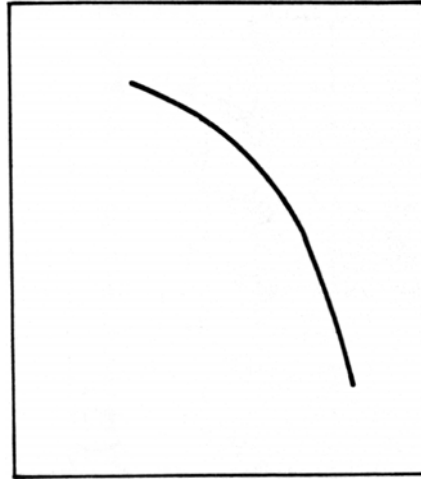


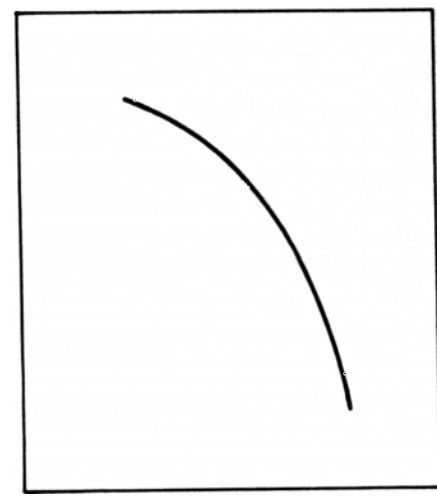
Fig.5 Examples of devices specifically developed for cooling potential hot spots in moulds include baffles (A), bubblers (B) and thermal pins (C).



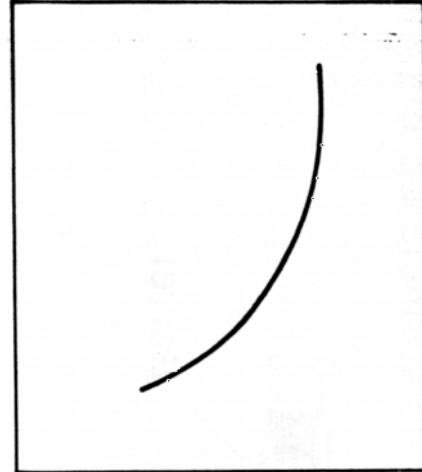
Injection Speed



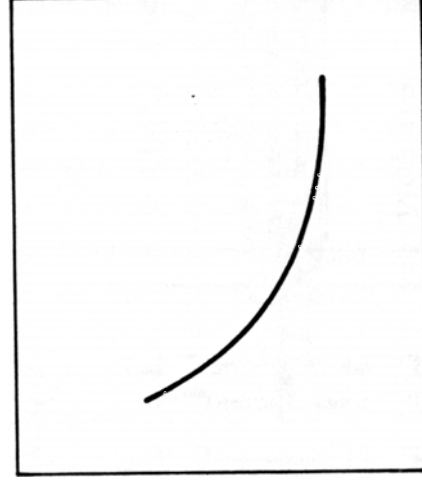
Mould Temperature



Melt Temperature



Residence Time



Packing Pressure

Fig.6 The effect of processing conditions on shrinkage (After (29)).

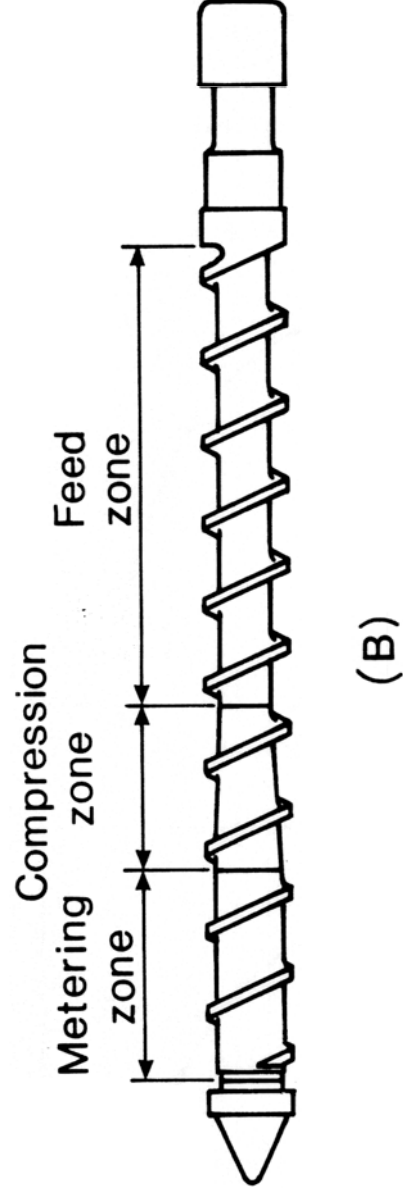
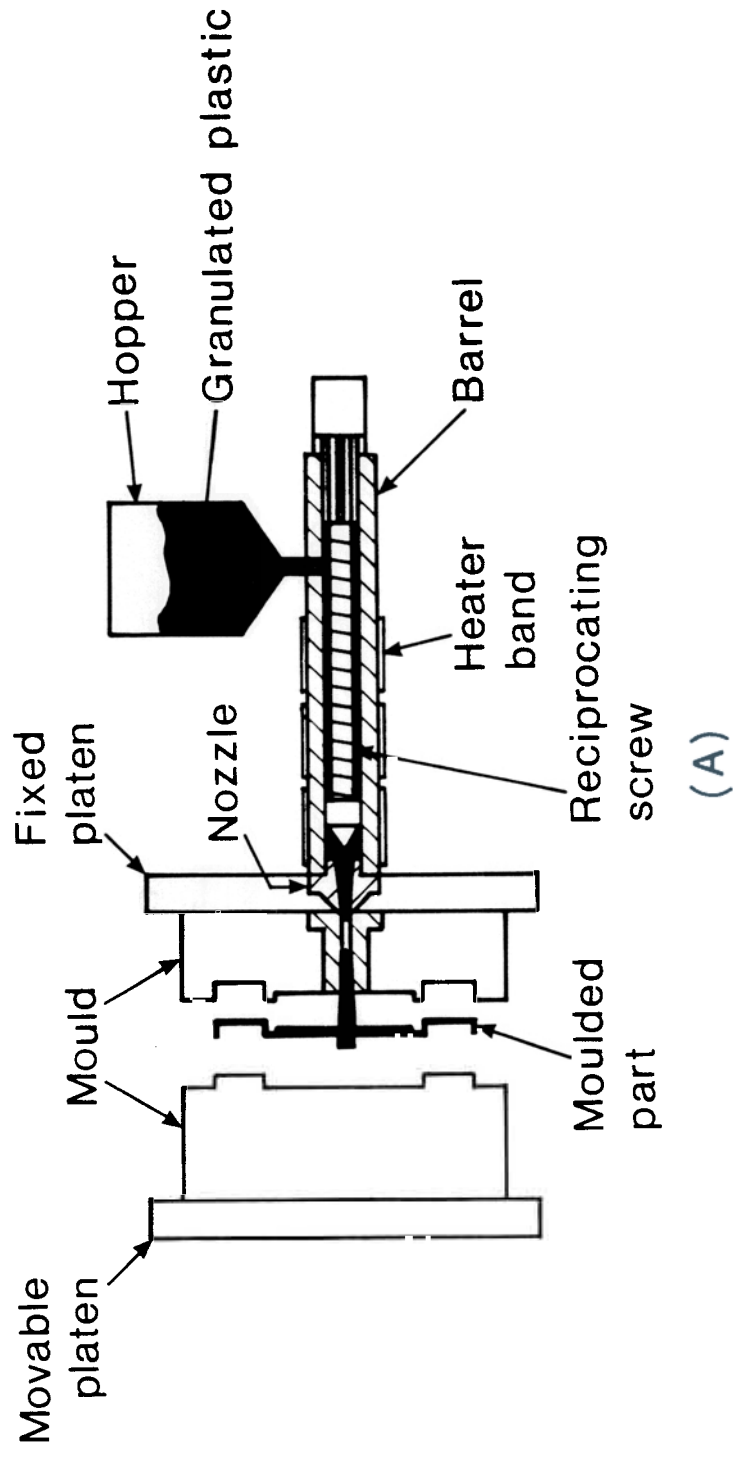


Fig.7 Schematic representation of an injection moulding machine (A). Details of the reciprocating screw showing the feed, compression and metering zones (B).