CMMT (A)60

Predicting and Controlling the Dimensional Stability of Injection Moulded Plastic Parts

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ABSTRACT

The dimensional stability of an injection moulded part will depend on its size and shape, the size and location of the gate feeding the mould, the grade and type of material and the processing conditions used to manufacture it. Unfortunately many of the factors that control the dimensional stability of moulded products are interrelated making it very difficult to design dimensionally stable products with confidence, despite the wealth of design and processing information currently available. However this situation is changing due to recent advances in software that simulates mould filling and estimates the shrinkage and warpage behaviour of moulded parts. The capabilities and limitations of these software packages together with their data requirements are described and discussed. Areas where further research could improve predictive capabilities are identified.

ISSN 1361-4061

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1 INTRODUCTION

Shrinkage of parts within the mould occurs during cooling of the melt because of thermal contraction. In the abscence of flow induced molecular orientation this shrinkage is isotropic and causes a small reduction in the overall dimensions of the part. In semicrystalline polymers further shrinkage occurs due to crystallization. This shrinkage is often anisotropic, being less in the principal flow direction along which the crystals align themselves. Shrinkage behaviour is also affected by the presence of fibres that limit the contraction of material along their length. This anisotropic shrinkage is often amplified over the part since the fibres become aligned in the directions in which the melt flows. Certain pigments and other additives can affect material shrinkage, either through changes in the kinetics of crystallization or in the rheological properties of the melt that in turn affects its processing characteristics.

Non-uniform shrinkage rates within the part can lead to variations in residual stress that may cause the product to warp. This can occur if different regions of the mould cool at different rates, or if there are differences in the shrinkage rates in directions parallel to and perpendicular to that of the flow. Non-uniform shrinkage can also occur during cooling of the melt as different regions of the mould freeze-off at different pressures. Pigments, additives and fibres added to the feedstock may also contribute to part warpage, indeed plastics containing reinforcing fibres are more prone to distortion than their unfilled counterparts. This behaviour is attributable to anisotropic shrinkage rates caused by the inhibition of shrinkage of the material in the direction of flow in which the fibres tend to align themselves with.

Some warpage problems (1) are caused by inappropriate storage of moulded parts. Typically after being ejected from the mould, parts are collected in bins and there is evidence to suggest that these mouldings, which are still warm and therefore ‘soft’, distort due to the weight of subsequently manufactured items acting upon them. Inappropriate packaging of parts for transit or storage can also cause post-moulding distortion.

2 BACKGROUND INFORMATION

Often companies cope with product warpage by modifying their manufacturing procedures, for example, by extending the cycle time so that the part is effectively annealed within the mould, or by jigging it after ejection. Many companies employing these practices may not realise that they have a warpage problem particularly if the remedial procedure is well established. Since companies *have* to overcome problems of dimensional instability, finding examples of problem products is difficult. However there are many instances where moulds have had to be refined or a different type or grade of material has had to be selected to produce acceptable mouldings.

Often firms manufacture a range of products that are variations in the size of a simple shape produced in a limited range of colours. Companies that have this type of product profile include manufacturers of pipes and their associated fittings, or those producing boxes for storage or to act as protective cases. The materials used to manufacture such items are limited either by the type of application or the need to conform to a particular standard. Usually the need to comply with these requirements only leaves the designer freedom to choose which supplier or grade of material to use. Such companies have a wealth of experience from which to draw regarding the location and geometry of gates and a practical understanding of how to optimise the processing conditions. It should, however, be noted that these companies can still produce unacceptable mouldings, particularly when manufacturing different coloured parts from a single mould cavity.

There are instances where occasionally often unexplained processing problems occur during production runs resulting in dimensionally unstable parts being manufactured. Many processors have experienced difficulties in moulding different coloured parts from the same mould due to differences in the shrinkage behaviour of pigmented materials (1). A recent example of this phenomenon occurred during the manufacture of shampoo bottle tops where excessive shrinkage of blue tops resulted in the fit to the bottles being too tight causing them to fracture on tightening (2). Currently injection moulding simulation software is unable to predict the mould filling behaviour of materials containing pigments unless they have been specifically characterised. Characterisation is both time consuming and expensive and the results obtained maybe unique to the particular concentrations of pigment and other additives present.

Because of competition in the marketplace, companies are experiencing ever increasing pressures to reduce the lead time between developing a design and beginning production. These reductions lead to products reaching their intended markets sooner thereby ensuring that often ephemeral customer demands can be met with products that are competitively priced. Evidence of this trend is seen in rapid prototyping (3). Rapid prototyping can refer to the manufacture of models that are cut from solid blocks of material or to the production of temporary moulds using stereo-lithography or similar techniques. Both these approaches use the co-ordinate information contained within CAD files. Pre-production moulds are typically made of epoxy contained within a shell of aluminium and can be used to produce a limited number of mouldings from wax. Using rapid prototyping techniques enables the 3-dimensional aspects of the design to be explored, i.e. fitness for purpose, appearance and feel. At this stage of the transfer from design to production there is some flexibility in the type of plastic to be used although this is influenced by costs and requirements for specific chemical, physical and mechanical properties.

Designing production moulds is an iterative process where the mould geometry and the characteristics of different materials or grades of a material have to balance in-service requirements of, for example, mechanical performance, surface finish and durability. Choices based on these criteria in turn are assessed against the design concept, the availability of a given material its processability and cost. The approach to tool design by different companies varies enormously ranging from those who design and manufacture tools 'in house' to others who subcontract these operations to consultants. In some circumstances the responsibility for ensuring that a given grade of material can be used to produce acceptable mouldings for a given tool design is taken by the material supplier. This situation tends to apply only to those companies that process large volumes of material who expect the material's supplier to assume liability in exchange for guaranteed sales. Cutting metal to form the mould is an expensive operation and for large moulds that can cost more than £250,000 this is a significant undertaking by the supplier in exchange for selling material to the processor. Discussions with companies suggest that consultants are either 'active' or 'passive'. 'Active' consultants offer constructive ideas regarding the design of the tool while those who act passively expect the customer to provide this information. These different approaches may be connected with issues of liability.

Before machining the cavity an allowance in its dimensions is made to compensate for shrinkage. This requires some knowledge of the materials shrinkage characteristics. The design and location of the gate or gates are also decided at this point based on either mould filling calculations or experience. Potential sites for the gate are often restricted by the requirement to put it in an unobtrusive position to avoid spoiling the finish of the part. Decisions concerning gate positions are also affected by the challenge of positioning several identical or dissimilarly shaped cavities into a mould. Companies vary in their approach to solving gating problems with some subcontracting the work to consultants while others do it 'in house'. Positioning and sizing the gate can involve some changes in the overall design of the part if calculations show that the mould is difficult to fill or if the rate of fill is uneven. Rectifying problems of this type may result in a local increase or reduction in the wall thickness that enhances or retards the flow of the melt into the mould thus ensuring an even fill rate or guiding the melt to areas that are difficult to fill.

Often the mould cavity is machined such that some 'excess' metal is left within it that can be subsequently removed if the shrinkage estimates are too conservative. Modifications to the mould are, however, expensive and time consuming and can significantly increase lead times. Overestimating shrinkage should be avoided since adding metal to the cavity is more expensive than removing it. Unfortunately any change in the dimensions of the cavity affects both the filling behaviour and the cooling characteristics of the mould that can lead to unexpected problems with part shrinkage or warpage. Most companies budget for 2-3 moulding trials to iron out problems of this nature with the mould and to optimise the processing conditions.

3 CURRENTLY AVAILABLE DESIGN INFORMATION

There is a wealth of information available to the designer or manufacturer of plastic parts that covers:

- structural considerations for part design, i.e. the dimensions of reinforcing ribs, bosses, and integral hinges,
- considerations for ease of moulding, i.e. draft angles and the location of seam lines,
- the design of feed systems for cavities including family moulds, i.e. runner and gate types, sizes and positions,
- the design of cooling systems, i.e. series or parallel cooling and the use of inclusions such as bubblers, baffles and thermal pins.

Much of this information can be found in articles aimed at designers and processors contained within (see Appendix 1 for examples);

- handbooks for injection moulders,
- design guides produced by software companies such as Moldflow and A.C. Technology,
- design guides produced by materials suppliers,
- general textbooks on plastic part design.

Some material supplier's guides can be down-loaded directly from the Internet. The Internet also has many discussion groups representing users of the principle software packages used for simulating injection moulding. These discussion groups provide a useful forum for airing processing or design problems and have the power to draw upon the experience of many people. While there is no doubt that this information is available, often those who seek to find it fail to do so through constraints on their time.

Despite the available information there are many instances where tool designers fail to produce good mouldings as they only partly follow established design procedures. A recent example of this occurred in a part where a rib section had been added to a flat region. The thickness of the rib was 2/3 of that of the wall on to which it butted, as recommended in design guides (4). However, attached to the rib was a comparatively large snap-fit connector. During moulding the snap-fit connector filled correctly but did not benefit from the packing pressure since the adjoining rib solidified before the snap-fit connector. This resulted in excessive shrinkage of the connector.

4 DESIGN ISSUES

Mould cavities have traditionally been, and still are designed according to the experience of the designer rather than by design software; similarly processing conditions are often found through a combination of experience and experiment. While these approaches are successful, they can be both time consuming and expensive to operate. There is always a danger that processing conditions discovered by trial and error will be on a boundary of the processing window and could fail to work due to some small changes in the feedstock composition or in the operation of the machine. More traditional practical approaches are less well suited to coping with developments in injection moulding technology, i.e. gas injection or in-line moulding of textiles. Many companies are now using software packages to design parts and optimise the processing conditions before production. In a recent survey (1) of moulders in the UK 60% of the respondents said that they used flow simulation software for evaluating designs.

There are many commercial advantages in using predictive software to design and model mould filling and to predict the dimensional stability of products that include;

- savings in man hours, for example CAD drawings can be transferred directly into software packages that model mould filling and hence into CAM software for manufacturing prototypes,
- savings in material due to lighter more efficient designs including that of the feed system to the mould cavity,
- savings in time due to improvements in the design of mould cavities that require less modification before being used in production,
- savings in man hours, material scrap and energy that would have been spent in finding suitable processing conditions for production runs.

5 PREDICTIVE SOFTWARE PACKAGES

The main software packages that are currently used to model mould filling and/or dimensional stability of moulded parts are:

- C-Mold (A.C. Technology (5)),
- Fillcalc (RAPRA (6)),
- Moldflow (7),
- Cadmould (8).

There is some feeling within the industry that the market leaders (Moldflow and A.C. Technology) have products that are equally successful at predicting filling of the mould. Modelling mould filling satisfies the needs of many users who then buy one or other of these products using issues such as purchase price, maintenance costs, training costs and technical support to discriminate between them. Users who wish to calculate optimum cooling arrangements or predict the dimensional stability of moulded parts will opt for either Moldflow or C-Mold as Fillcalc cannot currently predict warpage. There are differences between Moldflow and C-Mold in their data requirements for calculating warpage or shrinkage of parts. Moldflow obtain their shrinkage data from end-gated rectangular tab mouldings that have a grid pattern on one surface. After a period of equilibration of two weeks, measurements are made of the spacings between various points on the grid from which an empirical shrinkage relationship is derived (9). In contrast C-Mold requires the tensile modulus and Poissons ratio typically measured at room temperature to predict shrinkage (10). While obtaining these latter data is cheaper and less time consuming than generating moulded parts there is some question over its suitability for predicting the warpage of a production part at the temperature at which it is ejected from the mould.

6 PROBLEMS ASSOCIATED WITH PREDICTIVE SOFTWARE PACKAGES

Many issues affect the use of software packages as design tools, some of which are financial whereas others involve an element of resistance by employees and employers to changes in work practice. There have been many instances where software packages have been used to generate incorrect solutions. The software demands some understanding of the physics of mould filling and the origins of shrinkage and warpage. Occasionally there is evidence to suggest that some ‘problems’ associated with the software are due to the operator who may have an inappropriate background or be unfamiliar with all the nuances of the software. There are other instances where companies have used shortcuts to save money by establishing limited maintenance agreements with the software houses which results in them not being supplied with new versions of the programmes when they are released. While many ‘improvements’ in the software are cosmetic, developments are also made in the algorithms that lead to improved accuracy of the predictions. Using old versions of the software can be damaging for the reputation of the software house since users often refer to the product name and ignore the version number when they complain about accuracy.

Some problems have been experienced in companies who employ recently qualified staff who are more inclined to use predictive software than their older colleagues because of exposure to the packages at college and to compensate for their lack of moulding experience. This can lead to problems if the solutions generated by the software are significantly different to those that would have been used based on experience. There are examples of situations where toolmakers have refused to manufacture tools with novel low volume runners instead of large volume designs that they have manufactured for years and believe to be necessary.

Examples can be cited where using software has generated significant cost savings through improvements in the design of the sprue, runner and gate. These savings result from using less material in the feed system and running with a shorter cycle time. Information relating to the successful use of simulation programmes has mainly come from the software houses who are keen to promote their products. Information illustrating the technical limitations of the simulation packages is more difficult to find, particularly as many perceived deficiencies in the software can be attributed to user error.

7 CURRENTLY AVAILABLE DATA

Shrinkage data for comparative purposes are often presented as a rate expressed in cm/cm (or as a percentage) in the material suppliers data sheets. A single rate is given for isotropic amorphous materials while two values tend to be quoted for anisotropic semicrystalline materials, one reflecting the shrinkage in a direction parallel to the flow and the other perpendicular to it. This data is normally obtained from measurements made on 4 mm thick injection moulded dumbells (11). The processing conditions used to manufacture the dumbell tend to be those specified in the appropriate materials standard. In practice these published shrinkage rates at best provide only qualitative indications to the processor whose products are likely to have a variable wall thickness and be processed under different conditions to those recommended in the standard. In comparison quantitative predictions of the expected shrinkage and warpage behaviour of 'real' mouldings can be obtained using injection moulding simulation software. These packages do require significant amounts of rheological data to compute the flow of the melt into the cavity. Additional information is required to compute the shrinkage behaviour of the material. For C-Mold this amounts to a tensile modulus and Poisson's ratio, whereas Moldflow requires the coefficients of an empirical function. These coefficients are derived from measurements of the shrinkage that occurs in a moulded rectangular tab.

Although databases for the various software products have been continually expanding there are problems concerning funding of materials data collection programmes and who should decide which methods should be used to measure it. It can be argued that the material supplier should provide the data as the existence of their product in the database could benefit their sales. This can be very expensive for the supplier if the data requirements vary between the software packages and if the number of users of these products is small. Material users may pay for specific formulations to be characterised for their own use in the software following the argument that this investment will pay for itself through improved productivity in a reasonable time. It has also been suggested that the software house should pay for data collection since the presence of a large database will be beneficial to their sales.

A research project (12) has recently been carried out to develop standards concerned with obtaining rheological data for predicting the flow that occurs during cavity filling. This has been a particular problem for fibre-reinforced materials where the apparent viscosity of the melt can be influenced by the fibre type and content and the geometry of the rheometer (13).

8 PARTICULAR PROBLEMS ASSOCIATED WITH CALCULATIONS OF SHRINKAGE AND WARPAGE

Calculating the amount of shrinkage and warpage in a moulding is a complex task. The accuracy of these calculations depends not only on the quality of the algorithms used but on the quality of the materials data required. Often the amount of information that needs to be processed is reduced to limit the amount of computing time required to complete the calculations. This can be achieved by averaging mesh elements through the thickness of the moulding. This practice inevitably leads to a loss of information and accuracy which is traded for a saving in computation time and in the storage space required for temporary files generated during the calculations. (Noting that some of the temporary storage files can occupy 70 - 80 Mbytes of disc space).

Accurate predictions of anisotropic shrinkage and hence warpage require a knowledge of the following quantities:

- the volumetric shrinkage that occurs during cooling which is derived from Pressure-Volume-Temperature (PVT) data,
- the level of crystallinity within the material, calculated as a function of temperature during cooling of the melt until the no-flow temperature is reached,
- the residual stress within the moulding immediately prior to it being ejected from the mould,
- the molecular orientation that exists within the moulding, a time and directionally dependent quantity that is affected by the melt's shear history and molecular relaxation kinetics.

A number of assumptions have to be made in calculating any of the above quantities either to reduce the time required to complete the calculations or to model what is a complex problem. The accuracy of some calculations is limited by lack of suitable experimental data, for example PVT relationships are typically measured under semi-equilibrium conditions and are unlikely to represent the expected shrinkage behaviour of a melt being cooled at rates in excess of 100°C min^{-1}. Although it should be noted that at least one company has attempted to account for this disparity within their software (7). Similarly calculations of crystallinity levels usually contain parameters derived from the crystallization kinetics of a generic material type. Such calculations make no allowances for the often considerable changes in the crystallization behaviour that occur due to variations in the grade of material or to the presence of pigments, fillers or other additives. It should also be noted that the kinetics of crystallization will depend on how much molecular alignment remains within the melt and how it is cooled. Predicting the development of residual stress in the moulding requires a knowledge of the temperature dependence of the volumetric shrinkage, crystallization kinetics and molecular alignment.

It is perhaps not surprising from the above discussion that current predictions of shrinkage and warpage are limited in their ability to describe that which occurs in practice. To overcome these deficiencies one of the market leading software houses uses shrinkage data obtained from moulded rectangular plates to modify their calculations with the exception of feedstocks that have a significant glass-fibre content (>20%). These rectangular plates have a grid moulded into one surface and are moulded using a range of processing conditions. Shrinkage over the surface of the plate is measured at a number of points after a period of storage at room temperature. A least-squares fit to this data is used to determine values for coefficients that are used to weight the relative contributions from the volumetric shrinkage, the level of crystallinity, the amount of residual stress and the degree of molecular orientation. This procedure is both time consuming and expensive and only provides data for a feedstock of a particular composition. The data is of particularly limited use if the calculated dimensional instability of the moulding is unacceptable as the designer will not have the freedom to explore the influence of using different types and concentrations of pigment or additives on the predicted shrinkage or warpage behaviour.

9 THE WAY FORWARD?

Designers need to be able to accurately predict the dimensional stability of complex mouldings and to scan a range of differently pigmented feedstocks to ensure that the shrinkage behaviour of each is comparable. Matching shrinkage behaviour of feedstocks enables differently coloured parts to be moulded using a single cavity. To achieve these goals it will be necessary to obtain PVT data that reflects the cooling rates experienced by the melt during injection moulding and to improve the accuracy of the calculations of residual stress, levels of crystallinity and molecular orientation. The problem of obtaining suitable PVT data is being addressed at the present time (14) in a project directed at producing new designs for obtaining such data. The accuracy of residual stress calculations appears to be limited by the computing power currently available on work stations and personal computers. There is scope to improve predictions of the degree of crystallinity. This could be achieved by modelling the influence that the melt's shear history and the presence of pigments and other additives such as fibres have on the kinetics of crystallization. This information would allow the designer to get closer to achieving the goals described above and could lead to substantial savings in both time and money spent in experimentally measuring the shrinkage behaviour of rectangular plates.

10 SUMMARY

There is a wealth of information available covering both the design of plastic parts and the influence of processing conditions on the dimensional stability of moulded products (15). Unfortunately using this information effectively is difficult as the shrinkage behaviour of each part depends on its shape and size, the material and the processing conditions used to mould it. Moreover many of the factors that affect shrinkage cannot be altered independently. Recent developments in predictive software are helping to remove some of this uncertainty by calculating how the mould fills and the subsequent dimensional stability of the part. However the algorithms contained within the current software are unable to model the influence of pigments and other additives on shrinkage behaviour unless the rheological and shrinkage properties of the material are experimentally determined. This is important to plastic processors who use a single cavity to mould a range of coloured parts. Variations in the shrinkage of different pigments in the feedstock will result in variable part sizes and may induce warpage.

11 ACKNOWLEDGEMENTS

This work was funded by the United Kingdom Department of Trade and Industry as part of the ‘Materials Measurement Programme’, a programme of underpinning research. This document reflects the opinions of many designers, plastic processors and providers of software who cannot be identified for commercial reasons. The author would also like to thank Martin Rides and Beverley Aylett of the National Physical Laboratory for helpful discussions during its preparation.

12 REFERENCES

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7 Moldflow, Moldflow Pty. Ltd, Kilsyth, Victoria, Australia.

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9 Material Testing Theory Manual, Moldflow Pty Ltd, January 1992.

10 C-Mold Users Guide; Shrinkage and Warpage, A.C. Technology, Ithaca, New York, 1995.

11 ISO 3167 Plastics - Part 9. Sampling and test specimen preparation, 1993.

12 M. Rides “Polymer moulding models: The determination of the elasticity of polymer melts” National Physical Report, CMMT(B)85, 1995.

13 ISO 11443 Plastics- Determination of the fluidity of plastics using capillary and slit-die rheometers, 1995.

14 Further details of a project entitled 'Thermophysical Properties of Polymers (Project MMP12, 1996-1999)' are available from the author.

15 P.E. Tomlins "The dimensional stability of injection moulded parts: a critical review of the technology base", National Physical Report CMMT(A)60, 1996.

APPENDIX 1 SOURCES OF INFORMATION FOR PLASTIC PART DESIGNERS AND PROCESSORS

This appendix gives a brief list of handbooks and general design books that are currently available to help the designer in developing new moulds.

- C-Mold Design Guide: A Resource for Plastics Engineers, A.C. Technology, Ithaca, New York, 1994.
- Injection Moulding Handbook (2nd Edition), D.V. Rosato and D.V. Rosato, Chapman and Hall, USA, 1995.
- Shrinkage, Warpage and Stress Analysis Manuals, Moldflow Pty. Ltd, Australia, 1993.
- Plastic Part Technology, E.A. Muccio, ASM International, Ohio, 1991.
- Injection Moulding Materials, A. Whelan, Applied Science Publishers, Essex, 1982.
- Injection Molds: 108 Proven Designs, Society of Plastics Engineers, 1993.
- How to make Injection Moulds, Society of Plastics Engineers, 1993.
- Plastic Processing Technology, ASM International, Ohio, 1994.
- Warpage Design Principles: C. Austin, Moldflow Pty. Ltd 1991.

The Internet addresses listed below, give some insights into the information that is available on the world wide web:

- PolySort-Injection Moulding Discussion Group, *http://www.polysort.com/discuss/inject/messages/msgs26400.html*
- General Electric home page, *http://www.ge.com/plastics*
- General Electric ULTEM Design Guide, *http://www.ge.com/gep/ultem/udgtoc.html*
- Plastics Network, *http://www.plasticsnet.com*