Precision Injection Molding

Process, Materials and Applications

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1 Precision Injection Molding: Overview and Scaling Considerations

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1.1 Introduction

With the explosive growth in information technology over the past three decades and the advent of mass-produced information storage devices (e.g., CD, CD-ROMs and DVD), and other related products much attention has been given to the injection molding process as the most cost-effective and agile processing technology for manufacturing such demanding components on a mass scale. Also, microfluidic devices for medical diagnostics have recently created a new demand for injection molded precision parts. One of the key aspects of the production of such articles is the need to meet extremely tight dimensional tolerances—typically in the submicron range—and maintain these tolerances over the practical lifetimes of the molded articles. In addition, because many of the precision components are utilized in various optoelectronic applications, control of optical and electrical properties is often crucial.

The strict control of the geometric and functional features of precision components requires a systematic reexamination of the conventional injection molding (CIM) process with special consideration of its impact on the dimensions and electro-optical characteristics of the molded article. We will show, in fact, that precision injection molding (PIM) is a special subclass of the conventional process with a distinct set of design, processability, and optimization criteria. This volume examines precision injection molding from different perspectives, covering materials, process, and hardware with a special emphasis on the dimensional integrity and stability of the molded components. In the sections below we provide a general framework and key definitions for discussion and examination of PIM technology.

1.2 The M-Chain of Precision Molding

The attainment of tight dimensional and functional tolerances requires a complete—from the ground up—examination of the injection molding operation following the so-called M-chain of precision molding*:

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* This term was coined during the precision-molding project at Philips PMF in the late 1980s.

- *M*an/operator
- *M*achine
- *M*old
- *M*ethod
- *M*aterial

While most operations today are fully automated and robotics is widely utilized, the presence of a skilled operator ("*man*") is essential for high precision applications, when operating at the edge of the capabilities of injection molding technology. These operations are characterized by a very tight process window, where continuous monitoring and frequent intervention may be required to meet the demanding specifications of the corresponding products. High precision operations require close attention to detail and involve such diverse functions as material specification and handling, mold design, machine design, system operation and maintenance, clean room operations, and product handling and certification. All of these functions require skilled and experienced operators.

The *machine* is another key element in the chain. The machine is responsible for melting and plasticating the material and precisely and reproducibly metering the molten resin into the mold. This requires tight control on temperature, displacement volume, and injection speed, and fast and reproducible changeover from injection to packing (section 1.3). PIM machines are generally distinguished by precision machining and sophisticated closed-loop control systems used to deliver the necessary injection accuracy and reproducibility (chapters 10 and 11 [1, 2]). Micro-molding machines, designed to handle small injection volumes and precise displacement, are typically used for very small parts (chapter 9 [3]). These machines utilize somewhat different process control algorithms compared to more standard PIM machines because of the very small displacement volumes and thermal loads associated with these operations.

The *mold* is another crucial element in the M-chain. All parts and inserts of the mold must meet precise machining and assembling tolerances (chapters 8 [4] and 11 [2]). Additionally, it is important to ensure that the temperature of the mold is uniform and stable throughout the molding cycle, through careful design and maintenance of the mold cooling/heating system as well as close monitoring and control of mold temperature. When hot material is injected into the mold, it tends to expand perpendicular to the parting line, causing the two mold halves to separate in response to the hydrodynamic force exerted by the injected melt. The mold must be sufficiently stiff to minimize this displacement and prevent fluctuations in cavity dimensions cycle-to-cycle while maintaining the desired dimensional tolerances for the molded article.

Different types of molding operations (*methods*) are often considered for molding precision parts. The first type is the conventional molding process wherein a hot melt is injected into a relatively cold mold in which the final part is formed. In this process the mold is essentially "passive," in the sense that it does not contribute independently to the pressure within the mold cavity. A common variant of the conventional process is the so-called hybrid or injection-compression molding process in which pressure can be applied directly in the mold cavity (in a manner akin to compression molding) and independently of the molding machine [5]. In this case the mold is said to be "active." This latter process is considered more effective in replicating very fine surface features as in the case of the compact disc (section 1.3 and
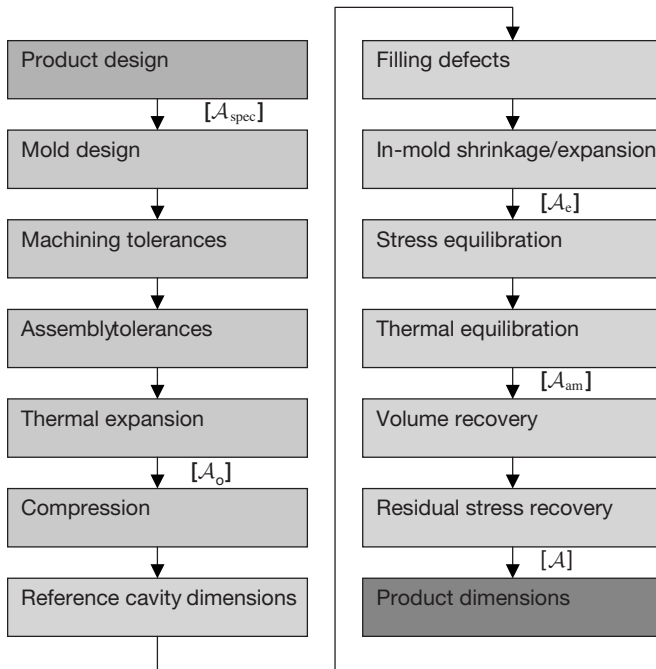
Figure 1.1: From product design to finished component: design and process steps of the M-chain of precision molding

chapter 4 [6]). Other variations of the conventional process (e.g., gas- or water-assist injection molding [7]) are also used to minimize shrinkage, sink marks, and other surface defects. In these processes carbon dioxide or water are typically co-injected into the mold to equalize and better control the pressure inside the mold cavity during the packing phase (section 1.3). Other modifications of the process with important implications for the achievable precision are two-component molding and over-, outsert-, and insert-molding [8]. All of these processes are capable of improving the dimensional integrity of the part since the effective shrinkage of the polymer is lowered by the presence of a preformed insert.

Finally, a key element of the M-chain is the *material*. Material (polymer) properties control both the processability and manufacturability of the molded article as well as its final attributes and functional performance. Mold shrinkage is one measure of the ability of a given material to accurately replicate fine features and meet tight dimensional tolerances (section 1.3). Typically, amorphous polymers exhibit lower shrinkage (0.3–0.8 %) than semi-crystalline polymers (1–3 %) [9]. The indicated values do not represent the best one can achieve with the given materials but it rather expresses the general level of difficulty in meeting tight dimensional specifications with the corresponding material type. Thus, it is clear that amorphous polymers are most suitable for PIM operations, although other material classes should not be, and, in fact, are not, excluded. It is known, for example, that shrinkage and other dimensional characteristics of the material can be substantially improved by the addition of inorganic fillers [10].

Dimensional stability, however, is generally enhanced with an increase in the glass transition temperature (T_g) of the polymer (chapter 2 [11] and section 1.4) relative to the service temperature of the part. Thus, high-T_g, amorphous polymers filled with an inorganic filler (nano- or micro-particles might be considered) would seem to offer the best dimensional stability, although the melt rheology, processability, and optical properties of such materials could be compromised, depending on the application.

A qualitative diagram representing the various steps and issues involved as we move from the product design phase to the final precision part is shown in Fig. 1.1. The final dimensions of the molded article can be influenced by many factors. The main steps affecting precision molds are listed on the left side of the diagram. The actual configuration (shape and dimensions) of the cavity at the instant of filling is generally considered as the reference configuration relative to changes occurring during the filling, packing, and cooling stages (section 1.3), which are listed on the right side of the diagram along with effects associated with the time-dependent response of polymers, such as strain recovery and physical aging. These material and process issues, relevant to PIM technology, are discussed in more detail in the following sections.

1.3   Dimensional Integrity

The configuration (shape and dimensions) of a molded part is intimately related to the thermo-mechanical history of the material in the mold cavity during the process cycle, the cavity geometry, the physical properties (particularly the compressibility and thermal expansion coefficient) of the material, and the environmental conditions and stresses applied on the part during its functional lifetime outside the mold. The configuration of the molded part can be generally decoupled into two main contributions: (a) the "as-molded" configuration (*dimensional integrity*) and (b) changes in configuration over time (*dimensional stability*). The as-molded configuration is determined by the state of the material in the mold cavity at the instant just prior to mold opening, the abrupt changes in pressure and stress upon ejection, and the subsequent unconstrained cooling of the solid part to ambient temperature after ejection from the mold. The final configuration of the as-molded part is controlled by several distinct, though strongly coupled, factors, including the pressure and temperature histories in the mold cavity, cooling (thermal) stress, warpage, and shrinkage.

The *pressure history (in-cavity pressure)* is imposed on the material during the molding cycle and is closely associated with several process parameters (e.g., injection pressure, holding/packing pressure, shot size, clamping force, injection rate), but its evolution over time depends on the cavity geometry, the temperature history of the material inside the cavity, and the thermal expansion coefficient and compressibility of the material. *Cooling (thermal) stress* is induced by the inhomogeneous cooling and solidification of the material in the cavity during the molding cycle, and it may lead to severe distortion of the as-molded part if not properly accounted for. *Warpage* relates to the distortion induced by the inhomogeneous shrinkage and relaxation of residual stress in the part once outside the mold, while *shrinkage* simply expresses the overall dimensional change as the unconstrained part cools down to ambient temperature.

The configuration of the molded part can be represented by the functional

$$\mathcal{A} = \mathcal{A}\left(\mathcal{A}_{o}, P, T; t\right) \tag{1.1}$$

where P and T are the spatially inhomogeneous pressure and temperature histories, and $\mathcal{A}_{o}$ is the cavity geometry. This configuration can be decoupled into two distinct contributions:

$$\mathcal{A} = \mathcal{A}_{am} + \Delta\mathcal{A}(t) \tag{1.2}$$

where $\mathcal{A}_{am}$ is the as-molded configuration, and $\Delta\mathcal{A}(t)$ expresses the change in configuration over time brought about by various material and environmental factors discussed in section 1.4. $\mathcal{A}_{am}$ can be further decomposed into two components

$$\mathcal{A}_{am} = \mathcal{A}_{e} + \Delta\mathcal{A}_{s} \tag{1.3}$$

where $\mathcal{A}_{e}$ is the configuration of the part at the end of the molding cycle, immediately after the part is ejected from the mold (i.e., at $t \sim t_{e}^{+}$, see Fig. 1.2) and $\Delta\mathcal{A}_{s}$ is the change in configuration caused by shrinkage, warpage and related phenomena as the part cools freely from its terminal temperature at the end of the cycle, T_{e}, to ambient (T_{amb}). $\mathcal{A}_{e}$ is controlled by the relief of residual stresses and the abrupt decompression as the solid part is forced to eject from the mold cavity. If the desired configuration is $\mathcal{A}_{spec}$ and the tolerance is ε, we require that

$$\mathcal{A} - \mathcal{A}_{spec} \leq |\varepsilon| \tag{1.4}$$

The tolerance is typically specified by the product designer and is expected to be quite small in PIM operations.

1.3.1   Pressure History

One of the most critical process functions in PIM is the in-cavity pressure history. To understand the role of in-cavity pressure, it is useful to examine a typical pressure history as recorded inside a mold cavity during the injection molding cycle (Fig. 1.2). As shown, the cycle can be divided into two phases: (i) filling, which is governed by the hydrodynamics of the melt flowing into the cavity as the material is injected into the mold and (ii) post-filling, which commences as soon as the cavity is completely filled and is controlled by heat transfer in the mold cavity and the compressibility of the solidifying melt. The latter can be further divided into two stages: (1) packing, for $t_{fill} < t < t_{gf}$, and (2) cooling, for $t_{gf} < t < t_{e}$. The post-filling phase is usually characterized by large and abrupt changes in pressure and temperature inside the mold cavity. During the packing stage, the pressure grows rapidly, under nearly isothermal conditions, to some high value, P_{p}, which is usually held for only a short interval and is controlled by the hold pressure applied by the machine hydraulics. At t_{gf} (the "gate freeze-off" time) the material in the gate area solidifies, and the material becomes effectively locked inside the cavity and physically isolated from the injection molding machine. After t_{gf}, the heat transfer to the mold surfaces and the compressibility of the material lead to a monotonous decay in pressure until
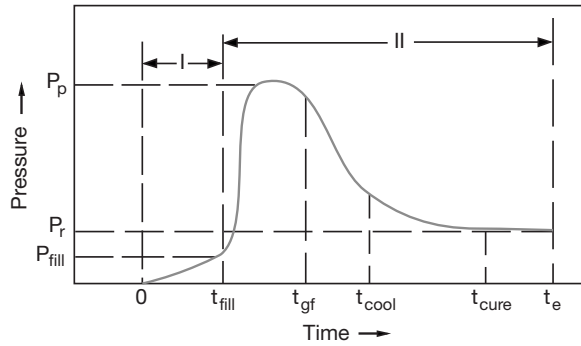
Figure 1.2: A schematic in-cavity pressure history

the termination of the cycle at t_e wherein the mold opens and the solidified part is ejected. t_{cool} and t_{cure} mark two important events during the cooling stage. At t_{cool} the material at the innermost point in the cavity passes through the glass transition temperature, T_g (for this discussion, we consider only amorphous polymers, although similar arguments can be applied to semi-crystalline polymers or thermosets), i.e., at $t > t_{cool}$ the material in the cavity is fully vitrified though not yet equilibrated to the mold temperature ($T_{mold} < T \leq T_g$). At t_{cure}**, the system approaches a thermal steady state, i.e., the temperature becomes evenly distributed throughout the cavity space ($T \approx T_{mold}$), and the pressure approaches an asymptotic value, P_r, the residual pressure. If the cycle is terminated before complete vitrification ($t_e < t_{cool}$) or even before thermal equilibration ($t_e < t_{cure}$), the part is likely to distort and warp in the subsequent free-cooling stage (cooling outside the mold from T_e to ambient) as a result of the ensuing inhomogeneous shrinkage. Similarly, if P_p is too low (insufficient packing), the pressure in the cavity will go to zero at $t < t_{cure}$ and the material will delaminate from the cavity walls before t_e (the *terminal time*), leading to inadequate replication of the cavity geometry. Several qualitative packing scenarios and corresponding trajectories on the volume-temperature space of the material are illustrated in Fig. 1.3. General criteria for selecting P_p and t_e and their impact on the part configuration are discussed elsewhere [12].

While the pressure could directly impact the part geometry, the complete thermo-mechanical history (i.e., the time evolution of pressure, temperature, and deviatoric stress) controls the thermodynamic state of the molded material, which carries some implications for the dimensional stability of the part (section 1.4). Because of the general spatial nonuniformity of the thermo-mechanical history within the cavity, injection molded parts are inherently inhomogeneous [13, 14], which could lead to inferior dimensional integrity and poor dimensional stability. This inherent deficiency can be practically mitigated by using a hybrid (injection-compression) molding process [5], whereby the pressure in the cavity during the post-filling stage is held at a constant level and is spatially uniform. This process requires an "active" mold and it involves a switchover from an injection to a compression mode at the beginning of

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**This is a misnomer as there are typically no curing reactions during the molding cycle. This term, however, is commonly used by molding engineers and machine operators.

Figure 1.3: (a) Three packing scenarios and (b) corresponding trajectories on the volume-temperature space of the material [12]

the packing phase, whereby the pressure in the cavity becomes constant while the volume (thickness) of the cavity decreases as the material cools down.

1.3.2   Cooling Stresses

Residual cooling (thermal) stresses are an inherent feature of the injection molding process with a potentially detrimental effect on the dimensional integrity and stability of the molded part. These stresses are induced by the inhomogeneous and rapid cooling in the cavity as the material vitrifies, and they often lead to complex residual stress and birefringence patterns [15–17]. For a one-dimensional case of a simple vitrifying liquid, the cooling stress can be scaled as

$$\sigma_c \sim \alpha \left(T_g - T_{mold} \right) \frac{EH^2}{(1-\nu)}.$$ (1.5)

Where α is the thermal expansion coefficient, E is Young's modulus, ν is Poisson's ratio of the solid polymer, and H is a characteristic thickness of the molded article. It must be noted that although Eq. 1.5 applies specifically to the case of free quenching of a slab, quite unlike the quenching in an enclosed molding cavity (constrained quenching) [18, 19], it may be used for scaling purposes. Based on Eq. 1.5, we can define a characteristic surface distortion (strain) by

$$\delta_c \sim \alpha \left(T_g - T_{mold} \right) H^2$$ (1.6)

Thus, the distortion induced by cooling stresses can be minimized by raising the mold temperature closer to T_g and by reducing the thickness of the part. In general, however, the residual stress distribution in the molding cavity is determined not only by thermal shrinkage but also by differential compression of the polymer melt during vitrification inside the cavity. Thus, tensile residual stresses are typically produced at the cavity surfaces wherein the material vitrifies under relatively low pressures during the filling phase, while compressive residual stresses are present away from the surfaces where vitrification occurs under relatively high pressures during the packing stage. The resulting residual stress can be superimposed on the thermal stresses represented by Eq. 1.5. At high mold temperatures the relative contribution of thermal stresses becomes small (see Eq. 1.6) and the pressure-induced residual stresses dominate. The presence of high residual tensile stresses at the surfaces of the part may lead to part failure, e.g., by crazing.

1.3.3   Shrinkage

The "shrinkage" (i.e., the change in volume of the molded article as it cools down freely after ejection from the mold) can be viewed as a manifestation of volume contraction associated with the change in temperature as the part cools from its terminal temperature immediately after $t_e(T_e^+$ at $t_e^+)$ to ambient. If one employs long cooling times, i.e., the material is allowed to thermally equilibrate inside the cavity (as recommended for PIM operations, see above), the temperature of the part is approximately uniform and equal to T_{mold} at t_e, and the total volume contraction can be estimated from

$$\Delta v \sim 3\alpha \left(T_{mold} - T_{amb} \right) v_o$$ (1.7)

The corresponding linear contraction strain is

$$\delta_s \sim \alpha \left(T_{mold} - T_{amb} \right)$$ (1.8)

Thus, the shrinkage will be small if T_{mold} is close to T_{amb}. However, because of detrimental effects on replication fidelity and cooling stress (Eq. 1.5) it is desirable to select T_{mold} closer to T_g and well above T_{amb}. For a finite residual pressure (P_r) at t_e the observed shrinkage is

partially offset by the decompression of the material as the part is ejected from the mold, and the pressure drops abruptly to ambient (Fig. 1.3).

1.3.4   Warpage

If the cooling to T_{amb} is uniform, the only effect of shrinkage is an absolute change in dimensions relative to the dimensions of the mold cavity, which can be readily compensated through changes in mold design. In most cases, however, the shrinkage is not uniform because of the flow-induced anisotropy of the thermal expansion coefficient and the spatial nonuniformity of the thermo-mechanical history and the corresponding residual stresses in the cavity. This nonuniformity can lead to "warpage," i.e., a shape distortion, in addition to volumetric contraction, which can be characterized by the following distortion strain (assuming it is dominated by the anisotropy of the thermal expansion coefficient),

$$\delta_w \sim f \left(\alpha \| - \alpha \perp \right) \left(T_g - T_{amb} \right) \tag{1.9}$$

where $\alpha \|$ and $\alpha \perp$ are the values of the thermal expansion coefficient parallel and perpendicular to the polymer chain axis, and f is a spatially variable orientation function ($-0.5 \leq f \leq 1$) representing the "frozen-in" molecular orientation in the solid part. The higher the anisotropy of the polymer matrix, the higher the absolute magnitude of f, and the higher the potential warpage of the molded article. Another potential cause for warpage is nonuniform mold temperature. If, for example, the two mold halves are not thermally balanced, a temperature gradient and a corresponding thermal stress will ensue across the part at t_e. As the mold opens, this thermal stress is relieved causing the ejected part to warp as soon as the temperature of the part approaches T_{amb} [20, 21]. This underscores the need to control and maintain uniform temperature in precision molds through improved design and maintenance of the mold cooling/heating system and better temperature control algorithms. More complete discussions of the shrinkage and warpage problems in injection molding can be found in chapters 3 and 5 of this volume [14, 22].

1.4   Dimensional Stability

By *dimensional stability* we mean the ability of the part to maintain its configuration within the specification range over time. The dimensional stability of the part is influenced by several external and internal factors including: (a) adverse environmental conditions (e.g., exposure to varying temperature and humidity), (b) physical aging, (c) recovery of internal residual strains, and (d) viscoelastic effects in response to external stresses (e.g., stress relaxation and creep). The relative importance of these factors depends on the physical properties of the solid polymer, the levels of residual stress and anisotropy in the molded part, and the prevailing environmental conditions during the useful lifetime of the article. If the part is not subjected to large external stresses during its functional use, moisture absorption, temperature fluctuations, physical

aging, and relaxation of internal stresses are the major mechanisms driving dimensional instability.

Physical aging (or volume recovery), usually manifested by a spontaneous rise in density, is inherently present in any glassy polymer [23]. For kinetic reasons the polymer cannot reach thermodynamic equilibrium as it is cooled through the glass transition. Consequently, an excess free volume is built up in the material, which will decrease slowly over time. Struik has shown that the kinetics of the aging process far from equilibrium can be represented by a characteristic "rate" parameter [23]:

$$\beta \equiv -\frac{1}{v}\frac{\partial v}{\partial \log t_a} \tag{1.10}$$

where v is the specific volume, t_a is the aging time, and β is a material characteristic that depends on temperature and the molecular structure of the polymer. This relationship has been explained in terms of the self-retarding nature of physical aging, i.e., with increasing density the molecular mobility of the material is reduced, and the aging process becomes increasingly more sluggish. Wimberger-Friedl and de Bruin have shown that the semi-logarithmic aging kinetics expressed by Eq. 1.10 does not hold for very long aging times in the case of polycarbonate, a polymer frequently used in high precision applications. For this material, a strong increase in the slope of the volume contraction curve on a logarithmic time scale (apparent β) was observed during aging at room temperature [24]. The temperature dependence of β for several amorphous polymers is illustrated in Fig. 1.4. For polymers with "weak" sub-T_g relaxations, the temperature dependence of β below T_g can be scaled by

$$\beta \sim \exp\left(T - T_g\right) \tag{1.11}$$

Thus, the rate of aging increases exponentially as the use temperature approaches T_g. This clearly suggests that high-T_g polymers with weak secondary relaxations are less susceptible to aging-induced dimensional changes due to the slower rate of aging at ambient conditions.

The volume recovery of polymers in the glassy state can also be influenced by pressure applied during vitrification (formation pressure), which may directly impact the density and dimensional stability of a molded article. When vitrified under pressure, the density of an amorphous polymer at ambient conditions is generally increased through an effect known as pseudo-compressibility [25]. The dependence of density on the formation pressure typically leads to density nonuniformity within the molded part [13, 26, 27] and may have a detrimental effect on its dimensional stability. During volume recovery the material formed under pressure tends to expand over time, thus offsetting to some extent the contraction associated with physical aging [27].

The aging rate can be reduced not only by the proper choice of material but also by a judicious annealing treatment. It has been noted [28] that the most efficient annealing occurs at ~ 10–$20\,^{\circ}$C below T_g, rather than at or near T_g, since by annealing close to T_g the glassy polymer is actually "rejuvenated" and the reduction in β is smaller. A judicious annealing program can be readily combined with the injection molding cycle; by proper selection of T_{mold} and the residence time in the mold (t_e), the thermal equilibration portion of the cooling stage ($t_{cool} < t < t_{cure}$, see Fig. 1.1) may overlap with the annealing step.
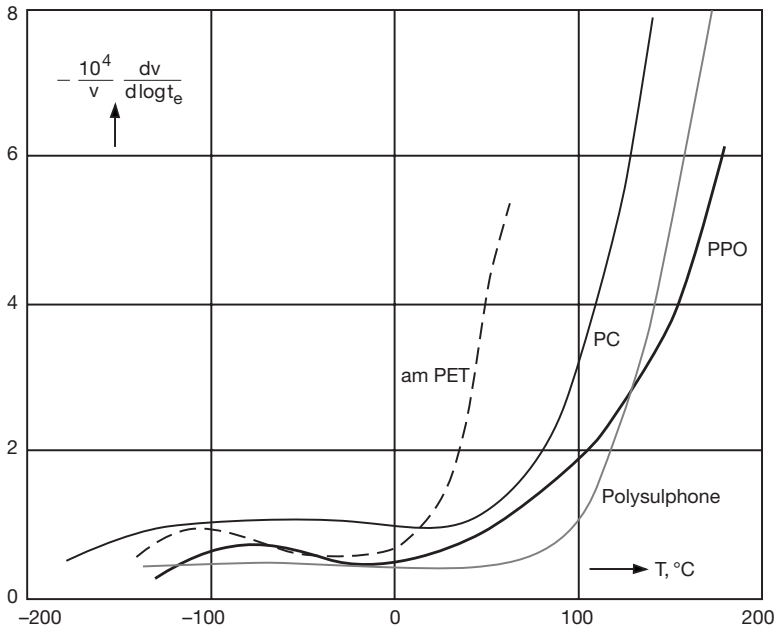
Figure 1.4: Aging rate parameter (ß) vs. temperature for several amorphous polymers [28] (Reproduced with permission of J. Wiley, Ltd.)

It has been shown that residual orientation stresses (stresses generated above T_g during the filling and packing stages, see Fig. 1.2) can give rise to an accelerated anisotropic shrinkage. This shrinkage is equivalent to the viscoelastic creep recovery effect, and it can be estimated from linear viscoelasticity theory by [28]

$$\delta_R \sim \sigma_R J\,(T_{amb}, t) \tag{1.12}$$

where δ_R is the recovery strain associated with a residual orientation stress, σ_R, which is the effective stress applied at the instant of vitrification, and J is the creep compliance of the material at ambient conditions. It is, thus, seen that the spontaneous deformation of the molded part can be minimized by lowering the level of residual stress in the part and/or by selecting materials with low compliance under ambient conditions. As noted above, lower residual stress is also desirable for minimizing warpage strain (Eq. 1.9). From careful measurements of the anisotropic dimensional changes of injection molded parts, Schennink has shown that at temperatures far below T_g the shrinkage is isotropic, thus indicating that physical aging is the dominant effect at low temperatures, while at elevated temperatures anistropic shrinkage is the prevailing effect [29]. General approaches for minimizing residual stress (and birefringence) in injection molded parts have been discussed elsewhere [30]. In cases involving relatively low internal stresses (e.g., various optical components having low birefringence), physical aging is likely the dominant factor controlling the dimensional stability of the part (chapter 7 [31]).