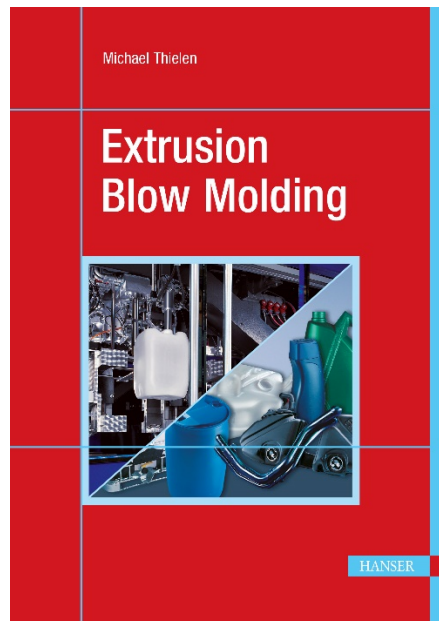


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Michael Thielen

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He has written several books on the subjects of blow molding technology and bioplastics and disseminated his knowledge of plastics in numerous presentations, seminars, guest lectures, and teaching assignments at universities of applied sciences both in Germany and in other countries worldwide.

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1

Introduction

■ 1.1 Hollow Plastic Parts – What Are They for?

In today's world, hollow plastic parts can be found everywhere. Hollow plastic articles are used for packing, storing, transport, or guiding of liquids or other bulky goods such as powders or the like. These hollow plastic articles are bottles, cans, drums, and tanks, but also pipes, tubes, or ducts. Hollow plastic parts are used besides "normal" packaging applications to provide protection, for example protective cases for sensitive electronic equipment. Due to the double wall structure, rigid lightweight structural components can be made of hollow plastic parts as well, e.g., transportation pallets, seat structures, or all kinds of panels. Hollow plastic articles are also used in the sports and play sector, for decorative objects (decorative fruits or animals), and a wide range of other applications.

■ 1.2 Processes to Produce Hollow Plastic Parts

1.2.1 Thermoplastics

There is a whole range of different processes for the manufacture of hollow plastic parts. Hollow parts made of thermoplastics can be produced by, for example

- *Injection molding* of two half-shells, which are then joined to form a hollow part in a second step by welding, gluing, snap-fitting, screwing, or the like.
- *Lost-core injection molding*: This process uses a core made of a low-melting (for example tin-bismuth) alloy, which is overmolded with thermoplastic material. The core can then be melted out of the injection molded part again at relatively

low temperatures using inductive energy. In this way, sophisticated piping with excellent inner surfaces and complex inner geometry can be produced, mainly for the automotive industry. The tin-bismuth alloy can be reused after melting out.

- *Rotational molding*: For thick-wall applications in small quantities, for example large waste bins, boats (kayaks), or special tanks, but also for decorative objects such as artificial animals.
- *Machining from a block*: This provides, at least theoretically, a way of producing hollow articles for very special applications or from certain materials such as polytetrafluoroethylene (PTFE).
- *Extrusion*: Pipes and hoses, as long as they are straight and have a constant diameter and wall thickness, are extruded hollow plastic articles.
- *Filament winding*: Thermoplastic semi-finished tape products reinforced with continuous fibers can be processed into sophisticated structural components in a special winding process. Here an extrusion blow molded liner can be used.
- *Twin-sheet forming*: Two special slot heads (or slit die heads) produce two melt sheets, for example in different colors. But also reheated semi-finished sheet products are used. By closing the mold, the two sheets are welded together and finally inflated to form a hollow part [1].
- *Blow molding*: This is a family of processes for producing a large variety of hollow articles in high volumes. Blow molding is subdivided into extrusion, injection, stretch, injection-stretch, dip blow molding, and more. The focus of this book is extrusion blow molding.

1.2.2 Thermosets

For the sake of completeness, it should be mentioned that thermosetting resins can also be processed into hollow parts. Thermosets are generally used for technical components, large tanks, or silos. They are often reinforced with glass fibers, carbon fibers, or other reinforcing fibers. Processes such as fiber-resin spraying onto a core, filament winding, and hand laminating are the most commonly used methods. In one application example, extrusion blow molded inner containers (so-called liners) made of polyamide are wrapped with glass fibers and unsaturated polyester resin. The Composite Pressure Vessel (CPV) thereby produced can be used to contain hydrogen used as an alternative fuel [2].

■ 1.3 Application Areas for Blow Molded Hollow Parts

Blow molding is used to produce hollow articles from thermoplastics shaped in almost any geometry. These include, for example, pharmaceutical packaging with contents of less than one milliliter and technical articles (e.g. plastic fuel tanks (PFT), air ducts in motor vehicles) or oil tanks with capacities of up to 10,000 L. The most commonly used processes are extrusion blow molding and stretch blow molding. While stretch blow molding is used almost exclusively to produce high volumes of PET bottles (more rarely also PEN or PVC, more recently also PLA or PEF), the spectrum of extrusion blow molded hollow parts is much wider. This book concentrates on extrusion blow molding.

Typical extrusion blow molded parts are transport, packaging and storage containers, such as bottles (Figure 1.1 and Figure 1.2), cans, tubes, jerry cans (Figure 1.3), drums and storage tanks, for example for fuel oil and chemicals (Figure 1.4), IBCs (Intermediate Bulk Containers, Figure 1.5), and foldable, thermally insulating transport boxes, e.g. with drainage channels in the base for frozen fish. After use, the latter can be laid flat to save space and can be reused in a return system.



Figure 1.1 Extrusion blow molded bottles (Image: Kautex Maschinenbau)



Figure 1.2 Extrusion blow molded PC water bottles (Image: Kautex Maschinenbau)



Figure 1.3 Extrusion blow molded canisters (Image: Kautex Maschinenbau)



Figure 1.4 Extrusion blow molded industrial bulk packaging (drums and storage tanks)
(Image: Kautex Maschinenbau)



Figure 1.5 Extrusion blow molded intermediate bulk container (IBC)
(Image: Kautex Maschinenbau)

Blow molded technical parts for motor vehicles, such as plastic fuel tanks (Figure 1.6), fuel filler pipes, oil and water tanks, expansion tanks, spoilers, bumper supports, headrests, instrument panels, child seats, bellows, as well as air ducts, intake pipes, and other piping in the interior and engine compartment (Figure 1.7), are also becoming increasingly important.



Figure 1.6 Extrusion blow molded plastic fuel tank (PFT) (Image: Kautex Maschinenbau)



Figure 1.7 Extrusion blow molded technical parts (Image: Kautex Maschinenbau)

For the household appliance and electronics industry, a wide variety of parts, such as spray arms for dishwashers, appliance doors and wall panels for washing machines and computers (Figure 1.8), desalinators housings, containers for condensation dryers, vacuum cleaner housings and collection containers, boiler housings, water ducts, underfloor heating elements, seat shells and tanks for lawnmowers, etc., are manufactured using the extrusion blow molding process. In addition, parts for the sports and leisure industry (kayaks, paddleboards, ski boxes, cooler boxes and accumulators, infant vehicles, parts for children's tractors, climbing

frames, slides, etc.), medical equipment (e.g. containers for blood pressure monitors, enema containers, infusion bottles, eye drop pipettes, ampoules, etc.) and cases for tools, microscopes, sewing machines, or laptops, etc., usually with integrated holding devices, can be blow molded [3].



Figure 1.8
Extrusion blow molded flat panel
(underbody paneling)
(Image: Kautex Maschinenbau)



Figure 1.9 Extrusion blow molded flat panel (table top) (Image: Kautex Maschinenbau)

2

Extrusion Blow Molding

Blow molding is a whole family of plastics processing methods that have one thing in common: the actual molding takes place by blowing a plastically deformable parison against a cooled mold wall. Here, the thermoplastic resin solidifies and a hollow article can be removed from the mold. One of the blow molding processes with the greatest economic significance is *extrusion blow molding*. Another important blow molding process that has gained in importance in recent decades is stretch blow molding, which is described elsewhere.

■ 2.1 Process Sequence for Extrusion Blow Molding

The basic process steps of extrusion blow molding are (Figure 2.1):

- Plasticizing and preparation of the thermoplastic melt in an extruder.
- Diversion of the melt into a vertical downward flow and forming a tubular melt “parison”. This parison is produced in the so-called parison head (also called blow head, die head, or just briefly head).
- A mold (blow mold), usually consisting of two half-shells, is closed around the parison hanging freely under the head and squeezes it at both ends (top and bottom).
- Insertion of a blow pin or (possibly several) blow needle(s).
- Inflating the plastic parison onto the cooled walls of the blow mold, where the plastic cools, solidifies, and assumes the final shape of the molded part.
- Venting.
- Opening the mold and demolding the blow molded part.
- Pinching off the squeezed off “flashes” at both ends of the blow molded part (deflashing).

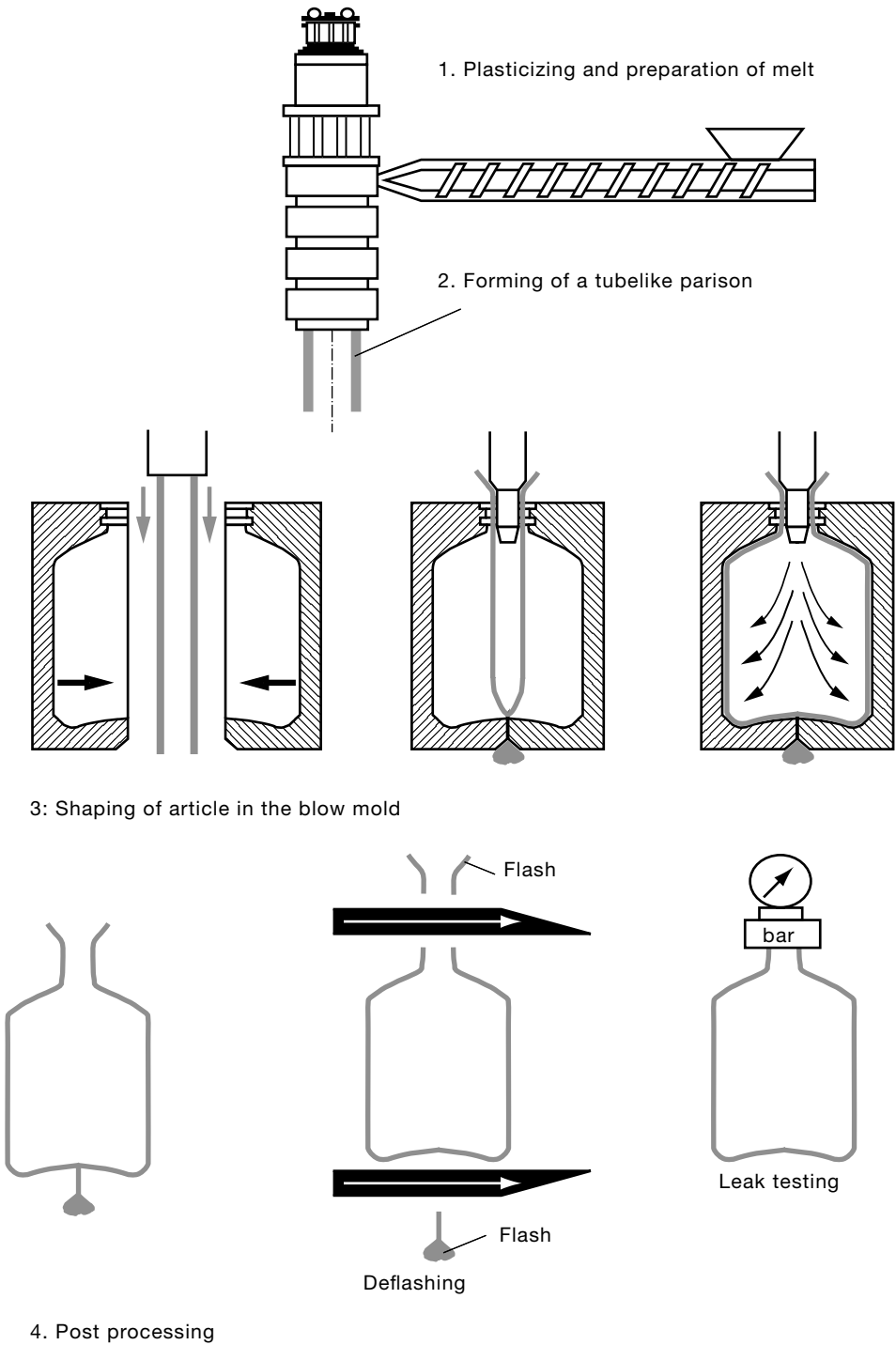


Figure 2.1 Basic process steps in extrusion blow molding

Further downstream processes can now follow, either in-line or off-line. Such process steps can be, for example, post-cooling to increase productivity, weighing of the blow molded articles, a leak test, optical checks for residual flashes, inclusions, or geometric properties (e. g. neck ovality). In addition to flame or corona treatment to prepare for printing or round neck milling for coex packaging, other possible steps include labeling. In the case of packaging articles, filling and sealing are just as much a part of this as other packaging processes, e. g. shrink film wrapping or palletizing. Technical parts, such as plastic fuel tanks, fuel filler pipes, air ducts or the like, can be completed by welding on further components such as nipples or fixing straps, for example.

■ 2.2 Raw Materials

2.2.1 Plastics

Plastics are high-molecular organic compounds, which are created either by the modification of high-molecular natural substances or by the chemical combination of low-molecular basic components, so-called monomers, through various chemical reactions [1]. Therefore, plastics are divided into modified natural materials and synthetic plastics. The synthetic plastics are additionally divided into polymerizates, polycondensates, and polyadducts according to their production process. These classifications say little about the practical use or properties of the plastics [1]. Therefore, plastics are also classified according to their molecular order. A distinction is made between thermoplastics, elastomers, and thermosets.

The basic building blocks of plastics are long chain molecules. *Thermoplastics* consist of linear or branched, non-crosslinked molecular chains. They are only connected by entanglement, hooking and weak intermolecular forces. In contrast to solid cross-links, such adhesion points can become loose and form new ones elsewhere [2]. These loose bonds explain the typical behavior of thermoplastics, which becomes rubber-elastic-soft when heated and plastic-doughy to liquid at higher temperatures. If a thermoplastic is loaded at high temperatures, it deforms. If the temperature is reduced under an existing load, the deformation state freezes. If the plastic is reheated without load, it largely resumes its old, undeformed shape. This behavior can be described as “memory effect”. This effect decreases with purely plastic deformation at high temperatures. High-polymer plastics also show a particularly pronounced viscoelastic behavior under mechanical stress compared to most other materials [3].

It can be distinguished between ideal elasticity according to Hooke:

$$\sigma = E\varepsilon \quad (2.1)$$

with σ stress and E modulus of elasticity σ

and ideal viscosity according to Newton:

$$\tau = \eta\dot{\gamma} \quad (2.2)$$

with τ shear stress, η viscosity, and $\dot{\gamma}$ shear rate

Polymer melts and rubbers are neither ideally elastic nor ideally viscous. The general term viscoelasticity is used to describe the mechanical behavior of these highly viscous materials. According to Ostwald and de Waele, the formulation

$$\tau = k\dot{\gamma}^n \quad (2.3)$$

with the constants k and n ; n = flow index

was introduced (Figure 2.2).

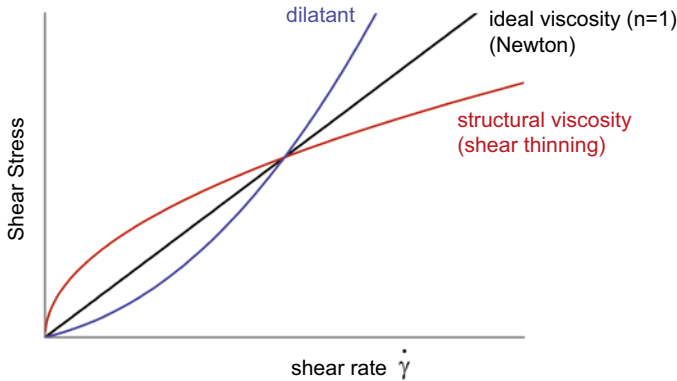


Figure 2.2 Differentiation between dilatant, ideally viscous, and pseudoplastic material [4]

An advantage of thermoplastics is that the material is hardly damaged by heating and deformation. The process can be repeated almost as often as required, provided that the molecular chains are not destroyed. In blow molding, it is thus possible to feed ground flash waste back into the process. As the grinding of the flashes and the conveying through the extruder always lead to the destruction of part of the molecular chains, e.g. by shearing, the addition of flash to the process is limited.

Thermoplastic macromolecules with a regular chain formation show the ability to lie against each other in the densest possible packing. Formation of this regular structure is called crystallization. However, due to the constantly occurring molecular entanglements, complete crystallization does not occur. This is why we speak of semi-crystalline thermoplastics (such as PE, PP, and PA), Figure 2.3a. If the structure of the macromolecules is irregular, the molecules cannot assume this densest packing. Their structure is then referred to as amorphous (shapeless), Figure 2.3b. These plastics (such as PVC, PS, PMMA, and PC) are transparent. Especially the so-called engineering thermoplastics, e.g. PA or PC, tend to absorb moisture. Therefore, the materials must be pre-conditioned for processing in a vacuum or dry air dryer according to the material manufacturer's instructions.

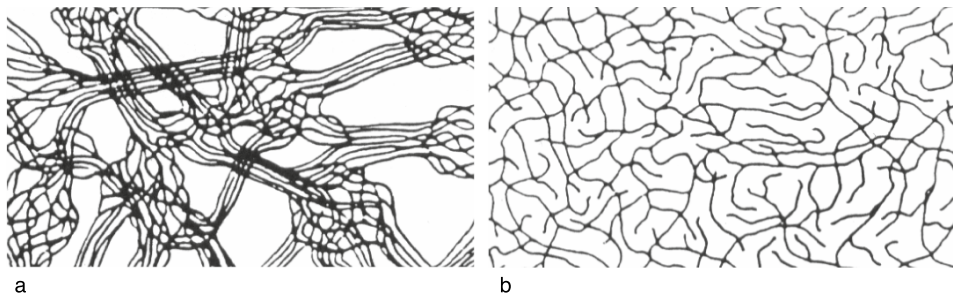


Figure 2.3 State of order of macromolecules in thermoplastics [1]
a: semi-crystalline, *b*: amorphous

In contrast to thermoplastics, the molecular chains of *elastomers* are loosely and widely cross-linked, Figure 2.4a. Due to this low cross-linking and the intermolecular “restoring forces”, this group of plastics behaves rubber-elastically at room temperature. They are not meltable, insoluble, non-swellable, and if heated too much, decompose, i. e. are destroyed.

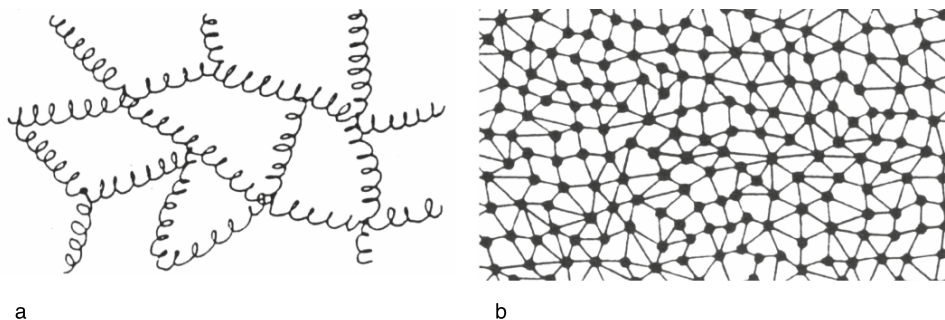


Figure 2.4 State of order of macromolecules in spatially cross-linked polymers [1]
a: wide-meshed cross-linked (elastomer), *b*: close-meshed cross-linked (thermoset)

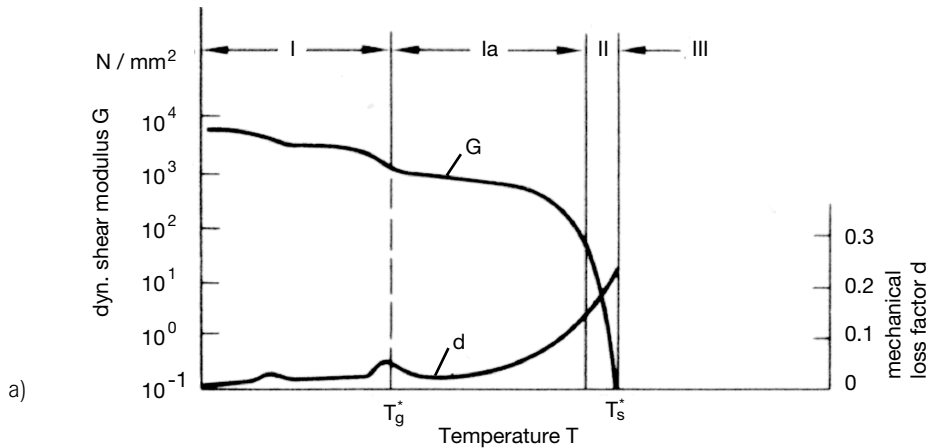
Highly cross-linked plastics are called *thermosets* or *duromers*, Figure 2.4b. With increasing cross-linking, thermosets become harder and more brittle. They are not meltable, insoluble, and non-swellable.

The behavior of polymers is strongly influenced by temperature. The most important parameters are listed below [5]:

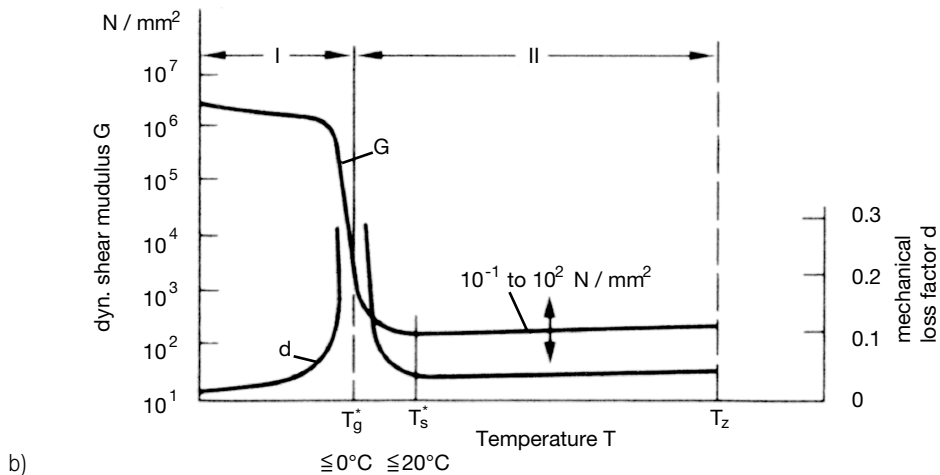
- *Glassy state:* The temperature range below the glass transition temperature is called the glass state. The Brownian movement of molecules comes to a standstill and the material freezes.
- *Glass transition temperature T_g range:* For thermoplastics and elastomers, the glass transition temperature T_g or the glass transition temperature range marks the transition from soft or rubber-elastic behavior to a hard or glassy state on cooling.
- *Flow temperature T_f range:* The flow temperature or flow temperature range indicates a lower limit temperature down to which primary forming in injection molding or extrusion is still possible. At temperatures below the flow temperature, only thermoplastic processing (forming) is still possible.
- *Crystallite melting temperature T_s range:* The crystallite melting temperature or crystallite melting range represents the upper limit temperature of the application range of reinforced, semi-crystalline thermoplastics. It is often only referred to as the melting temperature and thus also characterizes the transition from solid to liquid.
- *Decomposition temperature T_z :* The decomposition temperature indicates an upper limit up to which no or only insignificant molecular degradation caused by chemical reactions occurs. Above the decomposition temperature, the material is irreversibly damaged.

The preparation of the melt in the extruder of an extrusion blow molding process happens between the decomposition and crystallite melting temperature. As it leaves the die head, the material cools down to the flow temperature range, and on contact with the cooled mold wall, the melt enters the glass transition temperature range and solidifies.

For plastics, a time and temperature dependency must always be taken into account when specifying the tensile and shear modulus. The temperature dependence of plastics is shown in Figure 2.5. In a comparison of thermoplastic to elastomer, the large thermo-elastic range (I_a) can be identified as the application area for thermoplastics. This range is hardly present in elastomers ($T_g \approx T_s$). One way to characterize the deformation behavior of plastics for the extrusion and blowing process is to specify the melt flow index (MFI) and the molecular weight distribution.



- area I: glass state, amorphous areas frozen, plastic brittle,
 T_g : glass transition temperature for the amorphous parts,
 area Ia: amorphous parts thermoelastic, crystalline parts rigid. Usual field of application,
 T_s : crystallite melting temperature,
 area II: range of melting crystallites, plastic becomes thermoformable
 (narrow temperature range),
 area III: viscous flow behavior, range of thermoelasticity, primary shaping and welding



- area I : frozen state, material is brittle, temperature $< 20^\circ\text{C}$,
 T_g, T_s : glass transition temperature or melting temperature of the crystallites,
 area II : rubber elastic behavior (entropy elasticity),
 range of application of (loosely) crosslinked materials,
 T_z : decomposition temperature (indicated)

Figure 2.5 Temperature dependence of the dynamic shear modulus G and the mechanical loss factor d [1]

a: semi-crystalline thermoplastics such as PE, PP, PA, PET

b: elastomers such as soft rubber and soft PUR

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