1 Introduction

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■ 1.1 Plastics and Their Importance

Regarding the five basic human needs [1]:

- food
- health
- clothing
- home
- communication

plastics make considerable and valuable contributions in today's world. This is obvious and will not be further described here.

Compared to other material groups (metal, glass, ceramics, wood, paper), plastic is a very young material. From the mid-1920s onwards, Staudinger laid the ground for understanding polymers (macromolecules). In particular in the IG Farben corporation, development of various polymers followed, for example polyurethane in 1937 by O. Bayer. Polycarbonate was invented at Bayer in 1953. The economic production of polymers was accelerated by K. Ziegler and G. Natta and their catalysts.

Initially, plastics were produced discontinuously. The economic success of plastics is linked to the success of continuous production methods and, especially in the case of thermoplastics, to the success of extruders. The patent for the basic geometry of co-rotating twin-screw extruders was filed in 1944 and granted in 1953 in the Federal Republic of Germany.

■ 1.2 Processing and Compounding

In the past, new plastics were created by new base polymers. Today, a (new) ready-to-use plastic material is only created by the **processing** of a base polymer during and after the polymerization (synthesis) and by **compounding**, i. e. the subsequent incorporation of additional materials such as additives, fillers, fibers, and colorants. Figure 1.1 shows as an example the influences that fillers have on PTFE plastics [2]. Figure 1.2 shows a qualitative estimate of the development of the significance of "Plastics Compounding and Polymer Processing", our book title. The blue curve describes the number of newly developed base polymers and the green curve shows the volume of plastics produced.

	Filler						
Property	**Glass** (Up to 40%)	**Coal** (Up to 35%)	**Hard Coal** (Up to 35%)	**Graphite** (Up to 15%)	**MoS₂** (Up to 5%)	**Bronze** (Up to 60%)	**Steel** (Up to 60%)
Wear	↘	↘	↘↘	↘	→	↘↘	↘
Abrasion (counterpart)	↗	→	→	↘	↘	→	↗↗
Chemical resistance	↘	↘	↘	↘	↘	↘	→
Heat conductivity	→	↗	↗	↗	→	↗	↗
Gliding properties	→	→	→	↗	↗↗	→	→
Coefficient of friction	↗	↗	↗	↘	↘	↗	↗
Hardness	↗	↗	↗↗	↘	→	↗	↗
Stiffness	↗	↗	↗	→	→	→	→
Dry running properties	→	↗	↗	↗	↗	→	→

Trends: blue = neutral,   green = positive,   red = negative

Figure 1.1 Influence of fillers on the property profile of PTFE plastics [2]. With kind permission of pro-K Industrieverband Halbzeuge und Konsumprodukte aus Kunststoff e. V.

In the broadest sense, compounding means mixing, a process step which occurs frequently in polymer processing and which is one of the main operations. A distinction is made between

- mixing of solids and
- mixing in the melt phase of the polymer (melt compounding)

Mixing of solids is either carried out at room temperature, so-called "cold mixing", or the components are heated, so-called "hot mixing", whereby polymer granules or polymer powder remain solid while additives can liquefy.
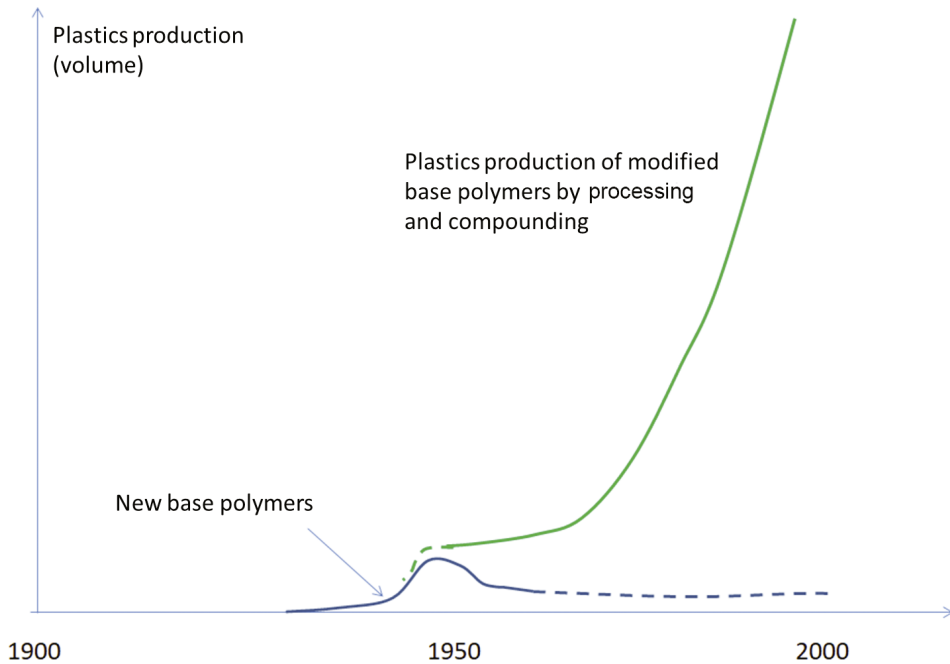
Figure 1.2 Importance of processing and compounding for plastics (estimate)

At the beginning of plastics development and production, "batch processes" were used. An overview of the corresponding batch apparatuses and machines is described in [3] and [4]. Today, especially for the economic production of the most frequently used plastics, thermoplastics, continuous manufacturing processes are used, which are described in this book with the corresponding apparatuses and machines. Melt compounding is normally carried out in extruders and is described in detail in this book.

■ 1.3 Recycling of Plastics

Plastics are indispensable materials. Due to their inadequate disposal, especially in some countries, and long shelf life, more and more plastics accumulate in the environment and plastics are increasingly coming under criticism. In Germany we have a good regulatory policy with regard to waste disposal. Figure 1.3 shows the recycling of plastic "waste" in Germany after its usage:

- 53% of waste is used for energy generation;
- 46% is recycled materially, often resulting in plastics of poorer quality;

- Only 1 % of the waste is converted back into raw materials that can be used again to produce plastics;
- Also only 1 % of plastics is finally deposited in a landfill.

Raw material and material recycling will become more important in the future. In this book, **solvent-based recycling** and **mechanical recycling**, the **re-compounding**, are briefly discussed. EU politics also deals with the topic of plastics recycling and demands: "We need less and better plastics" [7]. A change in production is required "as plastics are becoming the greatest environmental hazard".

Currently, also the media mostly report critically on the material "plastics". The advantages of this material over other materials must not be overlooked. Advantages were presented, for example, in the TV programs [8] and [9]. In the ideal case, of course, the aim should be to achieve a plastic that can be recycled and thus reused an infinite number of times. However, energy recovery of plastics that have already been used in applications is better than direct combustion of the crude oil, Figure 1.3.

The developers of processes for polymer preparation (processing) and of machines and apparatus for plastic compounding will have to face these challenges. Only those processes and machines that are most promising both ecologically and economically will prevail.
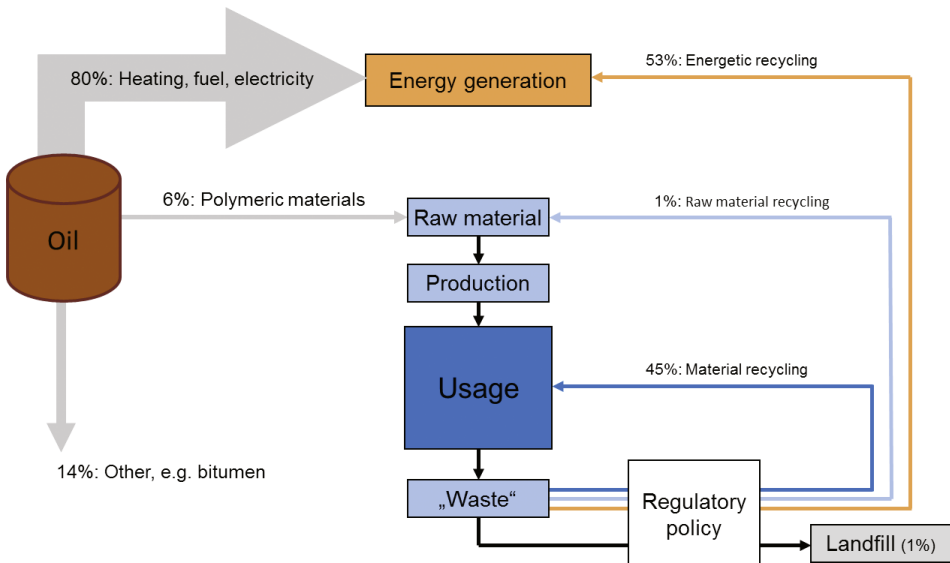

Figure 1.3 Oil as a basis for plastics including recycling of plastic products (according to [5], numbers for recycling according to [6])

■ 1.4 Guide to the Individual Chapters of this Book

This book is divided into four parts.

Book part "A" describes what is meant by polymer processing. Compounding is described in great detail, the path from polymer to ready-to-use plastic.

Part "B", the processing during the primary production of polymers, focuses on the "degassing" of polymers with the corresponding apparatus and machines.

Book part "C" deals with the extensive topic of compounding. Which additives and other auxiliary materials are used to modify the base polymers and make them ready for use? In "melt compounding", the additives are mixed in extruders. What types of extruders are available? Which extruders are particularly suitable for compounding and what are the advantages and disadvantages? These questions will be discussed.

Book part "D" deals with further important plant components of a compounding plant. These include topics such as melt filtration, pelletizing as the transition from melt to solid, and the solid processes. Metering and measuring technology are also important components of modern processes.

The editors were able to enlist experts as authors for book parts A to D and coordinated the contributions with the authors. Nevertheless, the contributions reflect the opinions and experiences of the authors. In some points they may differ from the experience of the editors. As a whole, all contributions are a valuable enrichment for the book and we would like to thank all authors once again at this point!

References for Chapter 1

[1]   Kaiser, W.: Kunststoffchemie für Ingenieure: Von der Synthese bis zur Anwendung, Hanser Verlag, 4th ed. 2015

[2]   pro-K Industrieverband Halbzeuge und Konsumprodukte aus Kunststoff e. V.: *https://www. pro-kunststoff.de/fachwissen/ptfe-kunststoffe-fuer-den-einsatz-in-sauerstoffanlagen.html*, accessed 9. 5. 2019

[3]   White, J. L., Coran, A. Y., Moet, A.: Polymer Mixing, Hanser Verlag, 2001

[4]   White, J. L., Bumm, S. H.: Encyclopedia of Polymer Blends: Volume 2: Processing, Section 1.2 "Methods of Compounding", 1st ed. Edited by Avraam I. Isayev. Wiley-VCH, 2011

[5]   PlasticsEurope, Association of Plastics Manufacturers

[6]   Consultic: Produktion, Verarbeitung und Verwertung von Kunststoffen in Deutschland 2015 – Kurzfassung, 2016

[7]   *https://eu-recycling.com/Archive/21436*: "Wir brauchen weniger und bessere Kunststoffe", accessed 23. 03. 2019

[8]   NTV: Revolution Kunststoff – Ein Material erobert die Welt, broadcast 13. 11. 2018

[9]   SWR: Plastik ist toll – Zeitreise der Kunststoffproduktion. *https//www.swr.de/odysso/ zeitreise-der-kunststoffproduktion/-/id=1046894/did=20400660/nid=1046894/.fv9ekk/index.html*, broadcast 16. 11. 2017

2

Polymer Processing – Process Technology of Polymer Production

Klemens Kohlgrüber

▪ 2.1 Introduction

The term **processing of polymers** is used in various ways in the literature. The term compounding is very common, but it is not as comprehensive as the term processing. The latter also includes the processing at the polymer manufacturer. This second chapter describes the process steps involved in processing in polymer production and in compounding. For this purpose, the polymers and the process steps are first considered in more detail.

The term plastic is understood to mean a separate class of materials. In English usage, the term "plastics" is common for synthetic materials. When biopolymers are included as natural substances, then a classification under the generic term polymers is possible, Figure 2.1.
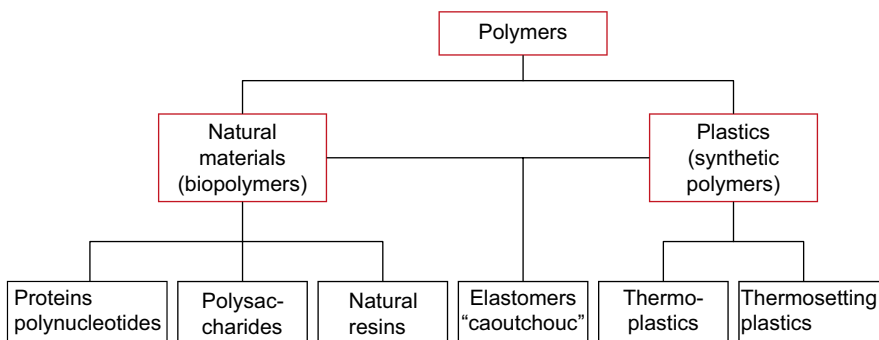

Figure 2.1 Classification of polymers by their origin (based on Kaiser [1] Fig. 1.14)

Polymers consist of macromolecules that have a natural or chemical origin.

If a classification is not based on the origin, but on the properties or the usability of the material, a distinction can then be made in the narrow sense between polymer and plastic; Bonten [2], page 60:

"Plastics are materials consisting of polymers and additives."

This clearly demonstrates that polymers are the raw materials for plastics, as the "pure base polymers" after their production are generally only suitable for use with additives. This is expressed very clearly in the foreword to the "Handbuch Kunststoff-Additive" (Plastics Additives Handbook) [3] (emphases added by the author):

> *"**Without plastic additives no plastics.** This statement applies at least as far as the practical and commercial use of plastics is concerned.*
>
> ***Additives protect plastics** from degradation by manufacturing processes, facilitate their processability, stabilize them against thermal or UV-induced degradation during use, and extend the property spectrum by **modifying material properties**.*
>
> ***Thus, additives enable the sustainable use of plastics in existing as well as new applications.**"*

Properties that are influenced by additives are, amongst others:

- Processing stabilization (thermal degradation, oxidative degradation, and application (use))
- Long-term stabilization (heat, light)
- Color
- Stability (fillers for mechanical influence)
- Inflammability (flame retardant)
- Surface effects (lubricants, mold release agents, antistatics)
- "Tendency to mold formation" (biocide)
- Property improvement by "mixing" with other polymers (blends)

The incorporation of additives into a polymer or plastic/rubber is called **compounding**. An overview of which additives are concretely used for the stabilization and modification of plastics is given in Section 4.3 (Diem). Furthermore, reference is made to the very comprehensive relevant literature, for example [3–5]. The terms additional materials and additives are sometimes used synonymously. For better distinction, additives, blends, and fillers are classified as described in Section 4.3. Additives are added in small quantities. Specifically, fillers can amount to more than 50 % by mass of the base polymer and are used to modify properties or reduce costs. Regarding the insoluble fillers, the stiffening effect (stability) is significantly dependent on the type, shape, and orientation of the filler.

A change in the properties of polymers or plastics can be achieved not only by additives, but also by chemical modifications. Thermoplastics, for example, can be cross-linked subsequently ([1], Section 2.2.6 in that reference).

According to the preceding paragraph, it can therefore be stated: Through the process step compounding, a polymer becomes a plastic. The term compounding is expanded in the following to the more comprehensive term **polymer processing**, which not only describes the incorporation of additives, but also includes further process steps which are particularly important in the preparation of the base polymers. The following Figure 2.2 illustrates the process chain from the monomer to the plastic product.
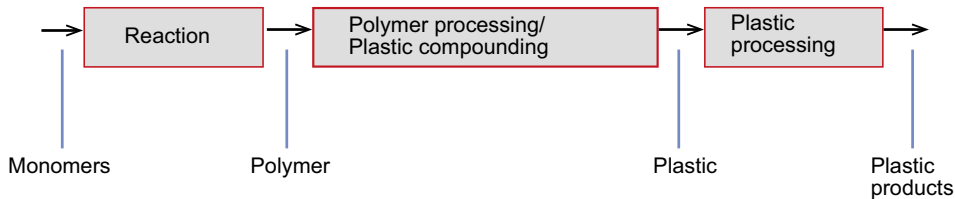
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┌──────────────┐    ┌─────────────────────────┐    ┌──────────────┐
│   Reaction   │    │  Polymer processing/    │    │   Plastic    │
│              │    │  Plastic compounding    │    │  processing  │
└──────────────┘    └─────────────────────────┘    └──────────────┘

Monomers          Polymer                        Plastic         Plastic
                                                                 products
```

Figure 2.2 Process steps for the production of a plastic product

The term processing has been used by various authors in the past. For example, in 1982 Zettler [22] described the three steps as follows: polymerization, **polymerizate processing**, processable thermoplastic. In an article [19] by H. Herrmann, formerly of the company Werner and Pfleiderer, with the subtitle "Die Kunststoffaufbereitungstechnik 1988" (The Plastic Processing Technology 1988), the term plastic technology was used as a generic term for the three steps shown in Figure 2.2. Furthermore, compounding is not additionally mentioned in the step processing. The mention of the processing without the important but contained compounding is actually better. Since the term polymer processing has not yet been established in this context and compounding is common worldwide, the term compounding is additionally listed as identification in Figure 2.2. The opinion that the term processing in this sense is less well-known is shared by the VDI (The Association of German Engineers), as the annual conference "Plastic Processing Technology" (*Kunststoff-Aufbereitungstechnik*), which has been held for decades, has been renamed "Compounding Conference" (*Compoundiertagung*).

As already described, the terms polymer and plastic are also often used synonymously. If it is not a ready-to-use material, a specification by the term "base polymer" can also be used as a raw material for plastics. The distinction is important from an application point of view. In terms of process, technology, consistency, and the necessary tasks are in the foreground. After the reaction, the polymer is usually existent as solution, powder, or melt; after processing, as granulate or melt. The polymer processing takes place partly simultaneously to the reaction, for example in the polycondensation. It can also be achieved partially during plastic processing (formation of the product part, e.g. via molding), if, for example, there are

still additives to be incorporated. After plastic processing, a finished component is usually available.

The properties of the "base polymers" are essentially determined by the chemical structure, the shape and the order of the molecules (linear, cross-linked) and by the size (molecular weight). Figure 2.3 shows the classic plastic pyramid with some polymers as an example.
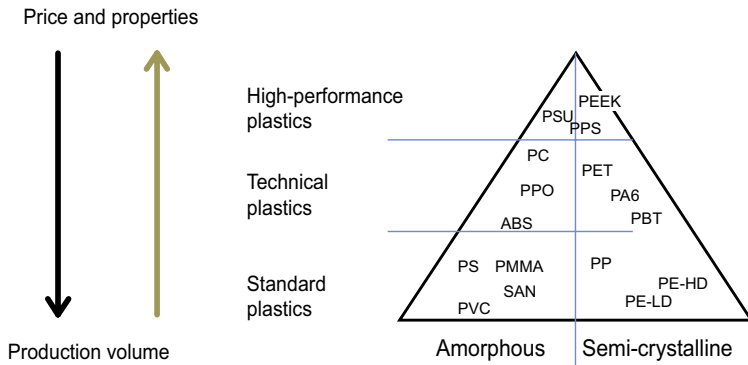

Figure 2.3 Classic plastic pyramid with qualitative depiction for price and characteristics (e. g. operational temperatures) and production volume

The depiction in Figure 2.3 is more likely to be qualitative and is intended to clarify that the high-performance plastics are priced higher and the production volume is low in relation to the standard plastics. In plastic development in the past, emphasis has been placed on the development of new "base polymers", particularly in order to apply new high-performance plastics with larger profit margins.

Today's product development for new plastics primarily takes place by compounding, even though research is still being conducted on new polymers. Numerous companies have their own plastics in the program which, by modifications of the base polymers, result in ameliorations of the application properties. In thermoplastics, improved and new plastics are predominantly produced by so-called melt compounding (the terms is described in detail below) in extruders.

In order to emphasize the economic importance of compounding for thermoplastics, Figure 2.4 shows the world production of plastics.
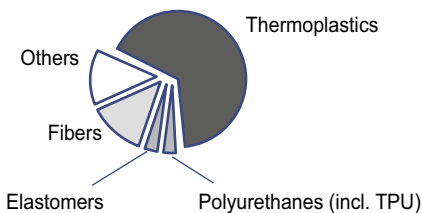

Figure 2.4
Plastic world production
(qualitative; current figures on the page
https://www.plasticseurope.org/en)

Thermoplastics dominate with more than 50 % of the world production of plastics. They are often used not only because of the price and the application profile. They can be re-melted several times and thus compounded and several times processed (transformed). Of course, the melting causes a thermal stress and can lead to undesirable quality losses. The procedural step often occurs twice during the manufacture of a plastic product, during compounding and during plastic processing. In a type of **recycling** of plastics, a so-called **recompounding** takes place, in which the "plastic waste" is also melted again.

Elastomers and thermoset material are known to be non-meltable and can be transformed only once and are not transformable after crosslinking.

The consideration of thermoplastics in this book is therefore of particular importance. Figure 2.5 shows an overview of corresponding process steps.
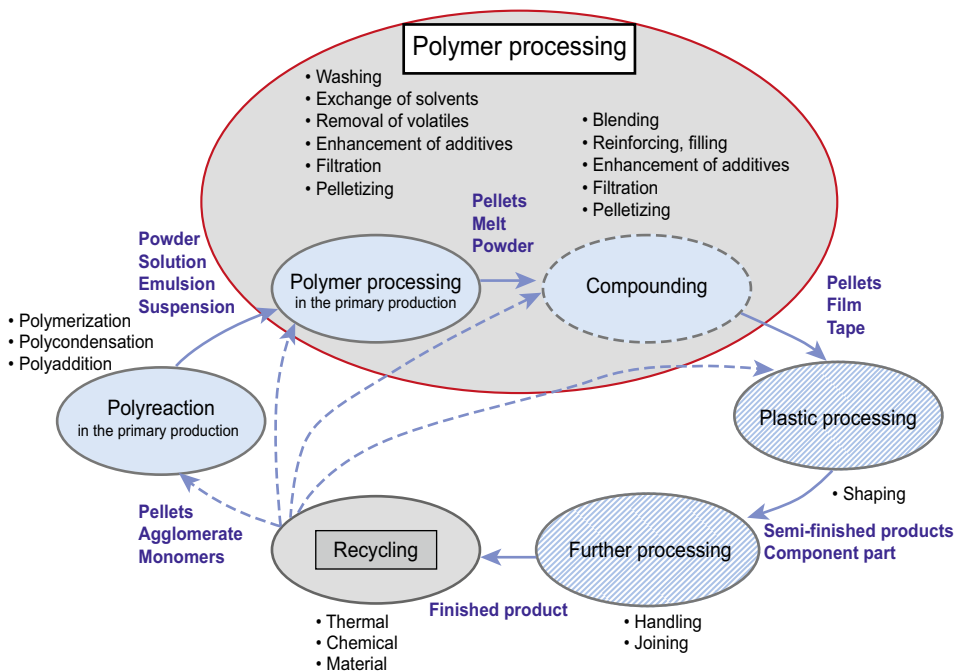

Figure 2.5 Polymer-process technology, overview using the example of thermoplastics

According to Figure 2.5, the term polymer processing includes many process steps, such as melting, degassing (solvent monomer removal), mixing and dispersing, conveying, dosing, extruding (pressure build-up), filtration, pelletizing, etc.

Tasks of Polymer Processing

How can the procedural steps of polymer processing be summarized in a shorter way? Following the literature source [1], the essential tasks of the polymer processing are as follows:

1. Removal of components

2. Incorporation of additives

3. Change of particle size

Kaiser [1] writes: *"The purpose of polymer processing is to produce from the plastic raw material a plastic molding compound with the best possible properties for plastic processing and/or application."* The plastic raw material usually is a base polymer.

The definition of reprocessing can also be applied to the production of a base polymer, as described in the following Section 2.2 using the example of the thermoplastics. For elastomers, reference is made to the literature, e. g. [5].

In summary, it should be defined according to [2]: the procedural steps from polymer to plastic are collectively called **polymer processing**. Especially the incorporation of additives takes place in the primary production and in the **compounding**, partly also during the **plastic processing**. The term additional materials includes additives (the substances listed previously that are added in small proportional amounts) and other substances such as fillers, whereat the terms are also used synonymously in the literature. Likewise, a distinction is not always made between the terms polymer and plastic. In the past, the term "compounding" was usually not so sharply demarcated from the "polymer processing".

■ 2.2 Polymer Processing during the Polymer Synthesis in the Primary Production

In order to understand the many and different processing steps of the polymers during their production, consideration of the polyreactions is necessary.

The production of polymers is carried out by **polyreactions** from monomer to the polymer, thus reaction for formation for macromolecules. Instead of polyreactions, the term synthesis reactions or polymer synthesis or, briefly, **synthesis** is used. Depending on the type of production, a reaction engineering or procedural classification can take place.

Classification of Production According to Chemical Reactions

The polyreactions can be classified into three classes ([1] and Figure 2.5):

- Polymerization (chain polymerization)
- Polycondensation (condensation polymerization)
- Polyaddition (addition polymerization)

The nomenclature has changed over time and instead of the term polyreaction, the generic term **polymerization** is used, which may lead to confusion [6]. For the present book this is of minor importance, since the procedural aspects are in the foreground.

Classification of Production According to Procedural Characteristics

From the point of view of the process technology, the manufacturing processes can be divided into three groups [7]:

- Polyreactions in substance (mass polymerization)
- Polyreactions in solution (solution polymerization)
- Polyreactions in dispersion (emulsion, suspension)

The production of a polymer with new properties can also be conducted by mixing different polymers. An example of a polymer blend is ABS.

Polymer reactions in substance are also called **mass processes** and can take place without solvents or other diluents. Therefore, high viscosities can occur already during the reaction. A reaction in mass may be a polycondensation. This splits off a "by-product" that needs to be removed. For example, polycarbonate can be prepared according to the "melt condensation process" or "transesterfication process", wherein phenol is separated and as completely as possible removed by a vacuum from the reaction mass. Thus, a degassing task is existent.

In the polymer reaction in solution, the viscosity of the reaction mass is greatly reduced by the use of solvents. This facilitates heat and material transport and the pumping. Polycarbonate as an example can also be produced by the "interphase process" and one or more solvents are used. After the reaction, the solvents must be removed again, and the polymer must be "isolated", Figure 2.5 and Figure 2.6. Again, here a degassing task is needed, which is also referred to as "evaporation".

In the reaction processes in dispersion, a further subdivision into suspension and emulsion can take place; details are in the literature, for example [1, 6, 7].

In the case of polyreactions in substance, a highly viscous mass is already present during the reaction. In the case of polyreactions in solution and polyreactions in dispersion, the highly viscous phase is avoided during the reaction. Then, high-viscosity phases or solid phases occur during the necessary processing. This requires special devices and machinery. At Bayer, Martin Ullrich introduced the term

high-viscosity technology, which has since become established. The author has made an extension to the high-viscosity, mixing, and reactor technology, in order to create an organizational and personnel basis for targeted advances in process technology with appropriate equipment and machinery.

The above description of the various polymer reactions shows that the processing of a polymer is, depending on the nature of the reaction, very diverse in terms of process technology. By the example of a polyreaction in solution (solution polymerization), some process steps of the processing shall be considered.

Directly after the chemically completed polymer reaction, a polymer can be existent e. g. in a solvent or in a solvent mixture. Then the polymer must be "isolated" from the blend. This procedural step of processing to remove the solvent is also called evaporation technology.
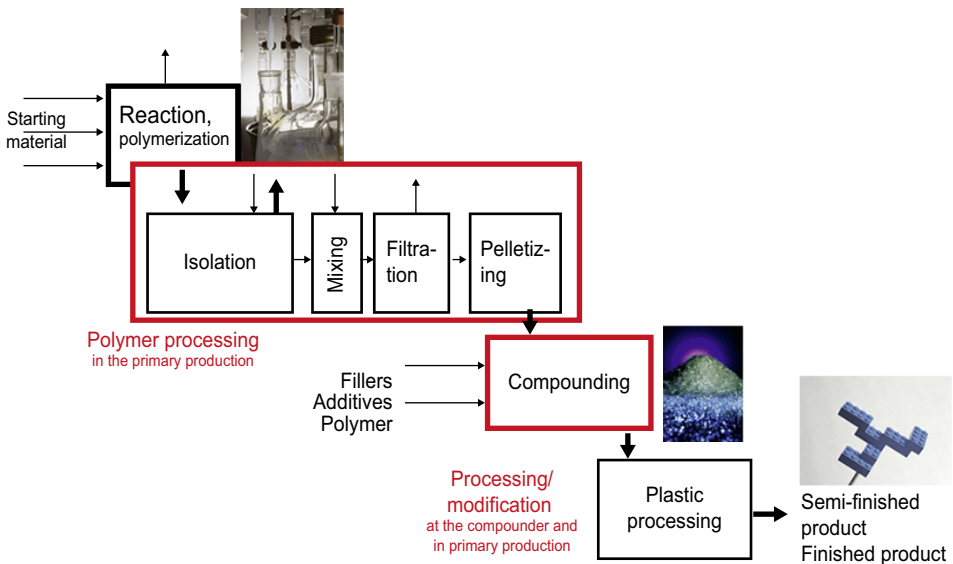

Figure 2.6 Polymer processing in the production and modification, example thermoplastic

Figure 2.6 illustrates the processing in primary production at the polymer manufacturer. In the example, the polymer must be isolated from a polymer-solvent mixture. For product stabilization, an additive is mixed in. Impurities are retained by filtration, followed by pelletizing.

Polymer reactions can – as listed above – also be carried out in "mass processes", i. e. without solvent. The reaction progress of a polycondensation takes place by the removal of the condensation product. In this manufacturing technique, reaction and processing, removal of volatiles (condensation product), are carried out in parallel.

After the reaction, a polymer can be in the form of powder. Because of the low bulk density and because of the formation of dust, the powder is usually melted (thermoplastic) and shaped to pellets. The granulation is an essential task of the processing and is generalized under the step "change of particle size". Thermoplastics are usually traded and transported in the form of pellets for further processing, the compounding.

The individual procedural steps in the processing of polymers in their manufacturing process are described in detail in various chapters, for example in Chapter 3, polymer degassing.

■ 2.3 Polymer Processing after the Polymer Production – Compounding

As described in Section 2.1, only additional substances (additives, etc.) enable the sustainable application of plastics. By blending additives into a polymer and mixing different polymers, modifications and new "tailor-made" plastics are created. This processing after the polymer production is called compounding. The compounding can be done at the polymer manufacturer or a compounder. The entire compounding plant is complex and this section describes the core task of compounding. The "heart" of a compounding plant is the associated extruder as this carries out the main compounding step, the melt compounding.

As thermoplastics are mostly available as pellets, during compounding the polymer is melted, has additives mixed in, then possibly degassed, and pelletized again. The central machine in a compounding line is an extruder, Figure 2.7.
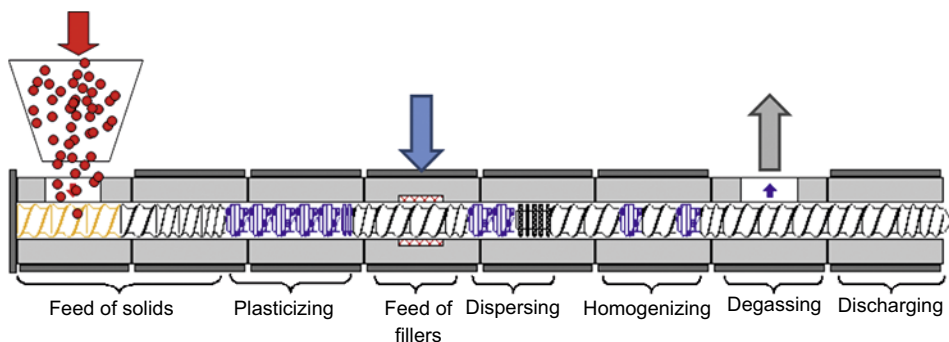

| Feed of solids | Plasticizing | Feed of fillers | Dispersing | Homogenizing | Degassing | Discharging |

Figure 2.7 Compounding extruder with conventional usual steps

Extruders can melt pellets and mix in additives very economically in a continuous process. The co-rotating twin-screw extruder is mostly used. This type of extruder is described in detail in [8]. An overview of other extruder types is given in Chapter 6 with a comparison in Section 6.8. The production of intermediate products, so called masterbatch production, also takes place with compounding extruders.

Compounding extruders are usually externally dosed, i. e. the throughput is determined gravimetrically by external dosing devices, usually differential weigh feeders.

2.3.1 Main Temperature Window when Compounding for Finish Mixture

The addition of the additives takes place simultaneously with the pellets or even after the plastification after the melting of the pellets. The real incorporation (mixing) of the additives takes place in the melt; that is why we also speak of **melt compounding**. Figure 2.8 illustrates the melt compounding with the main temperature window. In the melt, the finish distribution (by distributive mixing) of the additives takes place.
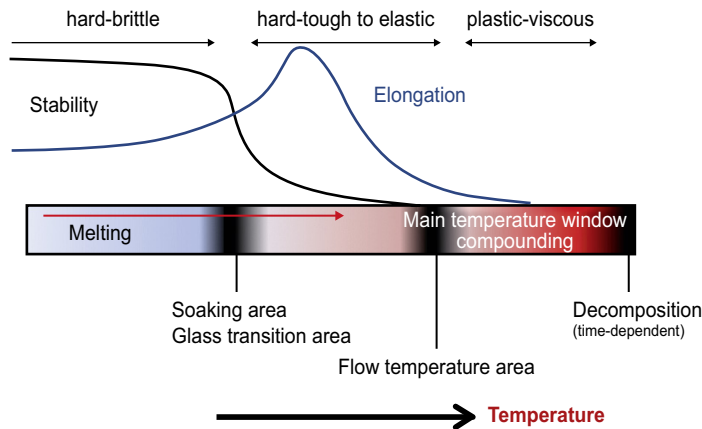

Figure 2.8 Illustration of melt compounding with main temperature window by the example of amorphous thermoplastics

There are hardly any applications in which a solid mixture of the reactants (polymer, additives) is sufficient for the production of a compound. In most cases, a comminution of additives (dispersion) and a fine distribution (distributive mixing) are necessary.

2.3.2 Mixing in the Extruder

Distributive, i.e. distributing mixing takes place in the melt by the very complex flow structure in an extruder. Cross mixing and longitudinal mixing play a decisive role here. The differences in effect between the cross mixing and the longitudinal mixing are described in more detail in Section 2.3.11.3.

Extruders can also dispersively mix very well, thus split solid matter or drops. The disperse mixing of, for example, solid additives takes place particularly well at high shear stress as described in the following Equation 2.1 [8, Equation 2.14 in the *Applications* book].

$$e_{melt} = \tau_m \cdot \overline{t}_{melt} \cdot \dot{\gamma}_m \, / \, \rho_m = \eta_m \cdot \overline{t}_{melt} \cdot \dot{\gamma}_m^2 \, / \, \rho_m \tag{2.1}$$

In the lower temperature range of the melt, the viscosity is higher and the dispersing effect better. On the left side there is the specific energy input, e.g. in the unit of J/kg. On the right side of the equation, there are the shear stress or melt viscosity and the mean dwell time of the melt, two quantities that are very important for disperse mixing. Both quantities must exceed boundary values in order to enable the splitting of particles (or drops of liquid). In other words, the agglomerate diameter resulting from disperse mixing depends on the height of the shear stress and the dwell time. For the splitting of agglomerates, a minimum shear stress – depending on the properties of the solid matter – is necessary which cannot be compensated by a longer mixing time. As the splitting of solid additives depends on the melt viscosity, there is also a dependence on the polymer. For example, ABS has a considerably higher viscosity level in the melt area than PA6. Dispersion in a PA6 melt is thus more difficult.

Also below the main temperature window there is a good dispersion, for example in the melting area, Figure 2.9.
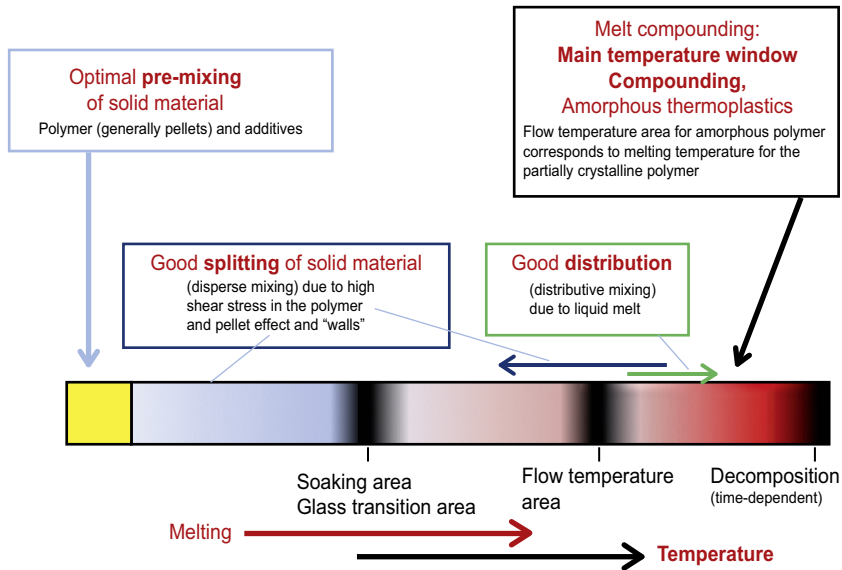
Figure 2.9 Important temperature and mixing ranges during compounding, illustrated by the example of amorphous thermoplastics

Solid matter is comminuted before and in the melting area by the "walls" of housing and screw and by not yet melted pellets by different types of stress. The usual types of stress [23] are illustrated in Figure 2.10.
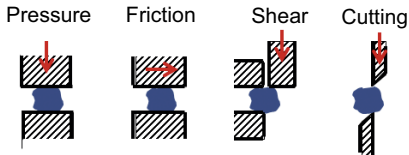

Figure 2.10
Types of stress for the comminution of solid matter

The polymer is usually existent as pellets. Pellets and additives or only additives can be premixed. A premixing (outside the extruder) may be useful for several reasons. A premixing of solid materials is usually associated with a much lower energy consumption than the mixing in the "viscous" melt area. Furthermore, the number of dosings (generally with differential weigh feeders) can be reduced. On the other hand, for difficult mixing tasks it may be advantageous to implement different addition positions, as the following description shows.

In principle, it is possible to mix distributively and disperse in the compounding extruder from the entry of the substances until the discharge of the compound. Due to the different effectiveness of the mixing effects (e.g. according to Figure 2.9, left, in the pellet and melting area, or right, in the melt area), different dosing concepts can be realized. Example: For compounding, a solid additive is to be in-

corporated into a polymer, whereby it is not only be mixed in a distributive manner, but also to split (diminish) it. According to Figure 2.11 different dosing possibilities arise.
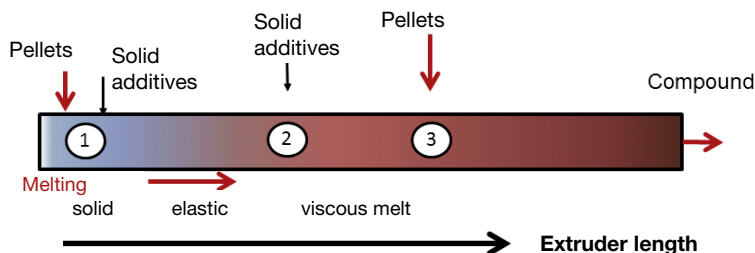

Figure 2.11 Compounding extruder: sketch illustrating different dosing concepts for mixing and dispersing additives in the polymer

In variant 1, the polymer pellets and the additive are dosed into the extruder at position 1. In this case, the additive in the pellet/melting area receives a dispersion through the pellets due to crush and friction processes. Whether a further dispersion of the solid additives takes place downstream in the melt depends amongst other things on the viscosity of the melt. At low viscosity (and thus shear stress = viscosity multiplied by shear rate), the dispersion effect is poor, Equation 2.1. If the viscosity is sufficient for dispersion, the additive can also be added at position 2. To increase the mixing viscosity downstream of position 2, it is also possible to dose only a partial stream of the polymer in position 1 and the additives at position 2. The amount of the remaining polymer needed for the mixture for the correct formulation can be added at position 3 and mixed in downstream.

In addition to the described position displacement of the feed positions due to the dispersion effect, there are other reasons for different feed positions, such as wear in the feed area or volatile matter of (then mostly liquid) additives which should not escape with the disappearing air during melting. Furthermore, small amounts of low-viscosity additives can hinder the formation of melt film necessary for plastification.

Finally, a distributive finish mixing in the main temperature window (mixing in the melt) is generally required. The main temperature window during compounding is above the flow temperature range for amorphous products or the melt range for partially crystalline polymers and below the decomposition. Example values for a polymer: The flow temperature range starts at PC according to Frank [6, page 98] at approx. 230 °C, also depending on the PC type (injection molding of low viscosity or high viscosity extrusion type differ). For the description and modeling of the melting of amorphous polymers (which do not have a sharp melting point) with experiments on single-screw extruders, a critical flow temperature is specified in

Han [9, Chapter 2], which is 200 °C for polycarbonate. In the following, the flow temperature range is considered again: according to Figure 2.17, 200 °C is a good "average value" for PC.

2.3.3 Temperature and Time Limits for Compounding

Compounding takes place very economically at high throughputs utilizing the specification limits of the compound. A limit is the thermal damage of product. Information in the literature about a temperature at which the chemical damage and finally decomposition begins often refers to longer exposure times. The decomposition depends, among other things, on temperature and time, and is thus not a pure temperature function. Figure 2.12 shows this connection qualitatively.
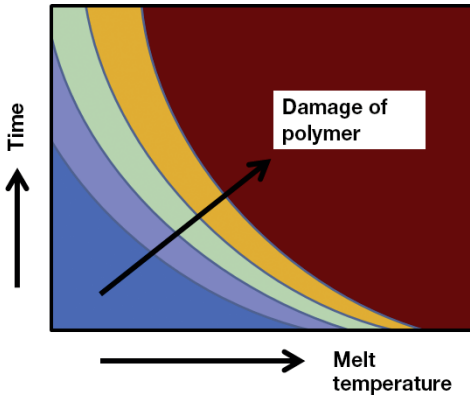

Figure 2.12
Damage of a polymer melt due to temperature-time stress (qualitative)

The beginning of a damage is given in Frank [6, Fig. 3.3.2], for example, for PC in [6] from about 320 °C. PC would endure this melt temperature for approximately 10 minutes until the beginning of an intolerable damage, as discussed below. For very short periods of time, the PC melt also withstands 400 °C. Therefore, the temperature limit of the product damage with the related temporal load should be considered in more detail.

According to a compounding process, the product temperature rises from melting to the main temperature window. In an extruder, the product is subject to a temporal temperature curve $T(t)$. The thermal product load or damage S can be described by an Arrhenius approach with integration over the temporal progress, Equation 2.2.

$$S = K \cdot \int_0^{t_E} \exp\left(-\frac{a}{T}\right) dt \qquad (2.2)$$

Where T is the temperature in Kelvin [K] and t is the time.

To compare the temporal load of a melt for different temperatures, constant temperatures T_E are considered, Equation 2.3:

$$S = K \cdot t_E \cdot \exp\left(-\frac{a}{T_E}\right) \tag{2.3}$$

For a clear quantitative idea of the temperature-time limit in the main temperature window compounding according to Figure 2.8, the parameters a and S/K should be roughly considered using the example of a polycarbonate type PC. Assuming that the damage of a 10 K higher stressed melt doubles at the same residence time, the parameter a would be, according to Equation 2.3, approx. 27,000 K, when a reference temperature of 350 °C is assumed.

On the other hand, the residence time t_E can also be calculated up to a certain damage, for example up to a still tolerable damage S, Equation 2.4:

$$t_E = (S / K) \cdot \exp\left(\frac{a}{T_E}\right) \tag{2.4}$$

By fixing a point (t_E, T_E), the pre-factor S/K in Equation 2.4 can be determined. One example for polycarbonate is here $S/K = 10^{-17}$ s (s = seconds).

Figure 2.13 clearly shows the result of the quantitatively rough calculation for the temperature-time load limit.
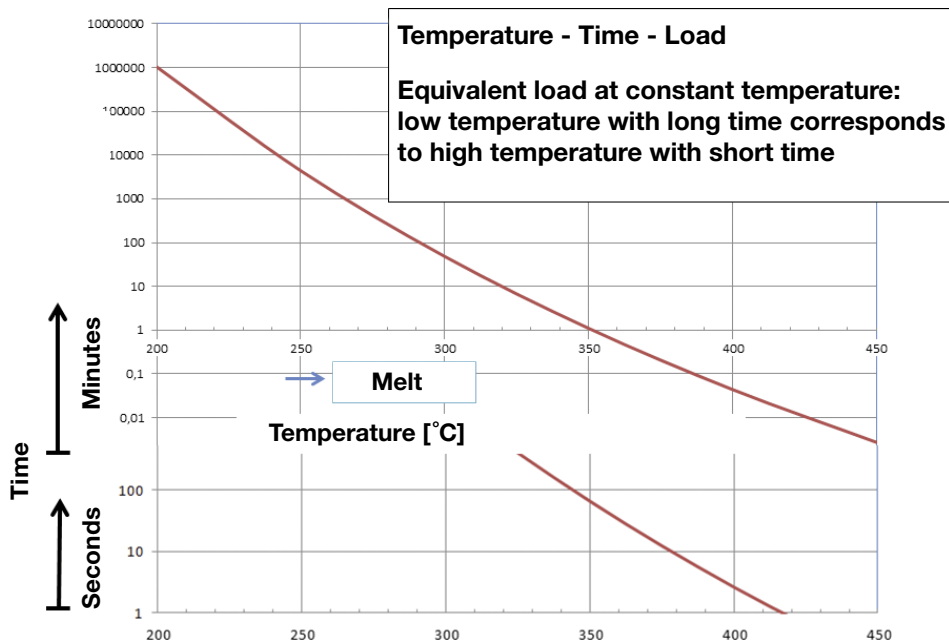

Figure 2.13 Equivalent temperature-time load limit for a polycarbonate example

In the case of a PC melt at 350 °C, the still tolerable damage limit occurs after one minute as shown in Figure 2.13. At 420 °C, the same damage is achieved after about one second. Normally, the temperature-time window for compounding is below the limit specified in Figure 2.13. The average residence times in traditional compounding extruders are today less than half a minute. However, a small proportion of polymer in the extruder, for example in gaps with high shear and thus temperature load, can come up to the damage limit. It should be noted that the damage, for example the Yellowness Index, depends not only of the thermal load, but also on the additives, for example the solvent and the solvent portion used. This displaces the damage limit in Figure 2.13. In particular, also a contact of the hot melt with air (oxygen) is to be avoided! Furthermore, it should be noted that the above-mentioned damage limit can change quantitatively due to changed specifications. In practice, due to economic reasons, it will be produced close to the specification limit. High throughputs are generally more economical, as illustrated by the simple principle depiction in Figure 6.7 in Chapter 6. See also Figure 2.14.
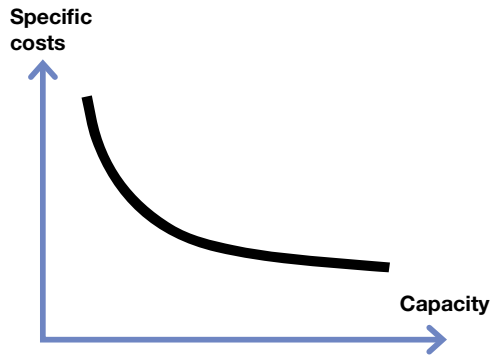

Figure 2.14 Schematic relationship between capacity and specific costs

High throughputs usually mean also a higher product temperature as the higher throughputs are usually only attainable at higher speeds. In fully filled extruder sections, the mean residence time falls in fact, and thus the temperature; however, with increasing throughput, with increasing speed, the mean temperature increases disproportionately. This is expressed by Equation 2.1 ($t \sim 1$/throughput, $n \sim \gamma$, $T \sim e$).

All in all, the temperature window for compounding PC compared to some other plastics is large (see also Figure 2.15). PC is more "stable" than PVC, for example. For PVC, the flow temperature area starts at about 175 °C and the damage range starts at about 210 °C [6]; for the last value, again a load duration applies.

Despite the problem of specifying permissible melt temperatures due to lack of time allocation, literature data on common temperature windows in the melt area [10] are given here, Figure 2.15.
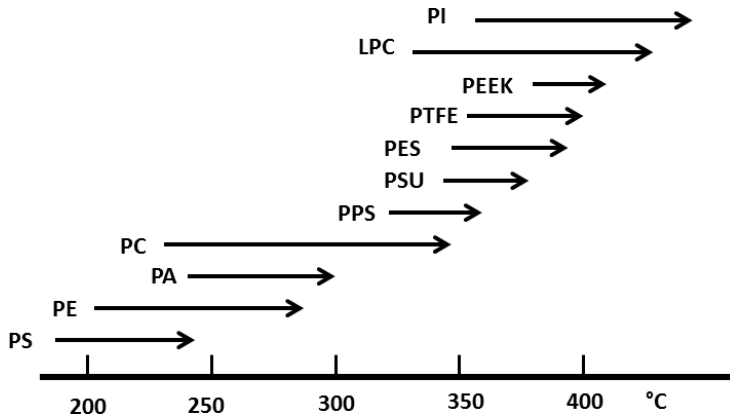
Figure 2.15 Processing temperature range of some types of plastic according to [10, Fig. 5, page 233]

Because of the "flowing limits" of reference values, other temperature ranges can also be found in the literature, for example in [6, chart 7.4.1] and [11, Fig. 3.4].

In order to keep the thermal polymer damage low, the temperature-time load should be minimized. As the temperature and residence time increase, undesirable side reactions, such as back reaction, degradation, and yellowing, increase. Oxygen contact also leads to increased damage at higher temperatures. Long melt residence times, for example in connecting lines between plant components, should be avoided.

2.3.4 Challenges when Compounding

Compounding is associated with special challenges:

- The "temperature window" for compounding can be small and lies before the thermal damage (explanations above).
- The material data (viscosity and others) of the mixtures are usually unknown.
- The melt behavior usually has to be determined experimentally.
- The melt behavior with additives can vary significantly.
  - Small amounts of low-viscosity additives may hinder the melt film formation necessary for plastification.
  - Conversely, highly viscous or solid additives cause an increased heat dissipation which can lead to thermal product damage.
- Additives do not always change only one property of the polymer/plastic, but can also change several properties. For example, dyestuffs for coloring plastics can not only change their appearance, but also other properties [12].

- In large extruders, product cooling via the housing is hardly possible.
- Not all extruder types are suitable for melting, in particular not for very high throughputs with the required drive energy (Section 6.8, Extruder Types – Comparison, Figure 6.110).
- Some polymer blends cannot be produced as there are different main temperature windows.

The last two points are explained in more detail: For mixing of polymers (so-called blends), the flow temperature range (Figure 2.8) must be exceeded. The flow temperature range can be so high in a polymer where another polymer is already decomposed, thermally damaged. Figure 2.16 shows examples of three products with different temperature windows.
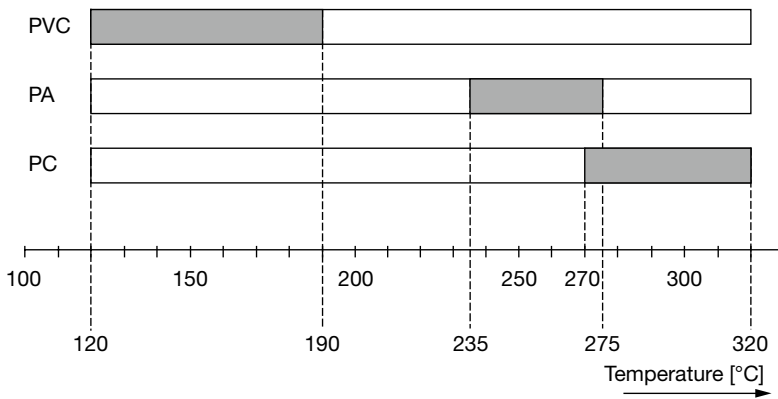

Figure 2.16 Melt temperature window for three polymers according to [13, Fig. 10.2]

The flow temperature range of polycarbonate (in the example a low viscosity CD type) begins only at a temperature level at which PVC already decomposes. It is impossible to produce a homogeneous plastic melt from these two polymers.

The temperature range of PVC in Figure 2.16 according to [13] differs from the information given above for PVC from the source [6], in particular with regard to the start of the flow. It should be noted that the flow, i.e. the viscous area, begins at a higher temperature (at about 175 °C) for rigid PVC and at lower temperature for soft PVC.

How else can the information about a "flow temperature" differ? It must be noted that a flow temperature is physically not exactly defined [6] and amorphous plastics always have a flow temperature range. Often, a flow temperature is then indicated from the lower area where an extrusion becomes possible. Figure 2.17 shows the flow temperature range for a medium viscosity PC type and the dependence on the measurement frequency [14]. The entropy-elastic range (T_F–T_g) increases with increasing frequency, whereby no increase occurs from about 500 Hz. It is also concluded that the flow temperature at faster compression is shifted to signifi-

cantly higher temperatures [14, page 115]. Therefore, the "melting temperature" T_F in extruders during melting of pellets is displaced in direction of higher temperatures. It was already referred above to the modeling of the melting in extruders [9, Chapter 2]. The temperature specification of 200 °C is in the range of the limits shown in Figure 2.17.
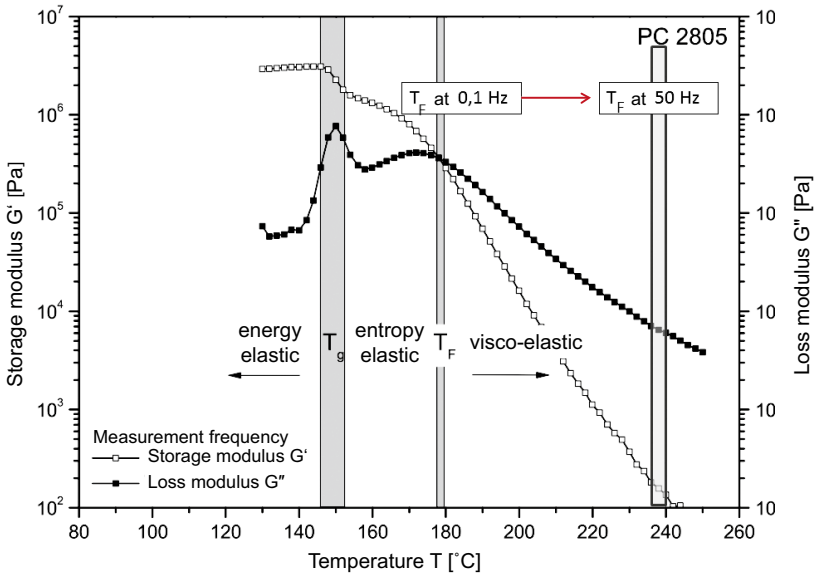

Figure 2.17 Glass temperature T_g and flow temperature range T_F for a medium-viscosity PC type [14] and change by the measurement frequency (the curves belong to 0.1 Hz)

For partially crystalline plastics, the flow temperature range is distinctly clearer and narrower, and the melting temperature of the crystallites is used as a sharp limit, Figure 2.18.
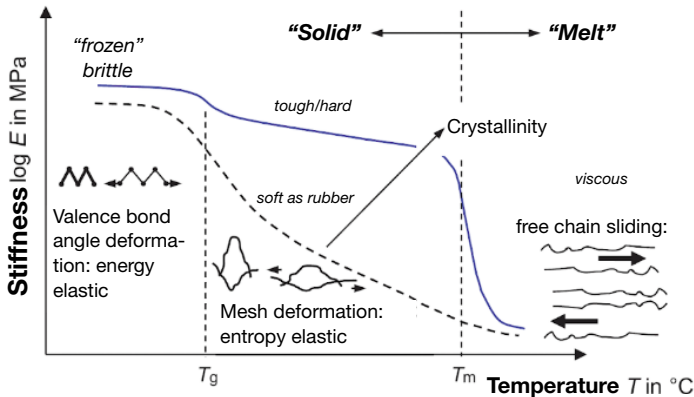

Figure 2.18 Deformation behavior of thermoplastics in dependence of temperature [15, Fig. 1.5]

2.3.5 Energy Requirement when Compounding

The compounding step which is carried out after the primary production can be directly coupled procedurally at the polymer manufacturer. Then the pelletizing and repeated melting of thermoplastics between the two processing steps (Figure 2.5 and Figure 2.6) can be omitted. This is energetically more economic and gentle regarding the product, but means a more complex overall line with low operational safety and flexibility as far as the variety of products is concerned.

Normally, compounders modify the polymers and create their own products with improved properties. The compounder receives the polymers normally as pellets – sometimes as powder – from the polymer manufacturer and therefore thermoplastics must be re-melted. Rubbers are not melted. Plasticizing in rubber technology means converting a viscoplastic state at room temperature into a sufficiently flowable state by converting mechanical drive energy into heat [5].

Required Specific Energy

As shown in Section 2.3.9, the required drive energy of the extruder shaft(s) P_W is expressed with the specific energy:

$$e_W = \frac{P_W}{\dot{M}_A} = \Delta e_{product} + e_{housing} + \Delta e_{pressure} + e_{degassing} \tag{2.5}$$

This means

$$\Delta e_{product} = c_A \cdot T_A - e_E \tag{2.6}$$

with

$$e_E = \sum(c_{Ei} \cdot T_{Ei} \cdot m_{Ei}) \qquad m_{Ei} = \dot{M}_{Ei} / \dot{M}_A \tag{2.7}$$

the specific energy of the input flows, thus usually of the base polymer and of the additives. The mass flow $\dot{M}_A$ is the mass flow of the compound that is discharged by the extruder. Equation 2.6 contains the specific heat capacity c_A of the compound at the extruder outlet, which consequently is of major importance.

Figure 2.19 shows the specific heat capacity of a polymer with the main temperature window for finish mixing of the additives, which is between T_1 and T_2. The importance of T_1 and T_2 is depicted in Figure 2.8. T_1 describes the flow temperature range described above, and T_2 the area where the damage is noticeable. According to the above descriptions, the temperature range T_2 is to be considered together with the temporal stress.
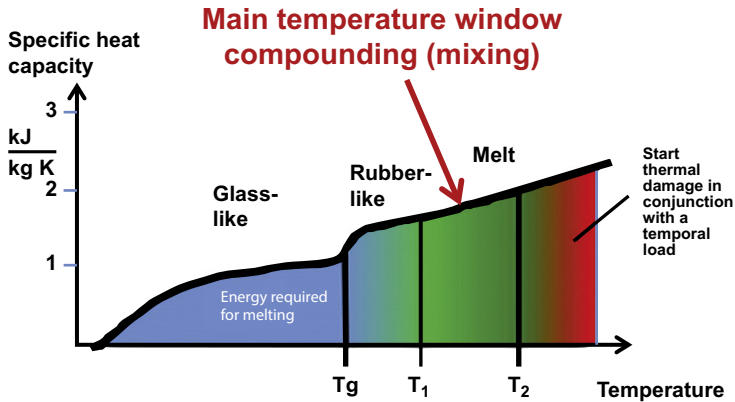
Figure 2.19 Energy requirement (area) for melting an amorphous thermoplastic [6, Fig. 6.3]

It is apparent that the essential part of compounding extruders is needed for the melting of the polymer. For simplification, only the polymer is considered instead of the mixture of polymer and additives, i.e. only the energy necessary for the temperature change from the extruder inlet to the extruder outlet of the base polymer without additives. The required energy input is represented by the area under the curve in Figure 2.19. Enthalpy temperature diagrams are more useful because by means of these the required energy can be read off directly.

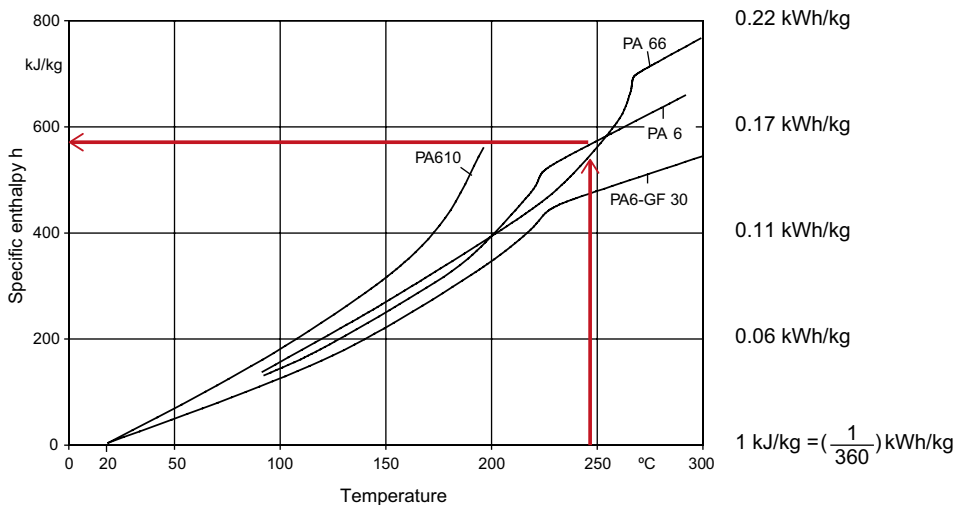As an example, Figure 2.20 shows the specific enthalpy for different types of polyamide [16].

Figure 2.20 Specific enthalpy for different types of polyamides (based on [16, Fig. 3.43])

The enthalpy change must be introduced into the polymer (proportional to D^3) by the extruder via the shafts. An energy portion can also be introduced via the housing walls. For larger extruders, this proportion is low (areas proportional D^2).

For the specific drive energy

$$e_{extruder} = P_W / \dot{M}_A \tag{2.8}$$

of extruders, the unit kW divided by kg/h is common. The unit customary for the specific enthalpy is kJ/kg; this can also be expressed in kW/(kg/h):

$$1\ \text{kJ} / \text{kg} = \left(\frac{1}{3600}\right) \text{kWh} / \text{kg}$$

Figure 2.21 shows this trivial correlation relating to ton/hour [t/h] for production machines. In addition, the performance is given in dependence on the throughput in Figure 2.22, where with the double logarithmic representation small throughputs are easier to read off.
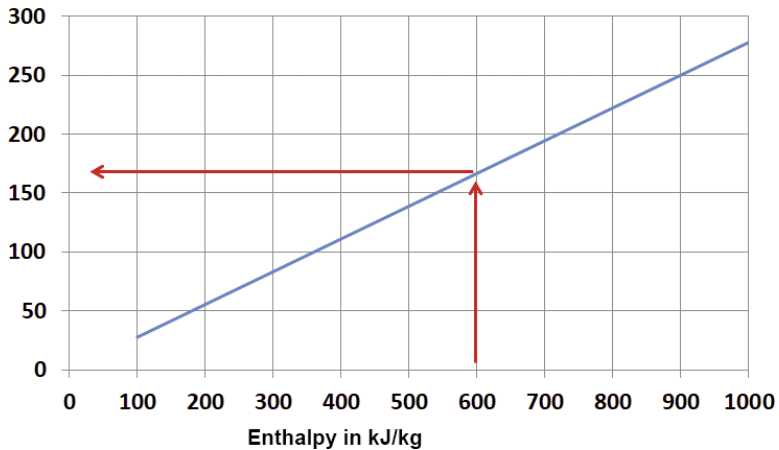
Energy in kW per t/h throughput

Figure 2.21 Required (minimum) drive energy of extruders for melting or for enthalpy changes (temperature changes) of polymers

Figure 2.21 and Figure 2.22 show the required minimum drive energy of an extruder to melt the polymer. Example: To melt PA6, just under 600 kJ/kg (= 0.17 kWh/kg) is required according to Figure 2.20. For a line with a throughput of 10 t/h, a minimum drive energy of approx. 170 kW · 10 = 1.7 MW is required according to Figure 2.21.
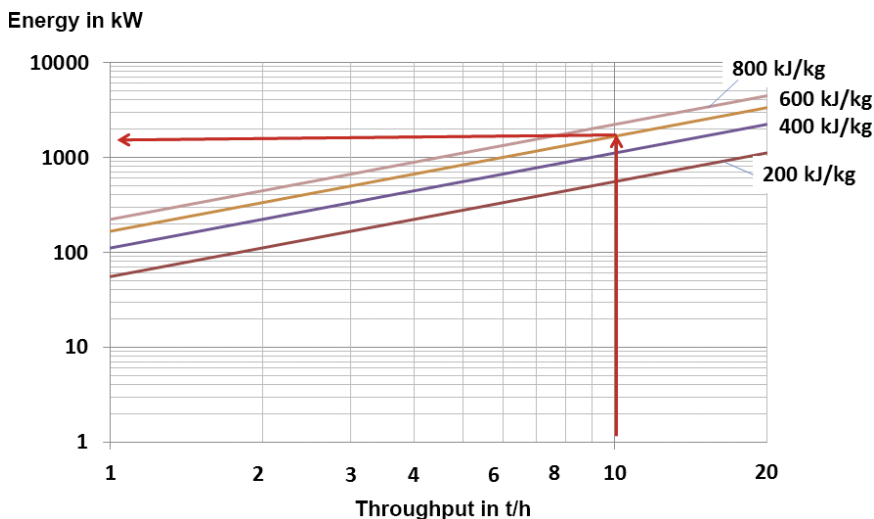
Energy in kW

Figure 2.22 Required (minimum) drive energy of extruders in dependence on the throughput with the required enthalpy change as parameter

In addition, there are energy inputs, which are given in Equation 2.5, that are introduced into the product by the extruder shafts and which, in addition to the enthalpy change (temperature change), lead to further energy release by the product. The energy portion for the pressure build-up is low, however. For a pressure difference of 50 bar between product outlet and inlet, assuming average material data, only about 5 kJ/kg is needed. This is about 1/100 of the proportion of the above numerical example for the enthalpy change. The energy portion of the cooling via the housing walls is also low in production machines, as shown in an example in Section 5.7 (Bierdel), below 5 %. The proportion $e_{housing}$ (sum heating minus cooling) is thus small in large compounding extruders compared to the enthalpy change of the product.

To calculate the electrical power, the energy losses of motor and gear (degrees of efficiency) must be added in addition to the required shaft energy.

Corresponding extruders with high drive energy are machines and not lightweight apparatus. Not all extruder types allow high throughputs with simultaneous melting of the polymer. Actual maximum throughputs are given in Section 6.8 (Extruder Types – Comparison).

Figure 2.21 and Figure 2.22 can also be used for so-called "melt feed extruders", i. e. extruders that do not need to melt polymer. These extruders are also called "hot feed extruders". Then, the enthalpy difference is decisive, which results from the difference between the discharge temperature of the product and the inlet temperature. Attention must be paid to mixtures, and, especially for degassing extruders, to the portion of volatile matter (evaporation enthalpy). The equations given in Section 2.3.9 take these proportions into account.

A comparison of amorphous polymers with partially crystalline ones shows that in partially crystalline polymers on average almost twice the melting energy is needed.

2.3.6 Range of Performance of Extruder

The above describes what drive energy a polymer requires during compounding. Which drive capacities do extruders offer? In order to consider the drive capacity independently of the exact screw diameter, a diameter is chosen as reference value. As described in the introduction to the co-rotating twin-screw extruder (Section 5.1), a reference diameter makes sense from a procedural point of view. As the co-rotating twin-screw extruder is the standard extruder in compounding, this is considered as an example of performance density and compared to a single-screw extruder.

Torque Density, Performance Density

For single-screw extruders, the torque of the shaft can be considered in relation to the diameter. The manufacturers of co-rotating twin-screw extruders specify the torque of a shaft related to the center distance.

Neglecting the clearance between the shafts, with the center distance $A = (D_a + D_i)/2$ and the torque M_{d1} of a shaft, the following relationship applies:

$$\frac{M_{d1}}{D_a^3} = \frac{M_{d1}}{A^3} \cdot \frac{1}{8} \cdot \left(1 + \frac{1}{\frac{D_a}{D_i}}\right)^3 \tag{2.9}$$

The values M_{d1}/A^3 and D_a/D_i are given by the manufacturers. With the total performance $P = z \cdot M_{d1} \cdot 2 \cdot \pi \cdot n$ with $z = 2$ for two shafts, the following performance density P_{LD} can be defined:

$$P_D = \frac{P}{D_a^3 \cdot n} = z \cdot 2 \cdot \pi \cdot \frac{M_{d1}}{D_a^3} \tag{2.10}$$

Example:

$$\frac{M_{d1}}{A^3} = 15 \frac{\text{Nm}}{\text{cm}^3} \qquad \frac{D_a}{D_i} = 1.66$$

which results in:

$$\frac{M_{d1}}{D_a^3} = 7.71 \frac{\text{Nm}}{\text{cm}^3} \qquad \frac{P}{D_a^3 \cdot n} = 96.9 \frac{\text{Nm}}{\text{cm}^3}$$

The performance density is, like the torque density, not dimensionless and has the same unit. A torque density thus corresponds to a performance density. The extruder user is primarily interested in what performance is needed for a certain throughput. The performance offered by the extruder can be calculated directly with the performance density. For this purpose, the units are advisably chosen so that the screw diameter can be applied in millimeters and the speed in 1/minute:

$$\left[\frac{\text{Nm}}{\text{cm}^3}\right] \cdot 60 \cdot 10^6 = \left[\frac{\text{kW} \cdot \text{min}}{\text{mm}^3}\right]$$

The performance density per shaft makes limited comparison possible with single-screw extruders or with multi-shaft extruders. Limited because the reference diameter can be defined differently. The extruder user is mainly interested in what throughputs can be realized. That is why the attainable speeds are very important.

Example Rubber Extruder

The permitted finish temperatures for rubbers are generally much lower than for thermoplastics, and the extruder speed and throughputs are correspondingly low. Basic data for so-called cold extruders are described in [5, Fig. 10.13]. Example: For a pin type extruder with a screw diameter of 300 mm, a drive power of 800 kW and a speed of 20/min are specified. The throughput is about 7 t/h (see also Figure 2.22). The speeds for co-rotating twin-screw extruders for thermoplastics are considerably higher: On a larger co-rotating twin-screw extruder with 380 mm screw diameter, 130 t/h of polyethylene (LLDPE/HDPE) are processed. It should be noted that the pin type extruder for rubber is a single-screw one, whereas that for polyethylene a twin-screw one.

The pin type extruder for the example rubber provides:

$$\frac{P}{D_a^3 \cdot n} = \frac{800\,\text{kW}}{300\,\text{mm}^3 \cdot \dfrac{20}{\text{min}}} = 88.9 \frac{\text{Nm}}{\text{cm}^3}$$

This is a value of the same size as the value of the twin-screw extruder (the value for the twin-screw extruder applies for two shafts, which corresponds to the total range of performance).

The twin-screw extruder is used for thermoplastics at higher speeds, in particular small machines can be operated at very high speeds. Figure 2.23 shows the simple connection, the performance P/D^3 for the example with Equation 2.10 in dependence on the screw speed.
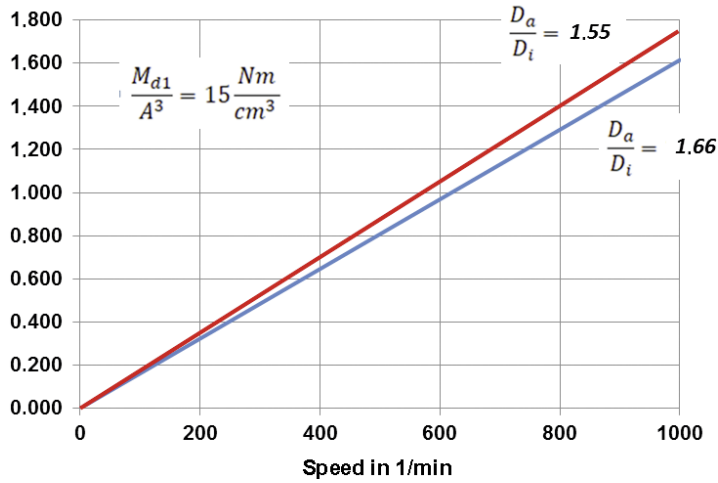
Performance P/D³ in W/mm³

Figure 2.23 (Offered) performance density of co-rotating twin-screw extruders in dependence on the screw speed with D_a/D_i as parameter

A numerical example for Figure 2.23: For an extruder with a diameter of 133 mm and D_a/D_i = 1.55 (Coperion) at 1000 revolutions per minute, a performance value of 1.75 W/mm³ arises. If this value is multiplied by 133³ mm³ this results in a performance of 4.1 MW. In a table from Coperion [17], 4.4 MW is stated for the motor performance as, amongst other things, also the dissipation loss of the gear (efficiency) is added.

Normally, the permissible torque M_{d1}/A^3 also changes with the diameter ratio. This will be dealt with in Section 5.1, where different diameter ratios are considered under different aspects.

The torque density specified by extruder manufacturers usually is the maximum available. A maximum available torque density M_{d1}/A^3 results in a maximal offered performance density $P_{Wmax}/(n \cdot D^3)$.

$$P_{D,Wmax} = \frac{P_{Wmax}}{n \cdot D^3} = z \cdot 2 \cdot \pi \cdot \frac{M_{d1,max}}{D^3} \tag{2.11}$$

The additional index W indicates that this performance is applied to the shafts. In Section 6.8, Extruder Types – Comparison, further performances of the extruder drive including the electrical drive performance are considered.

2.3.7 Throughput and Performance Density

The extruder throughput can be formulated dimensionless with the throughput key figure

$$\dot{V}^* = \frac{\dot{V}}{n \cdot D^3} \tag{2.12}$$

with the volume flow $\dot{V}$, the speed n, and a reference diameter. The throughput key figure is discussed in the relevant literature from Kohlgrüber [8] and Pawlowski [21], and is the most important key figure for extruders. Previously, Q was also used as a formula symbol.

For the polymer producer or compounder, the mass throughput is decisive. With the mass throughput $\dot{M}$ and a density ρ, the dimensionless volume flow is $\dot{V}^* = \dot{M} / \rho$. As the density changes in dependence on, inter alia, temperature, it is also useful to select a reference density ρ_B = 1 kg/l for comparison purposes. This can be used to define the following throughput key figure.

$$\dot{V}_B^* = \frac{\dot{M}}{n \cdot D^3 \cdot \rho_B} = \frac{\rho}{\rho_B} \cdot \dot{V}^* \tag{2.13}$$

The performance density according to Equation 2.10 can be expressed with the throughput key figure $\dot{V}^*$ and the specific performance e.

Neglecting the clearance between shaft and housing, the housing diameter D can be replaced by D_a. Together with the specific drive performance, the following arises for the performance density:

$$P_D = \frac{P}{n \cdot D^3} = e \cdot \dot{V}^* \cdot \rho = e \cdot \dot{V}_B^* \cdot \rho_B \tag{2.14}$$

Throughput Density

For example, the polymer blend density changes with the temperature or is un-known. Then, alternatively, as described above, the dimensionless throughput key figure $\dot{V}_B^*$ may be used with the reference density. Another possibility is to intro-duce a dimensioned throughput density:

$$\dot{M}_D = \frac{\dot{M}}{n \cdot D^3} = \dot{V}^* \cdot \rho \tag{2.15}$$

The throughput density describes clearly the throughput per revolution related to the screw diameter cubed.

$$\dot{M}_D = \frac{throughput\ per\ revolution\ \left(e.g.\ in\ kg\ /\ rev\right)}{screw\ diameter^3} \tag{2.16}$$

The required enthalpy change described above (e. g. for melting) results in the minimal required specific drive performance e_{min}, if the heating performance via the housing is not considered and other emitted energies (cooling, evaporation enthalpy, etc.) are ignored. This results in the dimensionless throughput key figure, as shown in Equation 2.14:

$$\dot{M}_D = \frac{P_{D,Wmax}}{e_{min}} = \dot{M}_{Dmax} \tag{2.17}$$

As a maximum value is the quotient in the equation, Equation 2.17 gives the maximal throughput density.

Equation 2.17 clearly shows that higher throughput rates are possible in extruders if

- e_{min} is smaller, i. e. the required enthalpy change from the product is lower (e. g. amorphous versus crystalline polymer)
- the torque density M_{d1}/A^3 or M_{d1}/D^3 is greater

Advantages of the throughput density:

- By standardization, the throughput density is independent of the speed and the actual extruder size. Big and small machines can be compared, which is important for scale-up and scale-down considerations.
- A comparison of single-screw and multi-screw extruders will be made possible.

For this the throughput density per screw can be considered:

$$\dot{M}_{D1} = \frac{\dot{M}_{1W}}{n \cdot D^3} \tag{2.18}$$

with z = number of screws and $\dot{M}_1 = \dot{M}/z$ the throughput per screw.

The consideration of the known conveying key figure [8] is also useful.

$$\Lambda = \frac{\dot{V}}{\dot{V}_{max}} = \frac{\dot{V}^*}{A_1} \tag{2.19}$$

Here A_1 is a conveying parameter which is also called profile parameter as it depends only on one special screw geometry.

It is possible to define a conveying parameter $A_{1,1}$ that relates to one shaft only.

$$\Lambda = \frac{\dot{V}}{\dot{V}_{max}} = \frac{\dot{M}_{D1}}{A_{1,1} \cdot \rho} \tag{2.20}$$

Applications of the equations to a comparison of extruders:

If the twin-screw ($z = 2$) is compared with the ring extruder ($z = 12$), then it follows for the same (total) throughput $\dot{M}$ of both machines:

$$\dot{M} = 2 \cdot \dot{M}_{1W,e} = 12 \cdot \dot{M}_{1W,ring} \tag{2.21}$$

and with Equation 2.18 and Equation 2.20:

$$2 \cdot n_{twin} \cdot D_{twin}^3 \cdot \Lambda_{twin} \cdot A_{1,1twin} = 12 \cdot n_{ring} \cdot D_{ring}^3 \cdot \Lambda_{ring} \cdot A_{1,1ring} \tag{2.22}$$

The same operating point Λ is considered for both extruders. The conveying behavior of a screw geometry is described by the conveying parameter $A_{1,1}$. It describes the maximum dimensionless throughput of one screw element per shaft. It is known [29] that a twin-screw extruder has a higher inherent throughput due to the gusset than a single-screw extruder with the same geometry (i.e. geometry of the twin-screw), although the eight-shaped cross section of the twin-screw is less than twice the cross section of the twin-screw. In the case of the ring extruder, one gusset is assigned to each shaft, whereas in the case of the twin-screw only one gusset is assigned to two shafts. Thus, it follows that $A_{1,1Ring} = a \cdot A_{1,1twin}$ with $a > 1$. With this, it follows, at the same speed of the machines:

$$D_{twin} = \sqrt[3]{(6 \cdot a)} \cdot D_{ring} \approx 1.8 \cdot D_{ring} \cdot \sqrt[3]{a} \tag{2.23}$$

As the value a will be only slightly above 1, the third root is almost 1. Example: Tests and throughputs with the smallest ring extruder of (presently) 19 mm can thus be compared with a twin-screw extruder of approx. 34 mm.

The extruder comparison with the result of Equation 2.23 was carried out with the conveying capacity of the screw geometry. Alternatively, it can also be "demanded" that both extruders shall have the same throughput density per shaft. From this results with Equation 2.18 and Equation 2.20 directly the connection Equation 2.23 without the factor $\sqrt[3]{a}$.

Following the above numerical examples of the maximal performance density, the throughput density is considered:

$$P_{D,Wmax} = 100\,\frac{Nm}{cm^3} \qquad e_{min} = 600\,\frac{kJ}{kg} = 0.17\,\frac{kWh}{kg}$$

For the maximal throughput it results in

$$\dot{M}_{Dmax} = \frac{100}{600} \cdot \frac{kg}{10^6 \cdot mm^3}$$

The number is not clear at first. The dimensionless throughput key figure

$$\dot{V}_B^* = \frac{\dot{M}_{Dmax}}{\frac{1\,kg}{l}} = \frac{100}{600} = 0.17$$

is without the reference density a known value [8] for the extruder experts.

Multiplication with a screw speed and the screw diameter cubed produces the maximal throughput. For D = 50 mm and n = 1000/min, the result is 1.25 t/h. For comparison, Figure 2.24 shows realized throughputs when compounding [18] PC with glass fibers for an extruder of the size 50 (more precisely 51.2 mm).
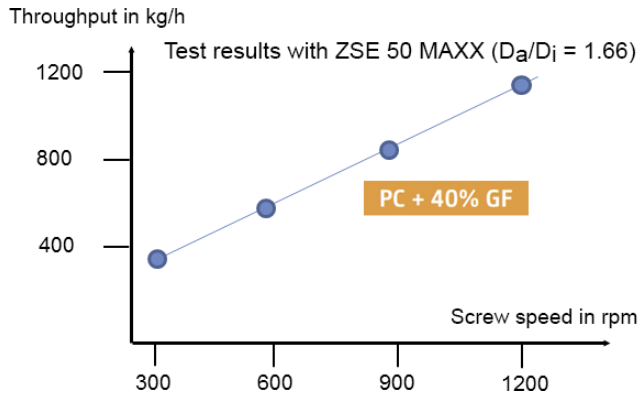

Figure 2.24 Measured throughputs with PC + 40 % GF

The example is only conditionally comparable as with PC + GF a slightly different value for the enthalpy change arises. The magnitude of the specific heat capacity of PC + GF is about 2 kJ/kg at somewhat above 300 °C. The value increases with increasing temperature, and decreases with increasing GF content. So, also in this example, about 600 kJ/kg (0.17 kW/kg) is needed for the product.

It should also be noted that even with the same enthalpy change real throughputs are below the maximum throughput of 1.25 t/h, firstly because the maximal torque is not used, and secondly because only the enthalpy of the polymer was taken into account at the specific drive performance for the example. In addition, when the housing is cooled, some of the energy produced by dissipation is not retained in

the product and the specific drive performance is higher and thus the maximal throughput is lower.

Already in the 1960s, highly productive extruders were expected to produce high specific drive performance of about 1000 kJ/kg (0.28 kWh/kg) (Mink [24, page 159]). According to the considerations of Lechner, Section 5.3, there are limits for the energy requirement of 0.15 to 0.25 kWh/kg for polymer bulk densities of 0.3 to 0.7 g/cm³ for compounding processes.

2.3.8 Performance Density in the Melt Area

As described above, most of the drive energy is needed to melt the polymer. This section specifically considers one melt area and asks, what is the influence of viscosity on the performance density? Some extruders, e.g. degassing extruders in polymer manufacture, are charged with melt, i.e. throughout the extruder there is a melt. The viscosity is then a mixed viscosity of polymer with solvents and additives.

For the melt area, a filled screw section is considered, and as a thought experiment a constant viscosity η. For this case, the "extruder equations" are known and described in detail in [8]. Regardless of the extruder size, the dimensionless performance for the considered screw section of length L is:

$$P^* = \frac{P}{\eta \cdot n^2 \cdot D^2 \cdot L} = B_2 \cdot \left(1 - \frac{\dot{V}^*}{B_1}\right) \tag{2.24}$$

Here, $\dot{V}^*$ is the throughput key figure, Equation 2.12, B_1 and B_2 are so-called "profile parameters", which only depend on the screw geometry. They are dimensionless and independent of the absolute extruder size. The initially asked question regarding the dependence on the viscosity can be seen from the above equation, but the connection with the torque on the performance density becomes even clearer:

$$P_D = \frac{P}{D^3 \cdot n} = \eta \cdot n \cdot \frac{L}{D} \cdot B_2 \cdot \left(1 - \frac{\dot{V}^*}{B_1}\right) = z \cdot 2 \cdot \pi \cdot \frac{M_{d1}}{D^3} \tag{2.25}$$

The performance density and the factor

$$\eta \cdot n \cdot \frac{L}{D} \cdot B_2 \; \sim \; \frac{M_{d1}}{D^3} \tag{2.26}$$

are therefore directly proportional to the torque. Consequently, in order to utilize fully an available torque, the viscosity, the screw speed, and the dimensionless length *L/D* are equivalent. In other words, if very high viscosities are present – e.g. in the melting area – then this is "at the expense" of a maximal extruder length. For special applications, extruder lengths of *L/D* > 100 are available.

According to the definition of the performance density, it is the performance of one extruder per revolution and related to the diameter and dimensioned. The performance profile parameter B_2 is dimensionless. This is discussed in more detail in Section 5.1.

2.3.9 Energy Balance and Product Discharge Temperature

Figure 2.25 shows an "extruder line", the core of a compounding plant, consisting of an extruder with drive and downstream equipment (pelletizing, optional melt filtration, etc.).
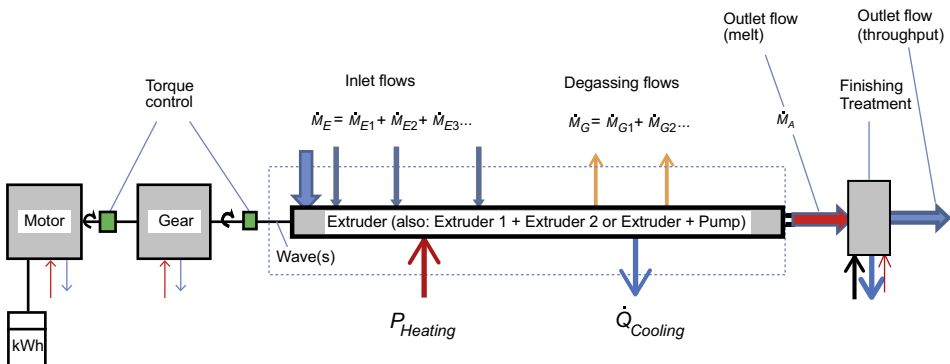

Figure 2.25 Extruder with drive and downstream equipment

For the extruder, an energy balance is set up in accordance with the dotted system limit shown in Figure 2.25. In terms of balance, these can also be two extruders connected in series. Alternatively, it may be one extruder with a downstream gear pump. When applying the energy balance given below, the process factors heating performance, cooling-heating flow, and drive performance must be applied analogously in accordance to the imaginary system limit. With the inclusion of an optional downstream gear pump, the performances of the extruder and the gear pump are to be used as sum under the drive performance. The balance can also be applied to the gear pump alone. In Section 7.4.2 it is applied to static mixers.

A stationary operation of the line is assumed and the first law of thermodynamics for open systems is applied. Above the audit space in Figure 2.25 the mass flows

are depicted which can be expressed together with the discharge flow by the enthalpy flows. The enthalpy flows are thermodynamic state variables in contrast to the heat flow, the drive performance, and the heating performance, which are process factors. State variables are "path-independent" and are described by their numerical values at the system boundary. The extruder can thus be well-balanced like a "black box". The process factors pass the balance limit at the bottom and left in the figure.

The energy balance provides for the depicted system boundary:

$$\dot{M}_A \cdot (c_A \cdot \overline{T}_A + \frac{p_A}{\rho_A}) + \dot{Q}_{housing} + \dot{H}_{degassing} = P_W + P_{heating} + \sum_{i=1}^{n} \left(c_{Ei} \cdot \overline{T}_{Ei} + \frac{p_E}{\rho_{Ei}} \right) \dot{M}_{Ei} \quad (2.27)$$

Where:

- $\dot{M}_A$ is the discharge mass flow (product flow).
- $\overline{T}_A$ is the energetic mean product discharge temperature.
- c_A is the specific heat capacity at constant volume at the temperature $\overline{T}_A$. For polymers, this differs only very slightly from the specific heat capacity at constant pressure. The difference becomes greater at very high pressures and temperatures.
- ρ_A is the density of the discharge flow at the temperature $\overline{T}_A$.
- p_A is the discharge pressure of the product at the system boundary. This may be the pressure in front of the die, but also the pressure downstream of the die, depending on where the system boundary is set. The discharge temperature changes depending on the system boundary. An example can be found in [8, page 335 in the *Fundamentals* book].
- $\dot{Q}_{housing}$ is the heat flow delivered or received via the inner screw housing. The value is a process factor and the algebraic sign was chosen so that a delivered heat flow (cooling) is positive. Formally, the heat flow can be expressed as follows [8, page 330 in the *Fundamentals* book]:

$$\dot{Q}_{housing} = U_G \cdot \int_{l1}^{l2} \alpha(l) \cdot \left(\overline{T}(l) - \overline{T}_{housing\ wall}(l) \right) dl \quad (2.28)$$

U_G is the inner circumference of the housing. Since the course of the variables in the equation is generally unknown, the heat flow can be roughly determined by averaging:

$$\dot{Q}_{housing} = U_G \cdot \left(l_2 - l_1 \right) \cdot \alpha_m \cdot \left(\overline{T}_m - \overline{T}_{housing\ wall,m} \right) \quad (2.29)$$