

HANSER

Co-Rotating Twin-Screw Extruder

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4 General Overview of the Compounding Process: Tasks, Selected Applications, and Process Zones

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4.1 Compounding Tasks and Requirements

The properties of polymers need constant refinement in order to meet the constantly increasing demands on plastic parts. Since the development of new polymers is steadily decreasing [1], deliberate modification of the properties of a base polymer by means of additives and/or blending with other polymers is becoming increasingly important. Herein lies the primary task of compounding.

According to an AMI study [2], 6,000,000 tons of compounds and 750,000 tons of masterbatches were consumed in Western Europe in 2003. The Western European compound and masterbatch market is shown in Fig. 4.1.

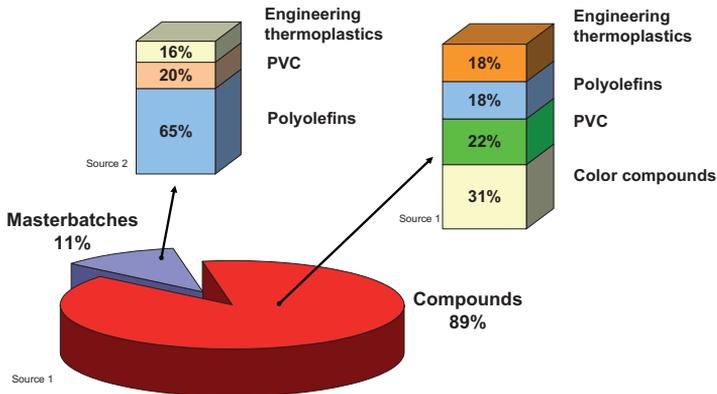


Figure 4.1: Compound and masterbatch market in Western Europe [3, 4]

The requirements of the compounding process are characterized by

- Increasing throughputs
- Decreasing batch sizes
- Increasing product variety
- Increasing quality requirements,
- Increasing filler contents
- New products (e.g., nano-filler materials, modified and blended polymers)

Today, compounding is predominantly carried out with co-rotating twin screw extruders with constantly increasing available drive powers, torques, and screw speeds.

In particular, increasing throughput means increasing the screw speed, which in turn leads to

- Higher thermal and mechanical polymer stress ($\dot{q} = \eta \cdot \dot{\gamma}^2$; $\tau = \eta \cdot \dot{\gamma}$)
- Shorter available processing times ($t_v = f(n, \dot{m})$)

This increases the risk of loss of product quality due to a decrease in the molar mass, thermal inhomogeneities and melting problems. The extruder and screw concepts need to be constantly optimized and adapted to avoid quality loss.

Typical compounding tasks include

- Reinforcing polymers
→ Incorporation of fibers (glass-, carbon- or natural fibers)
- Modification of thermoplastics to achieve high-impact resistance
→ Blending with rubber elastic components
- Improving the dimensional stability and compression strength of polymers
→ Incorporation of inorganic fillers, glass beads
- Improvement of flow, mold release, and flame retardant behavior of polymers
→ Incorporation of low-viscosity substances
- Production of polymer blends
→ Mixing compatible or incompatible polymer melts
- Coloring polymers
→ Incorporation of pigments, masterbatches, or liquid dyes
- Improvement of chemical/physical stability of polymers
→ Incorporation of low-viscosity stabilizers, antistatic agents.

The consumption of mineral fillers in Europe for thermoplastics processing alone was 1.5 million tons in 1999; a breakdown is shown in Fig. 4.2.

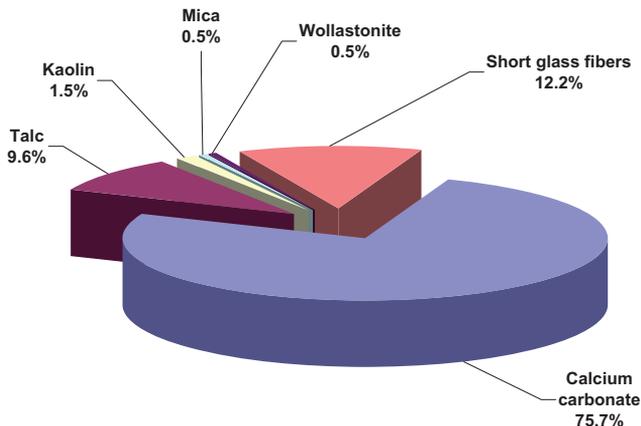


Figure 4.2: Consumption of mineral fillers for thermoplastic processing in Europe 1999 [5]

4.2 Tasks and Design of the Processing Zones of a Compounding Extruder

The various processing zones of a twin screw extruder are arranged in series, as illustrated in Fig. 4.3.

Each processing step is linked to the next. Therefore the different steps cannot be considered independently from each other. For example, coloring processes already take place in the plastification zone, the incorporation of fibers added to the melt takes place not only in the designated dispersing zone but also in the discharge zone and in partially filled screw channels.

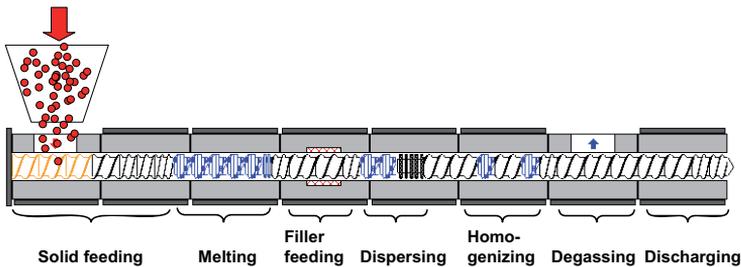


Figure 4.3: Processing zones of a twin screw extruder

Analyzing the unit operations in the extruder to a satisfactory degree is only possible when sufficient information about the rheological and thermodynamic properties of the polymers and polymer compounds is available. However, providing these data is very difficult, particularly in zones with considerable changes in state. Therefore, it is frequently necessary to refer back to model investigations and trials [6].

Figure 4.4 compares the independent setting parameters of the compounding process with the process values. Other than with a single screw extruder, the throughput rate can be chosen independently of screw speed.

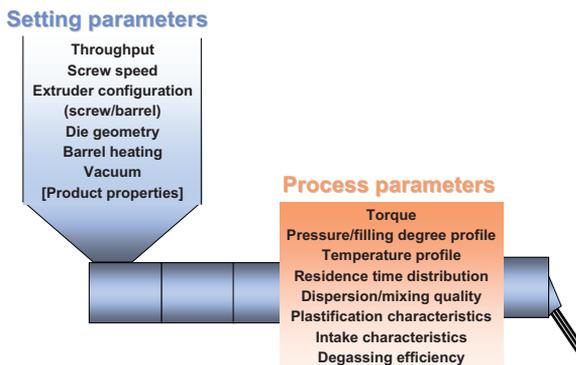


Figure 4.4: Parameters of the compounding process

Depending on the product to be processed and its requirements, the potential throughput of a compounding process is limited by the available volume, torque, and/or the maximum tolerable product temperature.

In the following, we will describe each processing zone in a co-rotating twin screw extruder.

4.2.1 Intake Zone

- Tasks:
- Convey and compress solids
 - Remove any air that is drawn in
- Key setting parameters:
- Screw speed
 - Throughput
 - Free screw volume
 - Pitch
 - Bulk density of the product
 - Friction between product and barrel wall

All intake processes are limited by volume [7].

The feed capacity depends on the free screw volume (channel depth, number of threads), the pitch, the screw speed, and the bulk density of the product. The product can only be conveyed if there is friction between the product and the cylinder wall.

Self-wiping screw elements with the maximum possible number of threads give the largest free cross-section (see Fig. 2.5, Chapter 2). Thus, triple-flighted elements should be used in the intake zone of twin screw extruders with $D_o/D_i < 1.3$, and double-flighted elements in the case of $D_o/D_i > 1.3$. An intake zone length of 4 to 6 D is generally adequate for effective product feed.

The pitch should be 1.5 D directly below the feed hopper. The pitch should be reduced to 1 D and/or 0.75 D towards the plastification zone in order to compress the products and to achieve a high degree of filling at the beginning of the plastification zone. This will result in improved melting characteristics (see Section 4.2.2). At the end of the intake zone, the compression of the solid can cause local pressures of up to 200 bar which, depending on the polymer, may lead to a greater or lesser degree of wear. It is therefore recommended that the elements at the end of the intake zone and at the beginning of the plastification zone are wear protected or have a reduced diameter.

An increase in the free cross-section and hence a 10 to 15% increase in the resulting maximum feed capacity is possible by using (non-self-wiping) pushing flight elements.

When conveying solids with a low bulk density, high fill rates in the intake zone can cause fluidization, if the air that is drawn in cannot escape from the extruder. This can be avoided by a partially filled downstream plastification zone (e.g., with conveying kneading blocks) and a vent opening installed downstream of the plastification zone.

The product is heated via the barrel wall and heating depends on the available heat exchanger surface and the throughput. Since the surface/volume ratio decreases as the screw diameter increases, product preheating in the intake zone is not relevant in large machines. Effective preheating prior to melting is therefore only possible in large machines before the

product is fed into the extruder [8]. The intake barrel is cooled in order to prevent low melting-point components, e.g., waxes, from adhering to the barrel wall or to the feed hopper, since this would severely affect the intake characteristics.

4.2.2 Plastification Zone

- Tasks:
- Melting of polymer
 - Pre-dispersion of fillers
- Key setting parameters:
- Screw speed
 - Throughput
 - Screw geometry
 - Heat flux
 - Specific heat capacity
 - Heat conduction
 - Melting enthalpy
 - Particle size

Comprehensive investigations of the polymer melting process in co-rotating twin screw extruders by Bastian/Gabor [9] yielded the following results:

- The melting process is influenced to a high degree by the screw speed and the throughput; in other words, the degree of filling and the residence time
- The required melting length depends substantially on the melting enthalpy of the polymer, the viscosity of the melt, and the screw geometry
- Significant melting starts at the point, where the screw is initially fully filled
- Varying the barrel temperature in the plastification zone makes hardly any difference to the melting process.

Melting can be accelerated by [9]:

- A high degree of filling
- Low melting temperatures
- Small pellet sizes
- A low degree of crystallinity
- Low melting enthalpy
- High melting viscosities
- Low flow activation energies (=temperature influence on viscosity variation)
- Narrow kneading discs

In addition, for polymer blends, the ratio of melt viscosities $r = \eta_{dispers} / \eta_{contin}$ of the blend partners has a major influence on the melting process. In this case, $\eta_{dispers}$ is the viscosity of the blend partner present in the dispersed phase and η_{contin} is the viscosity of the blend partner present in the continuous phase. The smaller the value of r , the sooner the melting process begins, but also the longer it takes [9]. In unfavorable process conditions, as yet unplasticized particles may be encountered in the compounded pellets (see Fig. 4.5).

The addition of low-viscosity additives can impede the formation of the melt film that is essential for melting. On the other hand, high-viscosity or solid additives can cause increased energy dissipation due to internal and external friction, which accelerates the formation of the melt film but can also lead to overheating of the viscous phase.

Along with the actual melting, part of the key tasks of dispersion and homogenization also takes place in the plastification zone.

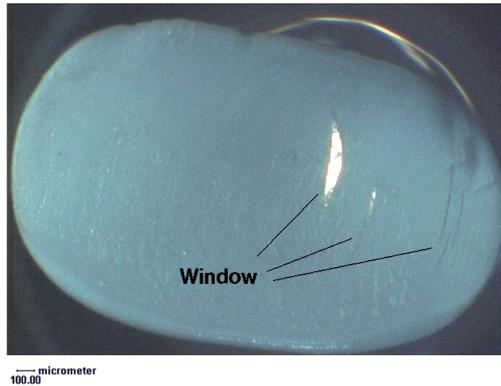


Figure 4.5: Unplastitized particles (so-called windows) within a single pellet

Depending on the subsequent process steps, achieving 100% melting at the end of the plastification zone may not be mandatory. Solid particles still present after the plastification zone can be melted in subsequent zones, e.g., in the dispersion or discharge zones. Figure 4.6 illustrates a typical melting profile along a plastification zone.

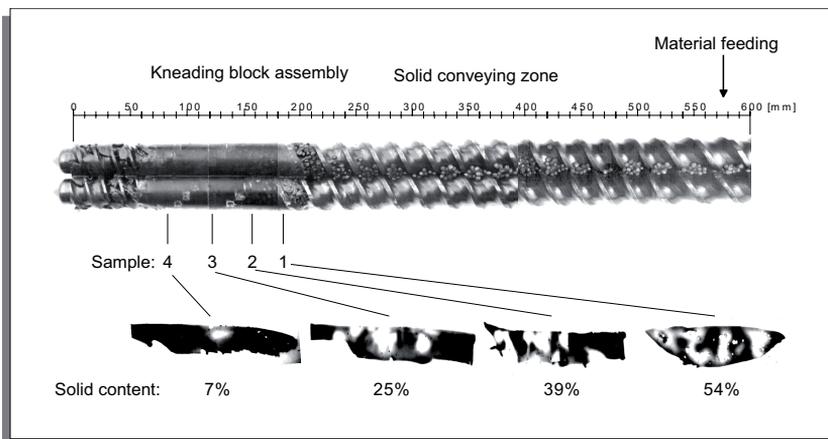


Figure 4.6: Melting profile along a plastification zone [10]

The energy required to melt the polymer components is largely transmitted via the screw shafts; the heat flow through the barrel wall serves only to form a melt film on the wall [6]. This melt film is important to create an adhesion of the polymer on the wall, thus generating a shear gradient [11]. To achieve this, the temperature of the barrel wall must be higher than the softening point of the polymer.

Up to 80% of the overall mechanical energy input in the twin screw extruder takes place in the plastification zone. Unfortunately, currently only rudimentary modeling capacities for the melting process are available.

Typically, double- or triple-flighted kneading blocks are used to facilitate melting. The influence of the kneading block geometry on the process parameters is shown using a double-flighted kneading block (see Fig. 4.7).

A larger staggering angle leads to:

- A reduction of the downstream conveying action of the melt and thus to
- An improved mixing performance because more leakage streams are generated (see Fig. 4.8) and the residence time increases.

A narrower kneading disc results in:

- Reduced shear in the kneading gap,
- Increased downstream conveying action of the melt and
- More efficient mixing due to the generation of more leakage streams.

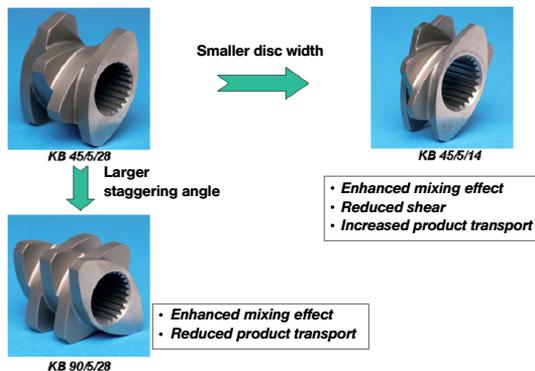


Figure 4.7: Geometric values and process variables of a double-flighted kneading block

Melting with triple-flighted kneading blocks results in less energy dissipation than with double-flighted kneading blocks. However, the melting length required is longer [9].

Melting is accelerated in completely filled zones. It is therefore beneficial to install a re-conveying element at the end of the plastification zone to cause back-pressure in the melt. Kneading blocks re-conveying or neutral, re-conveying screw elements or slightly re-conveying mixing elements are generally used for this purpose. However, the re-conveying screw elements can cause high pressure and temperature peaks and should be

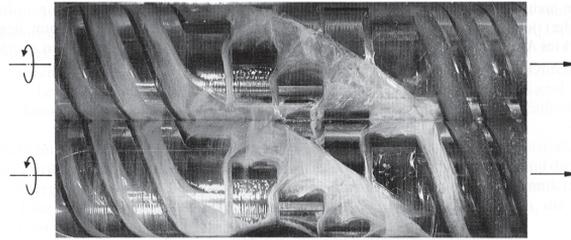


Figure 4.8: Melt streams in a kneading block zone – broad primary stream in the feed direction and narrow leakage flow [12]

avoided as far as possible (see Chapter 8). For complex melting operations, e.g., with high/low-viscosity multicomponent mixtures, sieve discs can also be used to create back-pressure, provided that the higher energy input generated by these discs is admissible.

If the basic polymer is a fine powder, or if it is necessary to incorporate low bulk-density fillers in large quantities, the plastification zone should be operated partially filled to prevent fluidization in the intake zone. Partial filling can be achieved when the plastification zone only consists of forward pumping kneading blocks and there are no re-conveying elements at the end of the plastification zone. In this case, however, the melting length must be considerably longer.

Melting in a fast-running, high-performance extruder can result in temperature peaks if conventional kneading blocks are used. These peaks can damage the polymer. To prevent these temperature peaks, less closely intermeshing screw elements have been developed. They reduce the shear peaks to provide a gentler compounding action. Examples include Multi-Process Elements (MPE) (Berstorff), triple-flighted eccentric kneading blocks with reduced external diameters and shoulder-type kneading blocks (e.g., Extricom, Coperion Werner & Pfleiderer). Scheel has shown, for example, that it is possible to achieve melting of polyamides with an MPE plastification zone with 10% lower energy input than with a conventional kneading block plastification zone (see Fig. 4.9) [13]. This means a reduced melt temperature with the same throughput and/or a higher throughput at the same melt temperature.

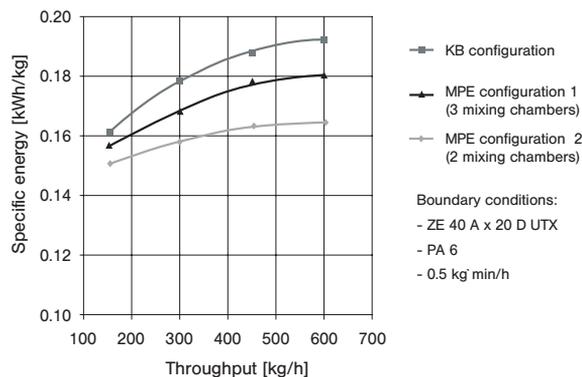


Figure 4.9: Energy input as a function of throughput for polyamide melting with kneading block and MPE plastification zones [13]