

# **International Plastics Handbook**

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## CHAPTER 4

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### PLASTICS PROCESSES

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Manufacturing of plastic parts can involve one or several of the following steps:

- Shaping operations - This involves transforming a polymer pellet, powder or resin into a final product or into a preform using extrusion or molding processes such as injection, compression molding or roto molding.
- Secondary shaping operation - Here a preform such as a parison or sheet is transformed into a final product using thermoforming or blow molding.
- Material removal - This type of operation involves material removal using machining operations, stamping, laser, drilling, etc.
- Joining operations - Here, two or more parts are assembled physically or by bonding or welding operations.

Most plastic parts are manufactured using shaping operations. Here, the material is deformed into its final shape at temperatures between room temperature and 350°C, using wear resistant tools, dies and molds. For example, an injection mold would allow making between  $10^6$  and  $10^7$  parts without much wear of the tool, allowing for the high cost of the molds utilized. One of the many advantages of polymer molding processes is the accuracy, sometimes with features down to the micrometer scale, with which one can shape the finished product without the need of trimming or material removal operations. For example, when making compact discs by an injection-compression molding process, it is possible to accurately produce features, that contain digital information smaller than  $1\mu\text{m}$ , on a disc with a thickness of less than 1mm and a diameter of several centimeters. The cycle time to produce such a part can be less than 3 seconds.

In the past few years, we have seen trends where more complex manufacturing systems are developed that manufacture parts which use various materials and components such as co-extrusion of multilayer films and sheets, multi-component injection molding, sandwiched parts, or hollow products.

Thermoplastics and thermoplastic elastomers are shaped and formed by heating them above glass transition or melting temperatures and then freezing them into their final shape by lowering the temperature. At that point, the crystallization, molecular or fiber orientation and residual stress distributions are an integral

feature of the final part, dominating the material properties and performance of the finished product. Similarly, thermosetting polymers and vulcanizing elastomers solidify by a chemical reaction that results in a cross-linked molecular structure. Here too, the filler or fiber orientation as well as the residual stresses are frozen into the finished structure after cross-linking.

This chapter is intended to give an introduction to the most important polymer processes<sup>1</sup>.

## 4.1 RAW MATERIAL PREPARATION

Raw material preparation is understood as the necessary steps taken before the polymeric material is processed into the finished product. Such steps include the addition of components or additives such as pigments, fillers, fibers, plasticizers, lubricants, stabilizers, flame retardants, foaming agents, solvents, or other polymers, or the material's transformation into a powder, paste or pellet. The most important material preparation operations are mixing, kneading, dissolving, granulating or pelletizing, and drying.

### 4.1.1 Mixing Processes

Today, most processes involve some form of mixing. For example, an integral part of a screw extruder is a mixing zone. In fact, most twin screw extruders are primarily used as mixing devices. Similarly, the plasticating unit of an injection molding machine often has a mixing zone. This is important because the quality of the finished product in almost all polymer processes depends in part on how well the material was mixed. Both the material properties and the formability of the compound into shaped parts are highly influenced by the mixing quality. Hence, a better understanding of the mixing process helps to optimize processing conditions and increase part quality.

The process of polymer blending or mixing is accomplished by distributing or dispersing a minor or secondary component within a major component serving as a matrix. The major component can be thought of as the continuous phase, and the minor components as distributed or dispersed phases in the form of droplets, filaments, or agglomerates. When creating a polymer blend, one must always keep in mind that the blend will probably be remelted in subsequent processing or shaping processes. For example, a rapidly cooled system, frozen as a homogeneous mixture, can separate into phases because of coalescence when re-heated. For all practical purposes, such a blend is not processable. To avoid this problem,

<sup>1</sup>For further reading in the area of extrusion and injection molding we recommend that the reader consult the literature. A list of books is given in the appendices of this handbook.

compatibilizers, which are macromolecules used to ensure compatibility in the boundary layers between the two phases, are common. Mixing can be distributive or dispersive. For example, the morphology development of polymer blends is determined by three competing mechanisms: distributive mixing, dispersive mixing, and coalescence. There are three general categories of mixtures that can be created:

- Homogeneous mixtures of compatible polymers,
- Single phase mixtures of partly incompatible polymers, and
- Multi-phase mixtures of incompatible polymers.

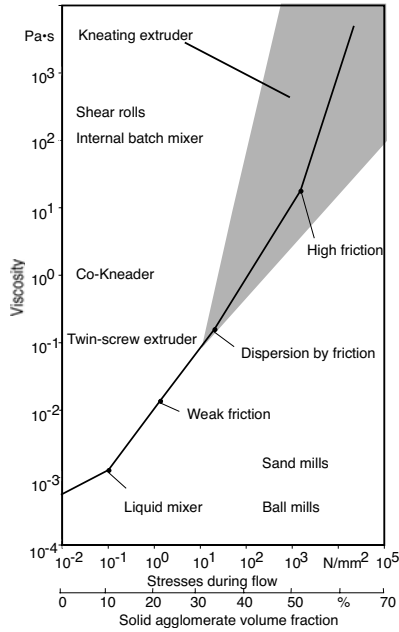
Table 4.1 lists examples of compatible, partially incompatible, and incompatible polymer blends.

**Table 4.1:** Common Polymer Blends

<i>Compatible polymer blends</i>	Natural rubber and polybutadiene Polyamides (e.g., PA 6 and PA 66) Polyphenylene ether (PPE) and polystyrene
<i>Partially incompatible polymer blends</i>	Polyethylene and polyisobutylene Polyethylene and polypropylene (5% PE in PP) Polycarbonate and polyethylene terephthalate
<i>Incompatible polymer blends</i>	Polystyrene/polyethylene blends Polyamide/polyethylene blends Polypropylene/polystyrene blends

Distributive mixing or laminar mixing of compatible materials is usually characterized by the distribution of the secondary phase within the matrix. This distribution is achieved by imposing large strains on the system such that the interfacial area between the two or more phases increases and the local dimensions, or striation thicknesses, of the secondary phases decrease. Imposing large strains on the blend is not always sufficient to achieve a homogeneous mixture. The type of mixing device, initial orientation, and position of the two or more fluid components play a significant role in the quality of the mixture.

Dispersive mixing in polymer processing involves breaking a secondary immiscible fluid or an agglomerate of solid particles and dispersing them throughout the matrix. Here, the imposed strain is not as important as the imposed stress which causes the system to break-up. Hence, the type of flow inside a mixer plays a significant role on the break-up of solid particle clumps or fluid droplets when dispersing them throughout the matrix. The most common example of dispersive mixing of particulate solid agglomerates is the dispersion and mixing of carbon black into a rubber compound. Figure 4.1 relates the viscosity



**Figure 4.1:** Overview of dispersive mixing equipment as a function of compound viscosity and volume fraction of solid agglomerates.

of the compound to the volume fraction of the solid agglomerates and the type of mixing device. When breaking up one polymer melt within a matrix, when compounding a polymer blend, the droplets inside the incompatible matrix tend to stay or become spherical due to the natural tendencies of the drop trying to maintain the lowest possible surface - to - volume ratio. However, a flow field within the mixer applies a stress on the droplets, causing them to deform. If this stress is high enough, it will eventually cause the drops to break up. The droplets will disperse when the surface tension can no longer maintain their shape in the flow field and the filaments break-up into smaller droplets. This phenomenon of dispersion and distribution continues to repeat itself until the stresses caused by the flow field can no longer overcome the surface tension of the small droplets that are formed. The mechanism of melt droplet break-up is similar in nature to solid agglomerate break-up in the sense that both rely on forces to disperse the particulates. It is well known that when breaking up solid agglomerates or melt droplets, the most effective type of flow is a stretching or elongational flow. Hence, devices that stretch the melt, instead of shearing it, lead to more effective mixers while significantly lowering energy consumption.

## 4.2 MIXING DEVICES

The final properties of a polymer component are heavily influenced by the blending or mixing process that takes place during processing or as a separate step in the manufacturing process. As mentioned earlier, when measuring the quality of mixing it is also necessary to evaluate the efficiency of mixing. For example, the amount of power required to achieve the highest mixing quality for a blend may be unrealistic or unachievable. This section presents some of the most commonly used mixing devices encountered in polymer processing.

In general, mixers can be classified in two categories: internal batch mixers and continuous mixers. Internal batch mixers, such as the Banbury type mixer, are the oldest type of mixing devices in polymer processing and are still widely used in the rubber compounding industry. Industry often also uses continuous mixers because they combine mixing in addition to their normal processing tasks. Typical examples are single and twin screw extruders that often have mixing heads or kneading blocks incorporated into their system.

### 4.2.1 Mixing of Particulate Solids

There is a variety of mixing drums that are used to blend granulated solids. They range from internal impeller speeds of less than 2m/s to speeds up to 50m/s. As the speed increases, so does the energy input and degradation of the mixed components. These types of mixers can be continuous or discontinuous. Just as is the case with mixers involving viscous substances, with continuous systems, the mixing impellers impose a conveying action on the particulates or mixture. Typical types of particulate solids batch mixers are presented in Fig. 4.2, and continuous mixers are found in Fig. 4.3, where the various mixers are equipped with different types of mixing elements or impellers such as augers, paddles or spirals.

The conical hopper mixers with the rotating auger have a capacity of up to 30 m<sup>3</sup>, while the silo mixers with an auger have a capacity of up to 100 m<sup>3</sup>. The discontinuous mixers with horizontal impellers have a capacity of up to 30 m<sup>3</sup>, and the continuous systems have a throughput of up to 450 m<sup>3</sup>/h.

### 4.2.2 Screw-Type Mixers

Screw-type mixing devices are used to continuously compound plastics to processable materials. They are fed by premixed solid agglomerates or they are fed or metered into the mixers by dosing systems. There are single screw and twin screw mixing devices. Table 4.2 presents various screw compounders with characteristic sizes, power consumption, and throughputs.

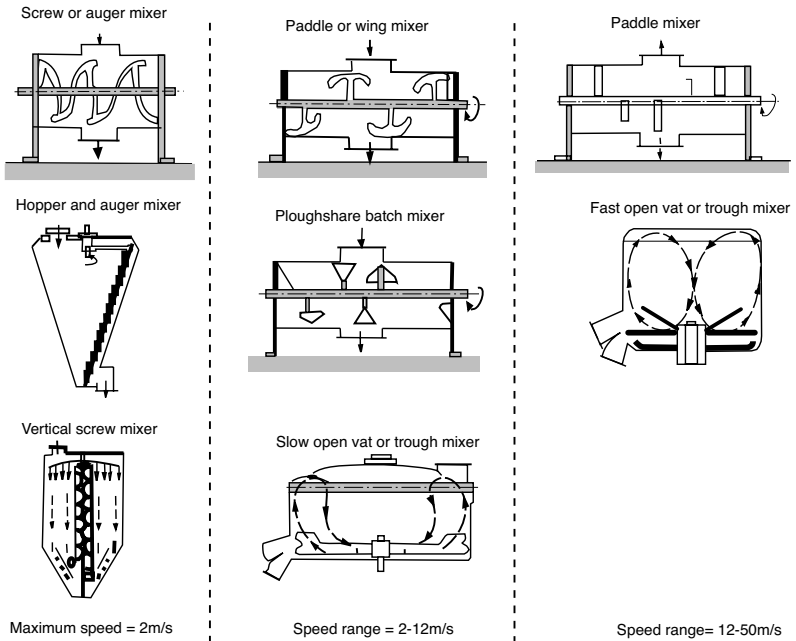


Figure 4.2: Solid particulate batch mixing devices.

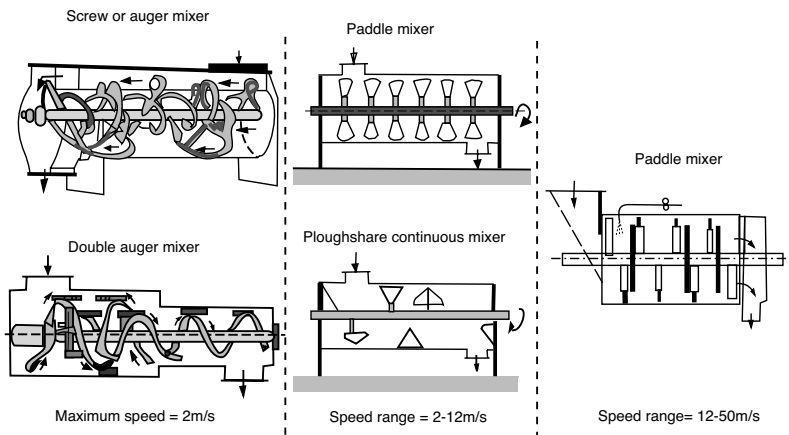
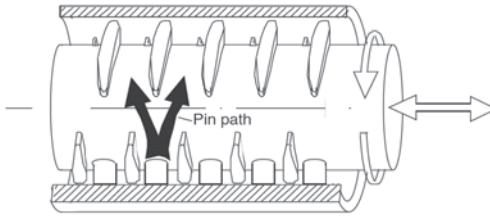


Figure 4.3: Solid particulate continuous mixing devices.



**Figure 4.4:** Schematic diagram of a co - kneader.

**Table 4.2:** Typical Sizes, Power Consumption, and Throughput of Screw Compounders

Compounder Type	Screw diameter mm	Power kW	Energy Input kW-h/kg	Throughput kg/h
Single screw type	250-800	500-6,700	0.07-0.13	4,000-74,000
Plasticizer	330-555	22-160	0.07-0.10	200-2,300
Co-Kneader	46-400	11-650	0.08-0.40	10-8,000
Twin screw type	25-380	75-20,000	0.10-0.40	10-75,000

**Co - kneader** The co - kneader is a single screw mixer with pins on the barrel and a screw that oscillates in the axial direction. Figure 4.4 shows a schematic diagram of a co - kneader. The pins on the barrel practically wipe the entire surface of the screw, making it the only self-cleaning single-screw extruder. This results in a reduced residence time, which makes it appropriate for processing thermally sensitive materials. The pins on the barrel also disrupt the solid bed creating a dispersed melting which improves the overall melting rate while reducing the overall temperature in the material.

A simplified analysis of a co - kneader gives a number of striations per L/D of

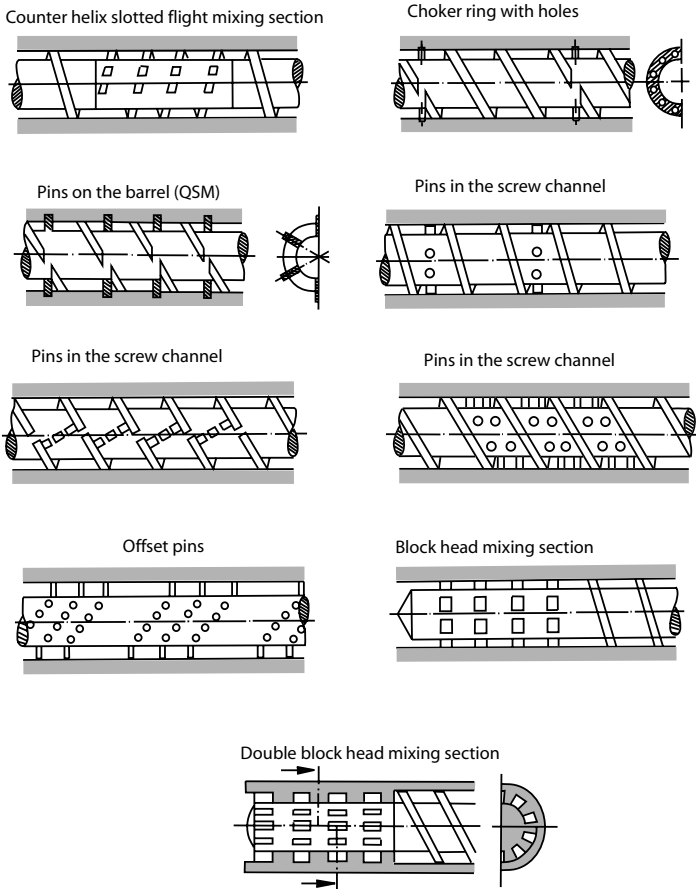
$$N_s = 2^{12} \tag{4.1}$$

which means that over a section of 4D, the number of striations is  $2^{12}(4) = 28^{13}$ .

**Mixing In Single Screw Extruders** Distributive mixing caused by the cross-channel flow component in single screw extruders can be enhanced by introducing pins (Fig. 4.5) or rhomboidal elements (Fig. 4.6) in the flow channel and slots on the screw flights. The pins can either sit on the screw or on the barrel as shown in Fig. 4.5. The extruder with the adjustable pins on the barrel is generally referred to as QSM-extruder<sup>2</sup>. In all cases, the pins disturb the flow by re-orienting

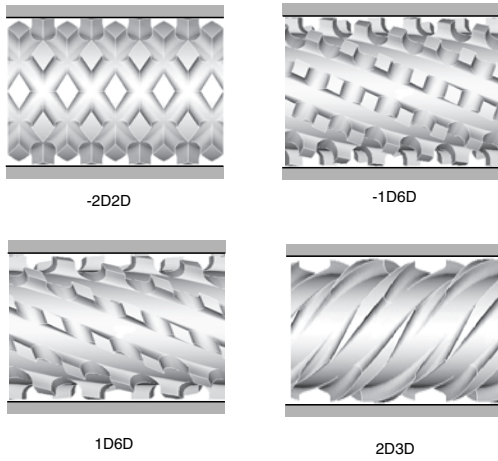
<sup>2</sup>QSM comes from the German words *Quer Strom Mischer* which translates into cross-flow mixing





**Figure 4.5:** Typical pin and slotted flight type single screw extruder distributive mixing sections.

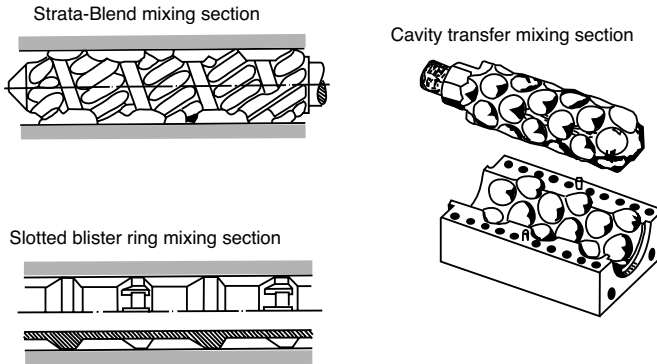
the surfaces between fluids and by creating new surfaces by splitting the flow. Figure 4.7 presents a photograph of the channel contents of a QSM-extruder. The photograph shows the re-orientation of the layers as the material flows past the pins. The pin-type extruder is especially useful for the mixing of high viscosity materials, such as rubber compounds; and is therefore, often referred to as cold feed rubber extruder. This machine is widely used in the production of rubber profiles of any shape and size. As mentioned earlier, dispersive mixing is required when breaking down particle agglomerates or when surface tension effects exist between primary and secondary fluids in the mixture. To disperse



**Figure 4.6:** Various rhomboidal single screw extruder distributive mixing sections.



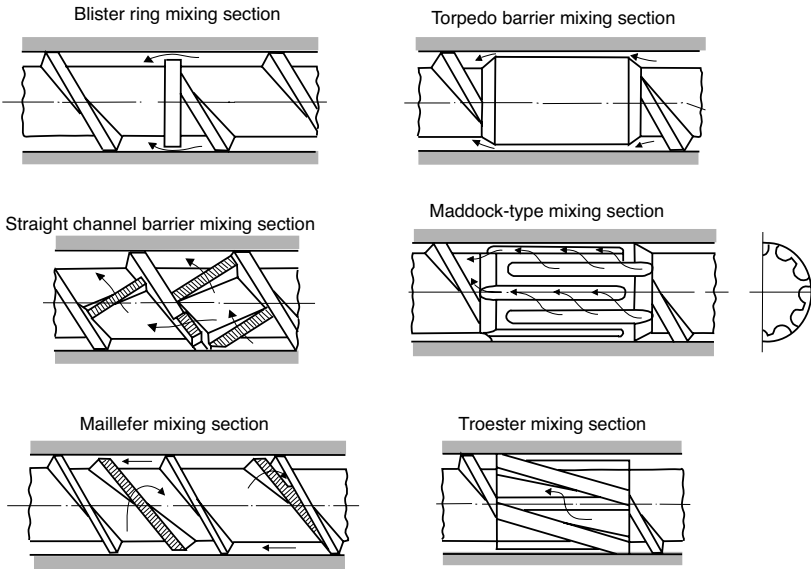
**Figure 4.7:** Photograph of the unwrapped channel contents of a pin barrel extruder. Courtesy of the Paul Troester Maschinenfabrik, Hannover, Germany.



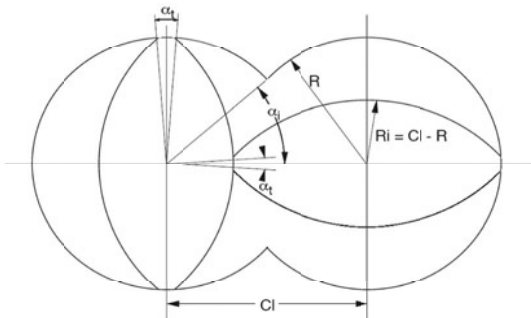
**Figure 4.8:** Typical single screw extruder distributive mixing sections with dispersive capabilities.

such systems, the mixture must be subjected to large stresses. Some distributive mixing heads, such as those depicted in Fig. 4.8, also have a strong dispersive component due to the stretching flows that they generate during mixing. A very popular one is the cavity transfer mixing (CTM) head depicted in Fig. 4.8. Barrier-type screws are often used in lieu of dispersive mixing heads, because they apply high shear stresses to the polymer melt when the molten material passes to the melt pool channel. However, more intensive mixing can be applied by using a mixing head intended for this purpose. When using barrier-type screws or a mixing head as shown in Fig. 4.9, the mixture is forced through narrow gaps, causing high stresses in the melt. It should be noted that dispersive as well as distributive mixing heads result in a resistance to the flow, which results in viscous heating and pressure losses during extrusion.

**Twin Screw Extruders** In the past two decades, twin screw extruders have developed into the best available continuous mixing devices. In general, they can be classified into intermeshing or non-intermeshing, and co-rotating or counter-rotating twin screw extruders. The intermeshing twin screw extruders render a self-cleaning effect which evens-out the residence time of the polymer in the extruder. The self-cleaning geometry for a co-rotating double flighted twin screw extruder is shown in Fig. 4.10 The main characteristic of this type of configuration is that the surfaces of the screws are sliding past each other, constantly removing the polymer that is stuck to the screw. In the last two decades, the co-rotating twin screw extruder systems have established themselves as efficient continuous mixers, including reactive extrusion. In essence, the co-rotating systems have a high pumping efficiency caused by the double transport action of the two screws. Counter-rotating systems generate high stresses because of the calendaring action



**Figure 4.9:** Commonly used single screw extruder dispersive mixing section.



**Figure 4.10:** Geometry description of a double-flighted, co-rotating, self-cleaning twin screw extruder.