

International Plastics Handbook

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CHAPTER 2

MATERIALS SCIENCE OF POLYMERS

This chapter is intended to give the reader a general overview of polymer materials science. It presents the general chemistry, structure and morphology of polymers as well as common modifications done on polymeric materials to enhance their properties. At the end of the chapter the topic of recycling is briefly discussed.

2.1 POLYMER STRUCTURE

The material behavior of polymers is totally controlled by their molecular structure. In fact, this is true for all polymers; synthetically generated polymers as well as polymers found in nature (bio-polymers), such as natural rubber, ivory, amber, protein-based polymers or cellulose-based materials. To understand the basic aspects of material behavior and its relation to the molecular structure of polymers, in this chapter we attempt to introduce the fundamental concepts in a compact and simple way, leaving out material that has academic and scientific interest, but that is not needed to understand the basic technological aspects of plastics. Further information is presented in subsequent chapters. For more details on specific plastics and polymers the reader should consult Chapter 6 of this handbook.

2.1.1 Chemistry

As the word itself suggests, polymers are materials composed of molecules of very high molecular weight. These large molecules are generally referred to as *macromolecules*. Polymers are macromolecular structures that are generated synthetically or through natural processes. Historically, it has been always said that synthetic polymers are generated through *addition* or *chain growth polymerization*, and *condensation* or *radical initiated polymerization*. In addition polymerization, the final molecule is a repeating sequence of blocks with a chemical formula of the monomers. Condensation polymerization processes occur when the resulting polymers have fewer atoms than those present in the monomers from which they are generated. However, since many additional polymerization pro-

cesses result in condensates, and various condensation polymerization processes are chain growth polymerization processes that resemble addition polymerization, today we rather break-down polymerization processes into *step polymerization* and *chain polymerization*. Table 2.1 shows a break-down of polymerization into step and chain polymerization, and presents examples for the various types of polymerization processes.

Table 2.1: Polymerization Classification

Classification	Polymerization	Examples
Step linear	Polycondensation	Polyamides Polycarbonate Polyesters Polyethers Polyimide Siloxanes
	Polyaddition	Polyureas Polyurethanes
Step non-linear	Network polymers	Epoxy resins Melamine Phenolic Polyurethanes Urea
Chain	Free radical	Polybutadiene Polyethylene (branched) Polyisoprene Polymethylmethacrylate Polyvinyl acetate Polystyrene
	Cationic	Polyethylene Polyisobutylene Polystyrene Vinyl esters
	Anionic	Polybutadiene Polyisoprene Polymethylmethacrylate Polystyrene
	Ring opening	Polyamide 6 Polycaprolactone Polyethylene oxide Polypropylene oxide
	Ziegler-Natta	Polyethylene Polypropylene Polyvinyl chloride Other vinyl polymers
	Metalocene	Polyethylene Polypropylene Polyvinyl chloride Other vinyl polymers

Linear and non-linear step growth polymerization are processes where the polymerization occurs with more than one molecular species. On the other hand, chain growth polymerization processes occur with monomers with a reactive end group. Chain growth polymerization processes include *free-radical polymerization*, *ionic polymerization*, *cationic polymerization*, *ring opening polymerization*, *Ziegler-Natta polymerization* and *metallocene catalysis polymerization*. Free-radical polymerization is the most widely used polymerization process and it is used to polymerize monomers with the general structure $\text{CH}_2 = \text{CR}_1\text{R}_2$. Here, the polymer molecules grow by addition of a monomer with a free-radical reactive site called an active site. A chain polymerization process can also take place when the active site has an ionic charge. When the active site is positively charged, the polymerization process is called a *cationic polymerization*, and when the active site is negatively charged it is called *ionic polymerization*. Finally, monomers with a cyclic or ring structure such as caprolactam can be polymerized using the ring-opening polymerization process. Caprolactam is polymerized into polycaprolactam or polyamide 6.

The atomic composition of polymers encompasses primarily non-metallic elements such as carbon (C), hydrogen (H) and oxygen (O). In addition, recurrent elements are nitrogen (N), chlorine (Cl), fluoride (F) and sulfur (S). The so-called semi-organic polymers contain other non-metallic elements such as silicon (Si) in silicone or polysiloxane, as well as boron or beryllium (B). Although other elements can sometime be found in polymers, because of their very specific nature, we will not mention them here. The properties of the above elements lead to specific properties that are common of all polymers. These are:

- Polymers have very low electric conductance (electric insulators)
- Polymers have a very low thermal conductance (thermal insulators)
- Polymers have a very low density (between 0.8 and 2.2 g/cm³)
- Polymers have a low thermal resistance and will easily irreversibly thermally degrade

There are various ways that the monomers can arrange during polymerization, however, we can break them down into two general categories: uncross-linked and cross-linked. Furthermore, the uncross-linked polymers can be subdivided into linear and branched polymers. The most common example of uncross-linked polymers that present the various degrees of branching is polyethylene (PE), as schematically depicted in Figure 2.1. Another important family of uncrosslinked polymers are copolymers. Copolymers are polymeric materials with two or more monomer types in the same chain. A copolymer that is composed of two monomer types is referred to as a *bipolymer* (e.g., PS-HI), and one that is formed by three different monomer groups is called a *terpolymer* (e.g., ABS). Depending on how

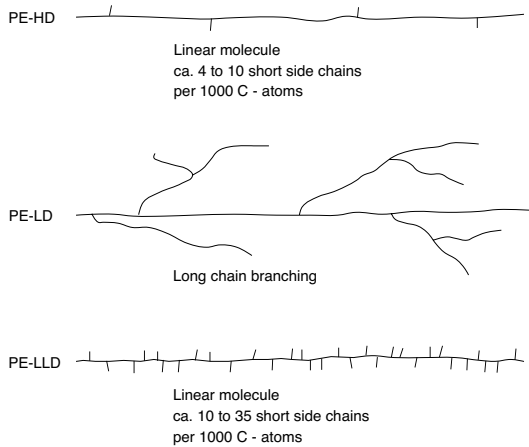


Figure 2.1: Schematic of the molecular structure of different polyethylenes.



Figure 2.2: Schematic representation of different copolymers.

the different monomers are arranged in the polymer chain, one distinguishes between *random*, *alternating*, *block*, or *graft* copolymers. The four types of copolymers are schematically represented in Fig. 2.2.

Although thermoplastics can cross-link under specific conditions, such as gel formation when PE is exposed to high temperatures for prolonged periods of time, thermosets, and some elastomers, are polymeric materials that have the ability to cross-link. The cross-linking causes the material to become heat resistant after it has solidified. The cross-linking usually is a result of the presence of double bonds that break, allowing the molecules to link with their neighbors. One of

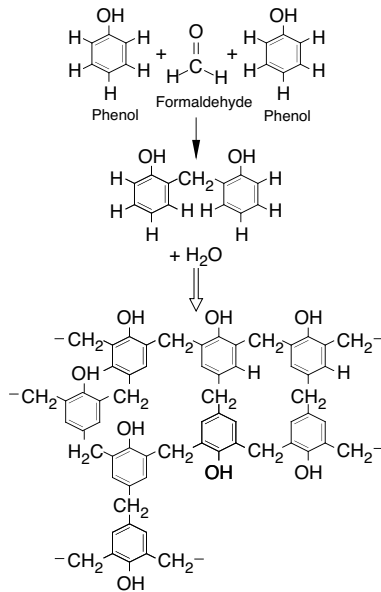


Figure 2.3: Symbolic representation of the condensation polymerization of phenol-formaldehyde resins.

the oldest thermosetting polymers is phenol-formaldehyde, or phenolic. Figure 2.3 shows the chemical symbol representation of the reaction where the phenol molecules react with formaldehyde molecules to create a three-dimensional cross-linked network that is stiff and strong, and leaving water as the by-product of this chemical reaction. This type of chemical reaction is called *condensation polymerization*.

Molecular Weight The size of the resulting macromolecules is the primary factor resulting from a polymerization reaction. After such a reaction, a polymeric material will consist of polymer chains of various lengths or repeat units. Hence, the molecular weight is determined by the average, or mean, molecular weight, which is defined by $M = W/N$. Here, W is the weight of the sample and N the number of moles in the sample. Figure 2.4 presents a schematic of a molecular weight distribution. The figure presents three molecular weight distributions. These are the *number average*, \bar{M}_n , defined by,

$$\bar{M}_n = \frac{\sum n_i M_i}{\sum n_i} \quad (2.1)$$

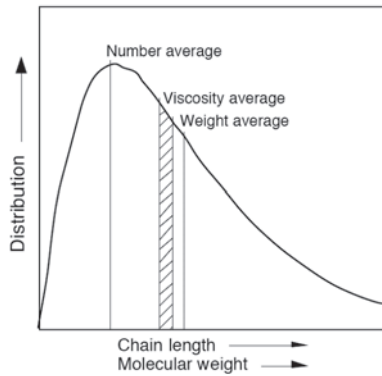


Figure 2.4: Molecular weight distribution of a typical thermoplastic.

the *weight average*, \bar{M}_w , defined by,

$$\bar{M}_w = \frac{\sum n_i M_i^2}{\sum n_i M_i} \quad (2.2)$$

and the *viscosity average*, \bar{M}_v . The viscosity average is a function of the viscosity of the polymers,

$$[\eta] = k \bar{M}_v^\alpha \quad (2.3)$$

where α is a material dependent parameter, which varies from $\alpha = 1$ for short molecules to $\alpha = 3.4$ for long molecules. The linear relation for short molecules is directly related to the intra-molecular friction, while the power relation of long molecules is related to the molecular entanglement.

Figure 2.5 presents the viscosity of various polymers as a function of molecular weight. The figure shows how for all these polymers the viscosity goes from the linear to the power dependence at some critical molecular weight. The linear relation is sometimes referred to as Staudinger's rule and applies for a perfectly monodispersed polymer. In a monodispersed polymer most molecules have the same molecular weight. A measure of the broadness of a polymer's molecular weight distribution is the polydispersity index defined by,

$$PI = \frac{\bar{M}_w}{\bar{M}_n} \quad (2.4)$$

Figure 2.6 presents a plot of flexural strength versus melt flow index for polystyrene samples with three different polydispersity indices. The figure shows that low

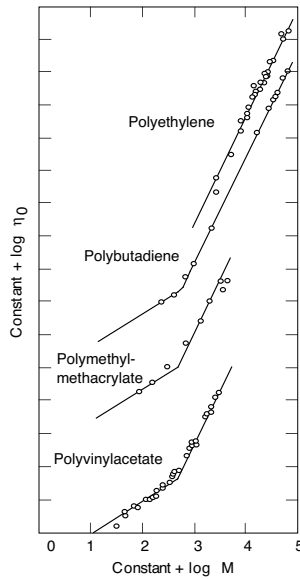


Figure 2.5: Zero shear rate viscosity for various polymers as a function of molecular weight.

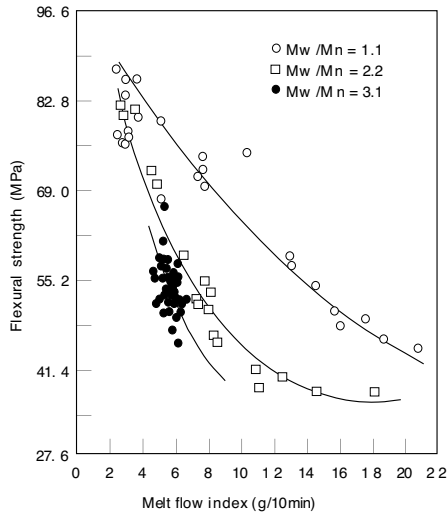


Figure 2.6: Effect of molecular weight on the strength-MFI interrelationship of polystyrene for three polydispersity indices.

polydispersity index grade materials render higher strength properties and flowability, or processing ease, than high polydispersity index grades. Table 2.2 summarizes the various techniques used to measure molecular weight of polymers and the molecular weight range at which they can adequately perform the measurement.

Table 2.2: Various techniques used to measure molecular weight of polymers and oligomers

Method	Measurement	Range
Sedimentation and diffusion with centrifuge (a)	\bar{M}_w	Up to 10^8
Light scattering (a)	\bar{M}_w	Up to 10^7
Electron microscopy (a)	\bar{M}_i, \bar{M}_n	*
Gel-Permeation-Chromatography (r)	$\bar{M}_w, \bar{M}_n, \bar{M}_v$	*
Solvent viscometry (r)	\bar{M}_v	*
Melt viscometry (r)	\bar{M}_w	‡
Membrane osmometry (a)	\bar{M}_n	$2 \cdot 10^4$ to 10^6
Vapor pressure osmometry (a)	\bar{M}_n	Up to 10^5
End-group determination (e)	\bar{M}_n	Up to $5 \cdot 10^4$
Cryoscopy (a)	\bar{M}_n	Up to $5 \cdot 10^4$
Ebullioscopy (a)	\bar{M}_n	Up to 10^4

(a) Absolute method, (r) Relative method, and (e) Equivalent method.
 * Dependent on solubility.
 ‡ Dependent on melting point.

Physically, the molecules can have rather large dimensions. For example, each repeat unit of a carbon backbone molecule, such as polyethylene, measures 0.252 nm in length. If completely stretched out, a high molecular weight molecule with say 10,000 repeat units can measure over 2 mm in length. Figure 2.7 serves to illustrate the range in dimensions associated with polymers as well as which microscopic devices are used to capture the detail at various orders of magnitude. If we go from the atomic structure to the part geometry, we easily travel between 0.1 nm and 1 mm, covering 8 orders of magnitude.

Conformation and Configuration The conformation and configuration of the polymer molecules have a great influence on the properties of the polymer component. The conformation describes the preferential spatial positions of the atoms in a molecule, which is described by the polarity flexibility and regularity of the macromolecule. Typically, carbon atoms are tetravalent, which means that they are surrounded by four substituents in a symmetric tetrahedral geometry. The configuration gives information about the distribution and spatial organization of the molecule. The general structure and symmetry of a molecule can be greatly influenced during polymer synthesis. This is illustrated in Fig. 2.8. Due to energy issues, linear polymers such as polyethylene, polypropylene, polystyrene and polyvinyl chloride prefer to polymerize through 1,2-addition. For technical polydienes, such as natural rubber (polyisoprene), polybutadiene and poly-

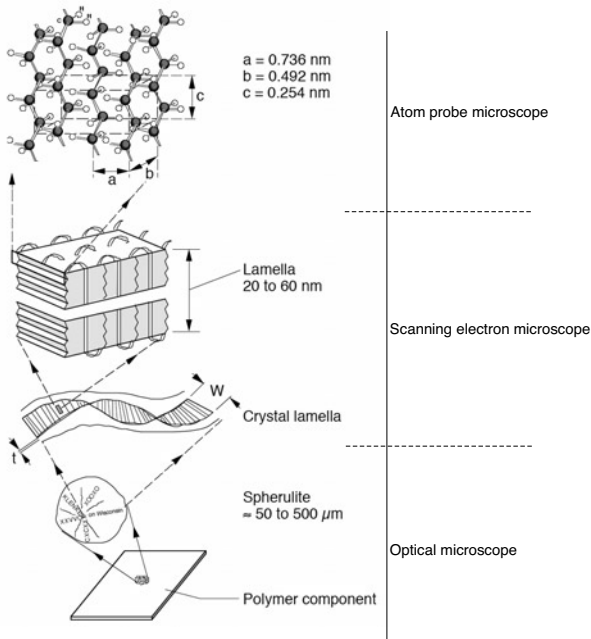


Figure 2.7: Schematic representation of the general molecular structure of semi-crystalline polymers and magnitudes as well as microscopic devices associated with such structures.

chloroprene, the preferred mode of polymerization is 1,4-addition. In effect, one can control the mode of polymerization by use of stereocatalysts as well as metallocene catalysts.

During polymerization it is possible to place the X groups on the carbon-carbon backbone in different directions. The order in which they are arranged is called the tacticity. The polymers with side groups placed in a random matter are called atactic. The polymers whose side groups are all on the same side are called isotactic, and those molecules with regularly alternating side groups are called syndiotactic. Figure 2.9 shows the three different tacticity cases for polypropylene. The tacticity in a polymer determines the degree of crystallinity that a polymer can reach. For example, polypropylene with a high isotactic content will reach a high degree of crystallinity and as a result will be stiff, strong, and hard.

Another type of geometric arrangement arises with polymers that have double bonds between carbon atoms. Double bonds restrict the rotation of the carbon atoms about the backbone axis. These polymers are sometimes referred to as

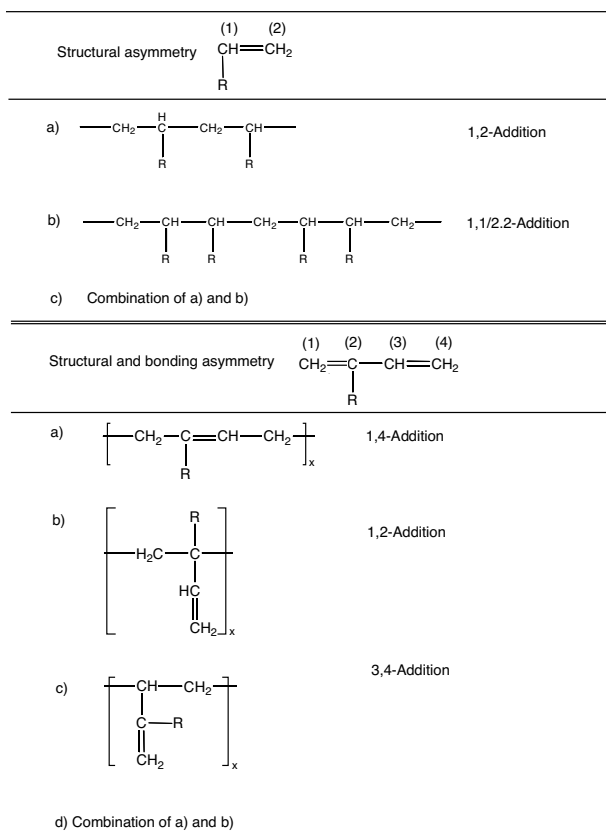


Figure 2.8: Constitutional isomer classification.

geometric isomers. The X groups may be on the same side (cis-) or on opposite sides (trans-) of the chain as schematically shown for polybutadiene in Fig. 2.10. The arrangement in a cis-1,4- polybutadiene results in a very elastic rubbery material, whereas the structure of the trans-1,4- polybutadiene results in a leathery and tough material. A cis-1,4- polybutadiene can be used to manufacture the outer tread of an automotive tire. A trans-1,4- polybutadiene can be used to make the outer skin of a golf ball. The same geometric arrangement is found in natural rubber, polyisoprene. The cis-1,4- polyisoprene is the elastic natural rubber used for the body of a tire, and the latex used to manufacture "rubber" gloves and condoms. The trans-1,4- polyisoprene, or the so-called gutta percha or ebony, was used to make dentures, statues, and other decorative items in the 1800s.

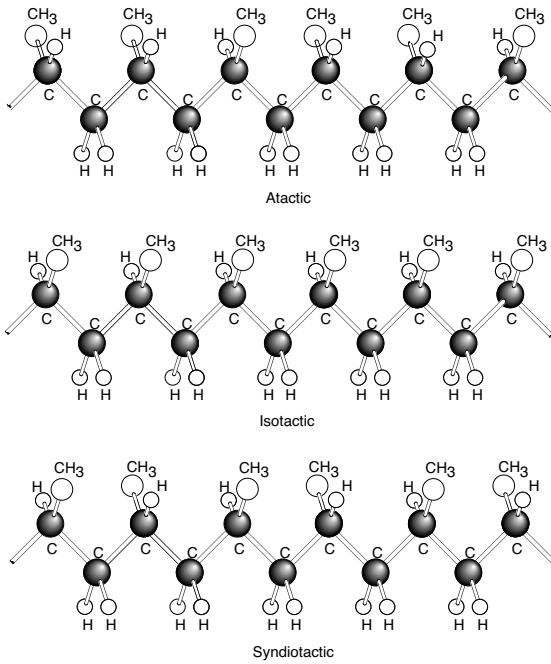


Figure 2.9: Different polypropylene structures.

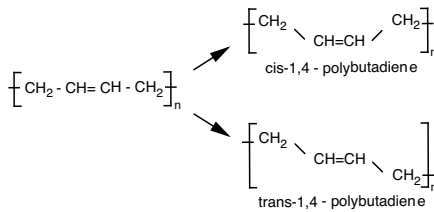


Figure 2.10: Symbolic representation of cis-1,4- and trans-1,4-polybutadiene molecules.

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CHAPTER 4

PLASTICS PROCESSES

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 processes¹.

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,

¹For 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

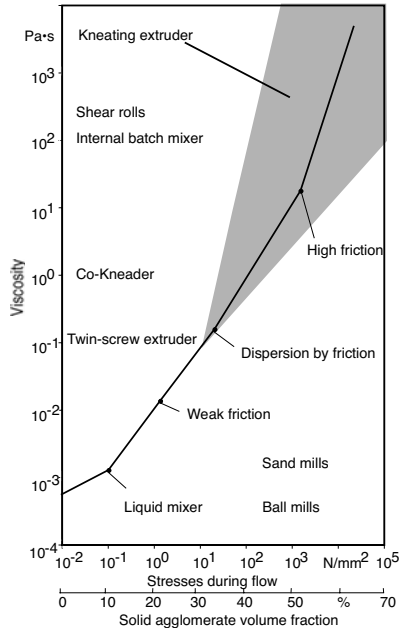


Figure 4.1: Overview of dispersive mixing equipment as a function of compound viscosity and volume fraction of solid agglomerates.

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 m³, while the silo mixers with an auger have a capacity of up to 100 m³. The discontinuous mixers with horizontal impellers have a capacity of up to 30 m³, and the continuous systems have a throughput of up to 450 m³/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.

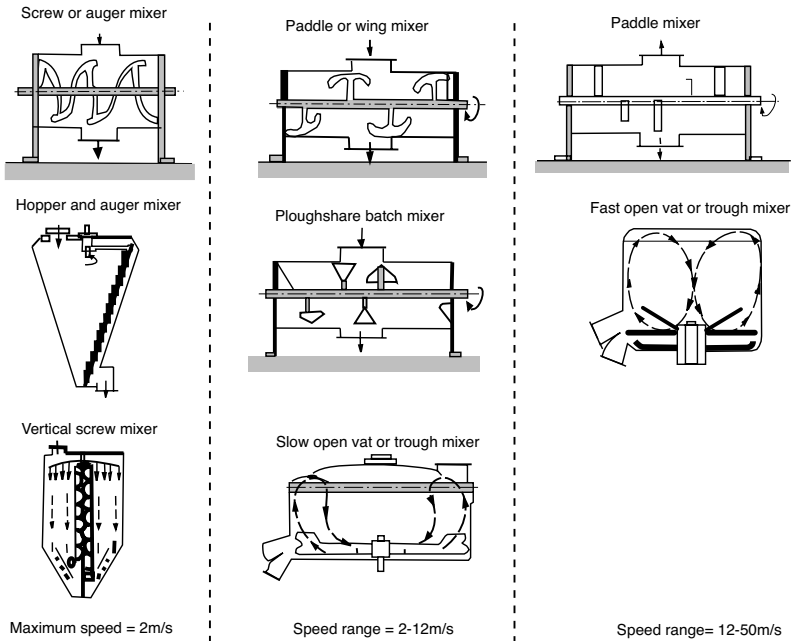


Figure 4.2: Solid particulate batch mixing devices.

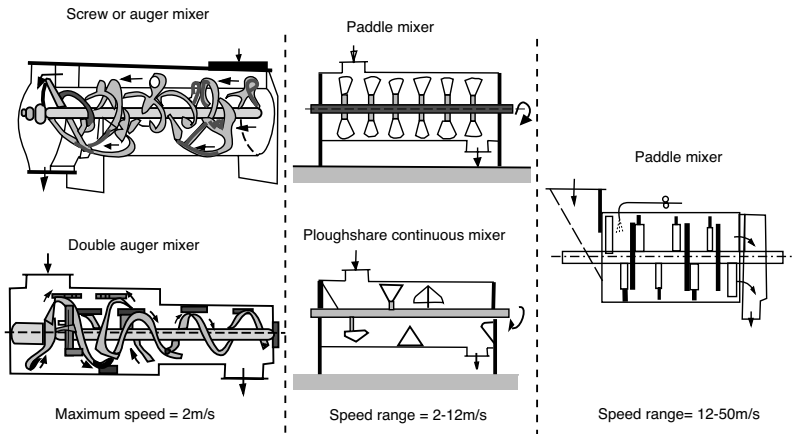


Figure 4.3: Solid particulate continuous mixing devices.

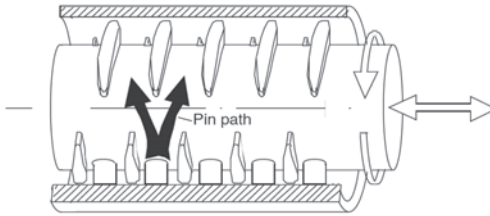


Figure 4.4: Schematic diagram of a co - kneader.

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-extruder². In all cases, the pins disturb the flow by re-orienting

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

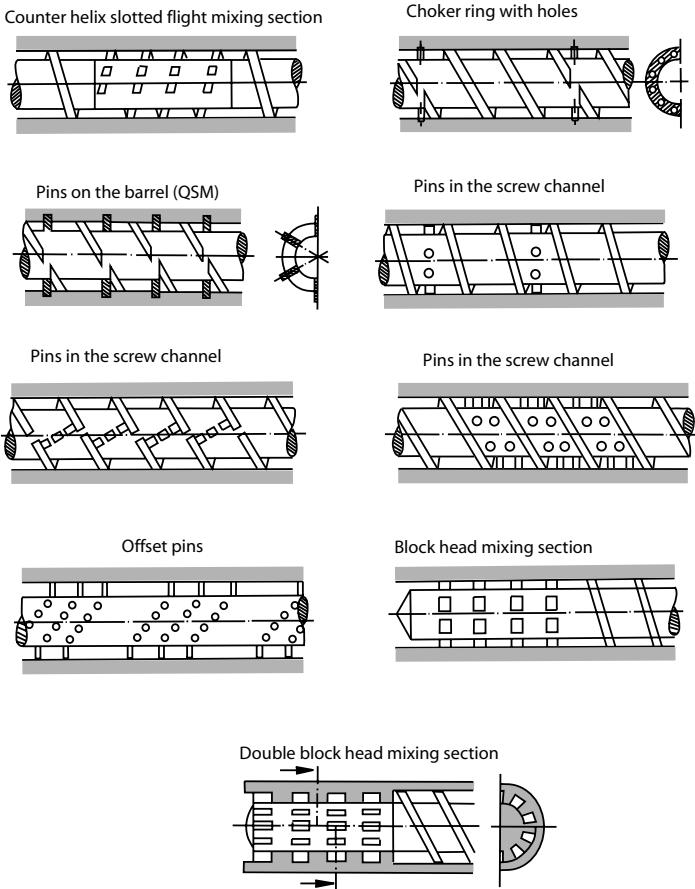


Figure 4.5: Typical pin and slotted flight type single screw extruder distributive mixing sections.

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

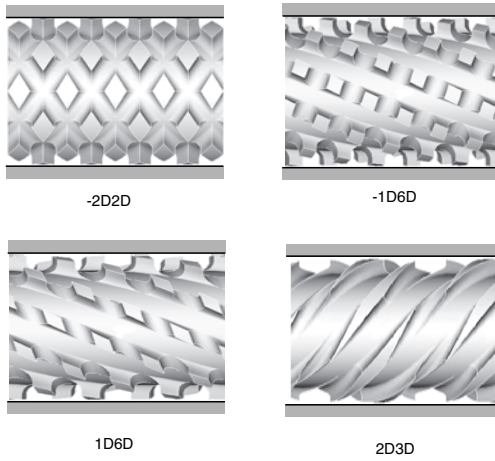


Figure 4.6: Various rhomboidal single screw extruder distributive mixing sections.

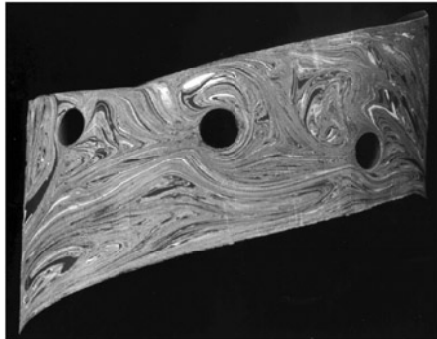


Figure 4.7: Photograph of the unwrapped channel contents of a pin barrel extruder. Courtesy of the Paul Troester Maschinenfabrik, Hannover, Germany.

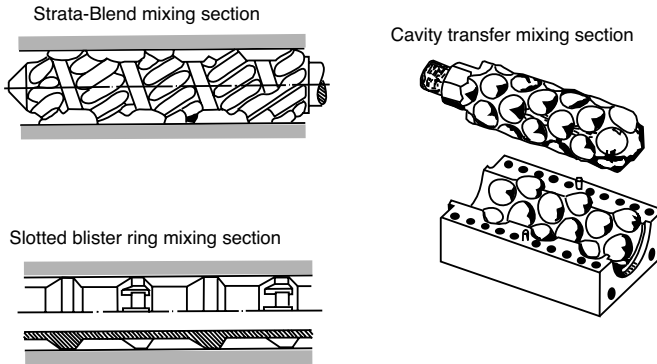


Figure 4.8: Typical single screw extruder distributive mixing sections with dispersive capabilities.

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

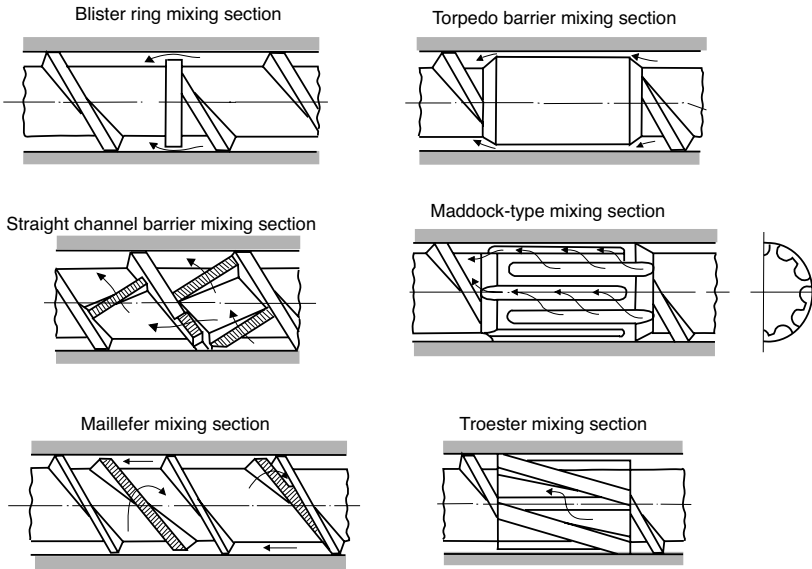


Figure 4.9: Commonly used single screw extruder dispersive mixing section.

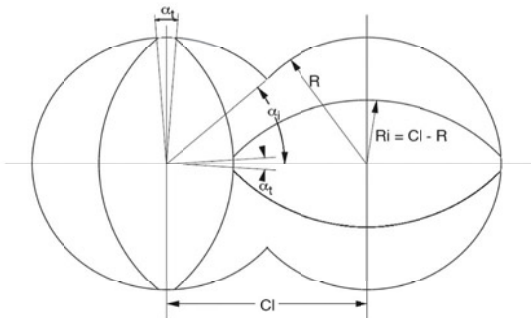


Figure 4.10: Geometry description of a double-flighted, co-rotating, self-cleaning twin screw extruder.

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PREFACE

As the title suggests, this handbook was written as a source of reliable information for the practicing engineer, in a world which is increasingly driven by globalization. While it was written for the American market, the book also includes international standards and information that is now often necessary for any practicing engineer. Plastics remains the material group with the largest growth rate worldwide. This is due to their unique characteristics; the ease of production of complex parts with relatively economical processes, and the ability to tailor the properties of the material to suit a specific application. Due to these attributes, today we find that plastics are not only replacing traditional materials, but are the driving force in innovation in the fields of electronic products, medicine, automobiles, household goods, and construction. Thus, we find uncountable examples of how plastics have improved our standard of living in the last decade alone; from lighter automobiles to thinner cellular telephones, and from more fuel efficient composite aircraft to improved human heart valves, all made possible by advances in plastics and plastics technology. The plastics industry will continue to grow and develop, as the properties of polymers achieve higher limits, continuously replacing other materials and making new applications and products

possible. The image of plastics has seen a positive turn in the last decade. Many studies have shown that plastics are the driving force in the solution of ecological problems; from making vehicles more fuel efficient, to allowing the manufacture of complex products with a fraction of the energy required when using metals. Furthermore, today we find ourselves revisiting the past, where plastics were made of renewable resources. At the end, it is really only a question of economics, whether we will make plastics from petroleum or from bio-materials. From this point of view, we can really say that the age of plastics is still in its infancy. *International Plastics Handbook* is based on a similar publication, which has been available to the German plastics engineer for the past 70 years. A new edition of the German book *Saechtling Kunststoff Taschenbuch*, now in its 29th edition, appears every three years at the K-Show, in Duesseldorf, Germany. In 1936, when the first edition of the German book was published, Dr. F. Pabst, the original author of the German handbook, wrote "*This book is intended to answer questions in the applied field of plastics.*" For this handbook, that is our intent as well. This first edition of *International Plastics Handbook* will appear at the NPE show in Chicago, in June of 2006. Due to the rapid changes in the field of plastics we are planning to present new editions of the handbook at NPE shows, every three years. In addition, this book will be accessible through the World-WideWeb where the authors will maintain updated versions of the handbook, including its tables and list of trade names. Each handbook contains an individual code on the inside front cover which provides access for the download of the electronic version of the book at www.hanser.de/plasticshandbook. The authors cannot possibly acknowledge everyone who in oneway or another helped in the preparation of this handbook. First of all wewould like to thank Drs. Wolfgang Glenz and Christine Strohm of Hanser publishers for being the catalysts for this project. Additionally, Dr. Strohm gave us her input and support during the years it took to prepare this handbook. Chapter 6 comes from the German Saechtling Kunststoff Taschenbuch materials chapter, which was translated by Dr. Strohm. We are indebted to her for all of this. Special thanks are due to Luz Mayed D. Nouguez for the superb job of drawing the figures. We are grateful to Sylvana García and Alejandro Roldán for the long hours they put into generating tables for the book and preparing the camera-ready manuscript. We thank Juan Pablo Hernández-Ortiz for developing the typesetting template. We also thank Oswald Immel for his support throughout the development of the manuscript. Above all, we thank our families for their patience, encouragement and support.

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