

Ulf Bruder

USER'S GUIDE TO PLASTIC

**Material – Processing methods – Mold design
Cost calculation – Post-molding processes
Assembly methods – Material selection
Design rules – Process optimization
Troubleshooting**

**2ND
EDITION**

HANSER



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Ulf Bruder

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Foreword

For many years, I had the idea of writing a book about injection molding, as I have spent over 45 years of my working life on this subject.

When I retired in 2009 I was given great support by my friends Katarina Elner-Haglund and Peter Schulz of the Swedish plastics magazine *Plastforum*, who asked me to write a series of articles about thermoplastics and their processing for the magazine.

I was also hired at this time to work with educational programs at the Lund University of Technology, the Royal University of Technology in Stockholm, and a number of industrial companies in Sweden, as a result of which this book was developed.

My aim has been to write in such a way that this book can be understood by everyone, regardless of prior knowledge about plastics. The book has a practical approach with lots of pictures and is intended to be used in secondary schools, universities, industrial training, and self-study. In some of the chapters there are references to worksheets in Excel that can be downloaded free from my website: www.brucon.se.

In addition to the above-mentioned persons, I would like to extend a warm thanks to my wife Ingelöv, who has been very patient when I've been totally absent in the "wonderful world of plastics" and then proofread the book; my brother Hans-Peter, who has spent countless hours on adjustments of all the images etc; and my son-in-law Stefan Bruder, who has checked the contents of the book and contributed with many valuable comments.

I would also like to thank my previous employer, DuPont Performance Polymers and especially my friends and former managers Björn Hedlund and Stewart Daykin, who encouraged the development of my career as a trainer until I reached my ultimate goal and dream job of "global technical training manager". They have also contributed with a lot of information and many valuable images in this book.

I also want said a big thank you to my friends and business partners in all educational programs in recent years, who have supported me and contributed with many valuable comments, information and images for this book, and a special thanks to those who have made this printing possible thanks to the ads in the beginning. The whole list would be very long but you will find some of them in the list of internet links in Chapter 31.

In this Second Edition:

This edition contains greatly expanded coverage of extrusion, collected into a new Chapter 20. There are also a number of new and updated figures, with numerous small improvements and corrections throughout the text. These are complemented by an all-new professional layout and structure, which I hope will help readers to navigate the book comfortably.

I would like to thank Mark Smith at Carl Hanser Verlag for all the support that I received during the last years with my book in various languages.

Ulf Bruder

Karlskrona, Sweden

Polymers and Plastics

Sometimes you get the question: What is the difference between polymer and plastic? The answer is simple: there is no difference, it's the same thing. The word "polymer" comes from the Greek "poly", which means many, and "meros", which means unity.

The online encyclopedia Wikipedia (www.wikipedia.org) states the following: "Polymers are chemical compounds that consist of very long chains composed of small repeating units, monomers. Polymer chains are different from other chain molecules in organic chemistry because they are much longer than, for example, chains of alcohols or organic acids. The reaction that occurs when the monomers become a polymer is called polymerization. Polymers in the form of engineering materials are known in daily speech as plastics.

By plastic, we mean that the engineering material is based on polymers, generally with various additives to give the material the desired properties, such as colors or softeners. Polymeric materials are usually divided into rubber materials (elastomers), thermosets and thermoplastics."

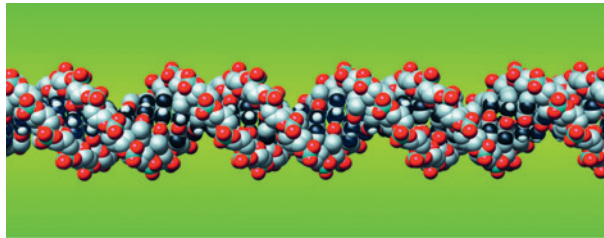


Figure 1.1 Polymers are large macromolecules where monomer molecules bind to each other in long chains. There may be several thousand monomer molecules in a single polymer chain.



Figure 1.2 Amber is a natural polymer. The mosquito in this stone got stuck in the resin of a conifer more than 50 million years ago—something to think about when considering the decomposition of certain polymers in nature.

Most polymers are synthetically produced, but there are also natural polymers such as natural rubber and amber that have been used by mankind for thousands of years.

Other natural polymers include proteins, nucleic acids, and DNA. Cellulose, which is the major component in wood and paper, is also a natural polymer.

In other words, plastic is a synthetically manufactured material composed of monomer molecules that bind to each other in long chains.

If the polymer chain is made up solely of one monomer it is called polymer homopolymer.

If there are several kinds of monomers in the chain, the polymer is called copolymer.

An example of a plastic that can occur both as homopolymer and copolymer is acetal.

Acetal is labeled POM (polyoxymethylene) and is mostly up-built of a monomer known as formaldehyde. The building blocks (atoms) in formaldehyde are composed of carbon, hydrogen, and oxygen.

Most plastic materials are composed of organic monomers but may in some cases also be composed of inorganic acids. One example of an inorganic polymer is a silicone resin consisting of polysiloxanes, where the chain is built up of silicon and oxygen atoms.

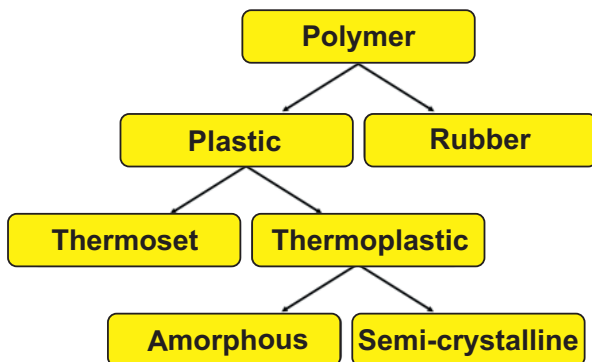


Figure 1.3 Here you can see how you usually divide the synthetic polymers into rubber and plastic, with subgroups thermoset and thermoplastic. Thermoplastic is in turn divided into amorphous and semi-crystalline plastics.



Figure 1.4 Kautschuk or natural rubber is a natural polymer used by man for thousands of years.

In 1839 the American Charles Goodyear invented vulcanization, a cross-linking process in which natural rubber is mixed with sulfur wherein molecular chains are cross-linked under heat and pressure. This process refined rubber's properties significantly.

Carbon and hydrogen are the other dominant elements in plastics. In addition to the aforementioned elements carbon (C), hydrogen (H), oxygen (O), and silicon (Si), plastics typically consist of another five elements: nitrogen (N), fluorine (F), phosphorus (P), sulfur (S), and chlorine (Cl).

It is extremely rare to work with a pure polymer. As a rule, different additives (modifiers) are used to affect a material's properties. Common additives include:

- Surface lubricants (facilitate ejection)
- Heat stabilizers (improve the process window)
- Color pigments
- Reinforcement additives such as glass or carbon fiber (increase stiffness and strength)
- Impact or toughness modifiers
- UV modifiers (e. g. to protect against UV light)
- Fire retardants
- Antistatic agents
- Foaming agents (e. g. EPS, expanded polystyrene)

1.1 Thermosets

In thermosets as well as in rubber, binding can occur between the molecular chains, which is described “cross-linking.” These cross-links are so strong that they do not break when heated—thus the material cannot be melted.



Figure 1.5 Plastic padding, or so-called two-component adhesive, is present in many homes. Here two components are mixed with each other, starting a chemical cross-linking reaction causing the material to harden. One of the components is therefore called “hardener.” In this case, the reaction occurs at atmospheric pressure and is referred to as a low-pressure reaction.



Figure 1.6 Polyurethane can exist as both a thermoset and a thermoplastic. It can also be rigid or soft as seen in the foam blocks shown here.

Thermosets occur in both liquid and solid form, and in some cases can be processed with high-pressure methods. Some common thermosets include:

- Phenolic plastic (used in saucepan handles)
- Melamine (used in plastic laminates)
- Epoxy (used in two-component adhesives)
- Unsaturated polyester (used in boat hulls)
- Vinyl ester (used in automobile bodywork)
- Polyurethane (used in shoe soles and foam)

Many thermosets have excellent electrical properties and can withstand high operating temperatures. They can be made extremely stiff and strong with glass, carbon, or Kevlar fibers. The main disadvantages are a slower machining process and difficulties of material or energy recycling.

1.2 Thermoplastics

Thermoplastics have the advantage that they melt when heated. They are easy to process with a variety of methods, such as:

- Injection molding (the most common process method for thermoplastics)
- Blow molding (for making bottles and hollow products)
- Extrusion (for pipes, tubes, profiles, and cables)
- Film blowing (e.g. for plastic bags)
- Rotational molding (for large hollow products such as containers, buoys and traffic cones)
- Vacuum forming (for packaging, panels, and roof boxes)

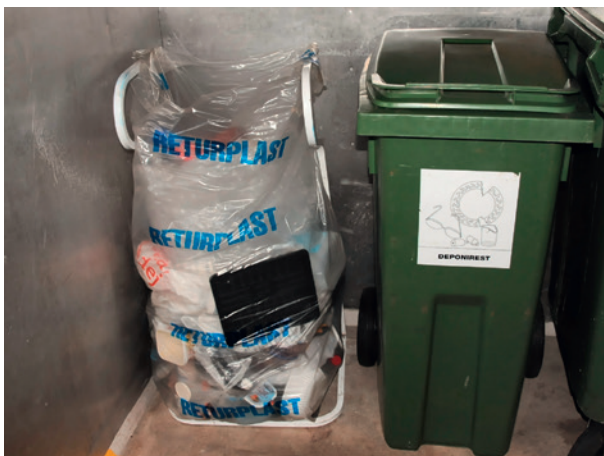


Figure 1.7 Many households now sort their garbage so that the plastic bottles, bags, film, and other plastic products can be recycled.



Figure 1.8 Discarded thermoplastic products can be recycled. These acoustic screens from Polyplank AB are an excellent example. [Photo: Polyplank AB]

Thermoplastic can be re-melted several times. It is therefore important to recycle plastic products after use. Commodities can usually be recycled up to seven times before the properties become too poor. In the case of engineering and advanced plastics, a maximum of 30% regrind is usually recommended so that the mechanical properties of the new material are not significantly affected. If you cannot use recycled plastics in new products, energy recycling through incineration is often a suitable choice. There is however another option called chemical recycling, although this process has not yet become popular due to the high costs involved versus virgin manufactured material.

1.3 Amorphous and Semi-crystalline Plastics

As shown in Figure 1.3 plastics can be divided into two main groups depending on the plastic structure, i.e. amorphous or semi-crystalline. Glass is another common amorphous material in our environment, and metals have a crystalline structure. An amorphous plastic softens as glass does if you raise the temperature and can therefore be thermoformed.

Amorphous materials have no specific melting point—instead we use the so-called glass transition temperature (T_g), when the molecular chains begin to move. Semi-crystalline plastics do not soften in the same way—instead they change from solid to liquid at the melting point (T_m).



Figure 1.9 Thermoplastic polyester (PET) is a plastic that can be either amorphous, as in soft drink bottles, or semi-crystalline, as in the iron.

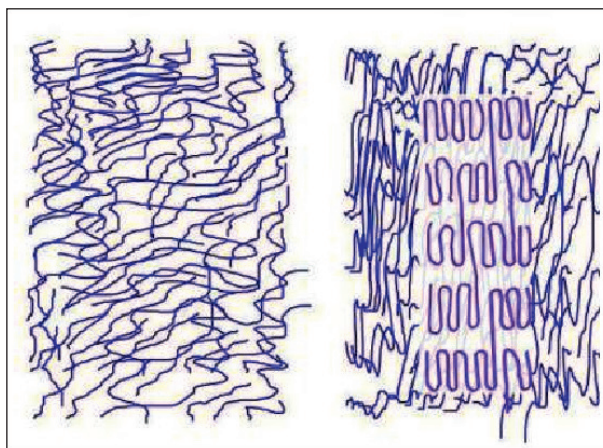


Figure 1.10 The amorphous structure is completely disordered, whereas in the semi-crystalline plastic the molecular chains align themselves in orderly layers (lamellae).

As a rule, semi-crystalline plastics cope better with elevated temperatures than amorphous plastics and have better fatigue resistance and chemical resistance. They are also not sensitive to stress-cracking. Semi-crystalline plastics are more like metal and have better spring properties than amorphous resins. Amorphous plastics can be completely transparent and can be thermoformed. They generally have less mold- and post-shrinkage and have less warpage than semi-crystalline plastics.

It is important that designers and processors of plastic products are aware of the type of material being used since amorphous and semi-crystalline materials behave differently when heated and require different process parameters.

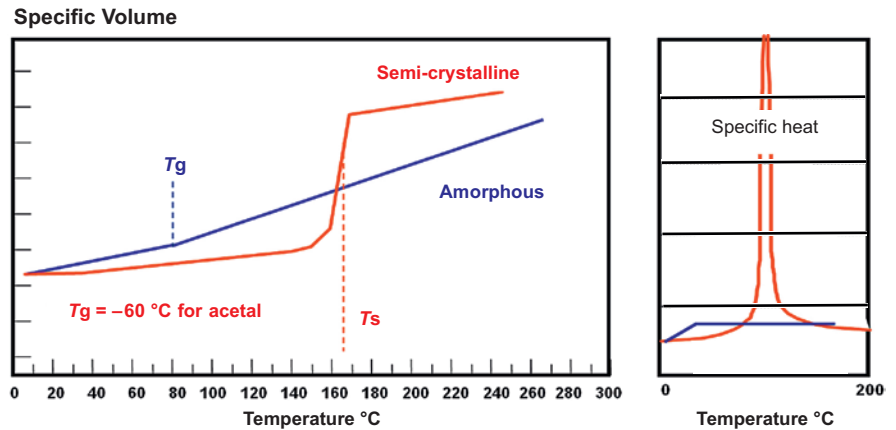


Figure 1.11 Heating increases the specific volume linearly above and below the glass transition temperature (T_g) of the amorphous material. The semi-crystalline material also has a glass transition temperature as there are no plastics with 100% crystallinity. Around the melting point (T_m) the specific volume increases significantly. For acetal this is about 20%, which explains the high shrinkage with injection molding. Amorphous materials have no melting point and significantly less shrinkage. The energy required to raise the temperature one degree remains constant above the T_g of the amorphous material, as shown in the right-hand figure. The semi-crystalline material requires a significant increase in energy to achieve the melting point, the so-called specific heat, to convert the material from a solid to a liquid state. This causes problems for the injection molding processor, as it requires a large energy input when semi-crystalline plastics freeze in the nozzle or hot runners in the mold. Sometimes you have to take a blowtorch to melt the frozen slugs in the cylinder nozzle.

Commodities

2.1 Polyethylene (PE)

Polyethylene or polyethene is a semi-crystalline commodity, denoted as PE. It is the most common plastic, and more than 60 million tons are manufactured each year worldwide. “Low-density” polyethylene (LDPE) was launched on the market by the British chemicals group ICI in 1939.



Chemical facts:

Polyethylene has a very simple structure and consists only of carbon and hydrogen. It belongs to a class of plastics called olefins. These are characterized by their monomers having a double bond, and they are very reactive. The chemical symbol for ethylene, the monomer in PE, is C_2H_4 or $CH_2 = CH_2$, where the “=” sign symbolizes the double bond. Polyethylene can be graphically described as:

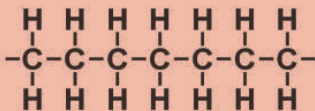


Figure 2.1 One reason that PE has become the main commodity is its extensive usage as a packaging material. Plastic bags are made of LDPE.

2.1.1 Classification

Polyethylene can be classified into different groups depending on its density and the lateral branches on the polymer chains:

- UHMWPE Ultrahigh molecular weight
- HDPE High density
- MDPE Medium density
- LLDPE Linear low density
- LDPE Low density
- PEX Cross-linked

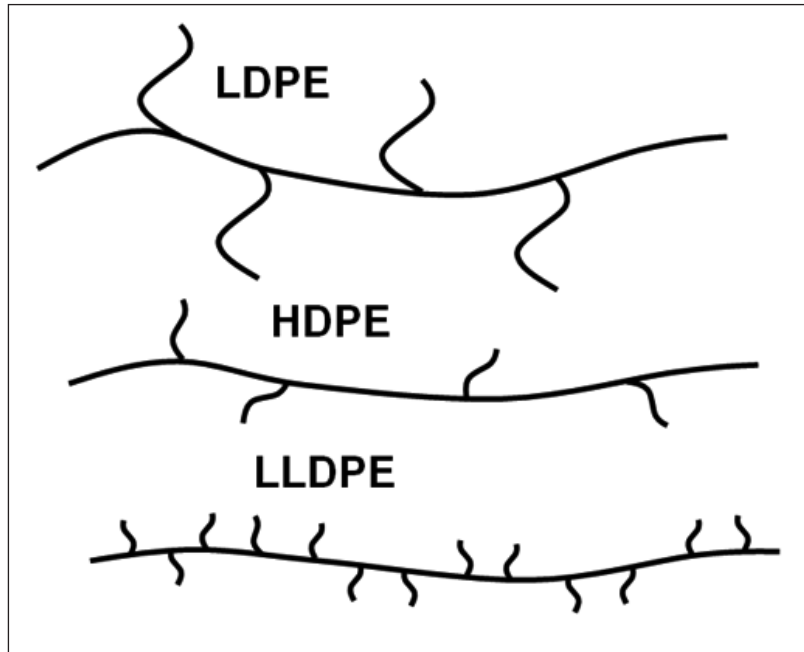


Figure 2.2 When polymerizing ethylene to polyethylene, there are various processes resulting in more or less lateral branches on the molecular chains. A smaller number of lateral branches give a higher crystallinity, molecular weight, and density, since the chains can thus be packed more densely. HDPE has few or no lateral branches and is also called linear polyethylene.

2.1.2 Properties of Polyethylene

- | | |
|--------------------------------------|--|
| + Low material price and density | + Excellent wear resistance (UHMWPE) |
| + Excellent chemical resistance | + Easy to color |
| + Negligible moisture absorption | - Stiffness and tensile strength |
| + Food-approved grades are available | - Cannot handle temperatures above 80 °C |
| + High elasticity down to < -50 °C | - Difficult to paint |

The mechanical properties depend largely on the presence of lateral branches, crystallinity, and density, i. e. the type of polyethylene.

2.1.3 Recycling

Polyethylene is one of the most recycled plastic materials. Many of the bags, garbage bags, and dog bags that we use are made from recycled polyethylene. If you use the recycled materials in energy production, the energy content is on par with oil.

When it comes to recycling, the following coding is used:



2.1.4 Application Areas

1) UHMWPE is processed mainly by extrusion into pipes, film, or sheets.

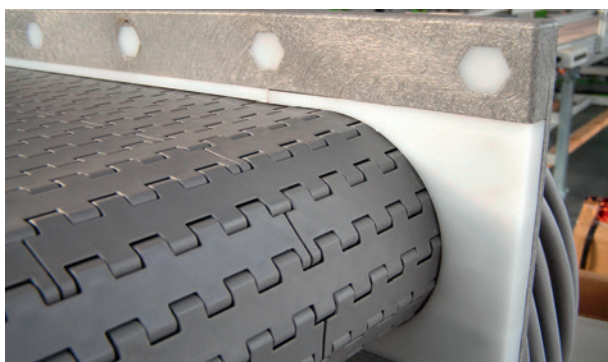


Figure 2.3 Slide rail.

UHMWPE has excellent friction and wear properties and is used in demanding industrial applications, such as this white slide rail for a conveyor belt in gray acetal.



Figure 2.4 Rubbish bins.

HDPE is low cost to produce and easy to mold, even in great detail.

2) HDPE is used for injection molding, blow molding, extrusion, film blowing, and rotational molding.



Figure 2.5 Tub and bottles.

HDPE is appropriate for blow molding and meets food industry standards.



Figure 2.6 Hosepipes.

HDPE is suitable for extrusion. A water hose is tough and strong, approved for drinking water, and can handle the pressure of the mains water supply for the foreseeable future.

3) LDPE is used for film blowing and extrusion.

A large part of all the polyethylene produced is used for film blowing. If the film is soft and flexible, it is either made of LDPE or LLDPE. If it has the rustle of the free bags at the grocery store, it is probably made of HDPE. LLDPE is also used to improve the strength of LDPE film.



Figure 2.7 Garbage bags.

LDPE is excellent for film blowing and is the most common material used in bags, plastic sacks, and construction film.



Figure 2.8 Cable jacketing.

LDPE is used in the extrusion of jacketing for high voltage cables

4) PEX

Cross-linked polyethylene is mainly used in the extrusion of tubes. The cross-linking provides improved creep resistance and better high-temperature properties.



Figure 2.9 Tubes in PEX resist both high temperatures (120°C) and pressure and are used for the hot water supply of cleaning or washing machines.

You can even copolymerize ethylene with polar monomers and get everything from viscous products (e. g. melting glue) to tough films and impact-resistant hard shells such as golf balls.

A common copolymer is EVA (ethylene-vinyl-acetate). By varying the concentration of vinyl acetate (VA) from 2.5 to 95%, you can control the properties and produce a range of different types of material. Increased VA content leads to higher transparency and toughness.

Adhesives, carpet underlay, cable insulation, carriers of color masterbatches, stretch film, and coating film for cardboard and paper are typical uses of EVA.

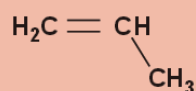
2.2 Polypropylene (PP)



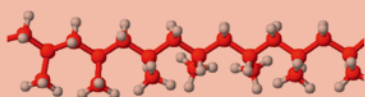
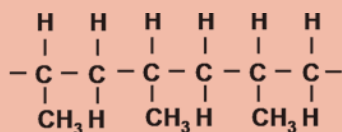
Chemical facts:

PP has a simple structure and is made up, like PE, only of carbon and hydrogen. It also belongs to the category of plastics called olefins.

Polypropylene is made up of a chain of carbon atoms, where every other carbon atom is bonded to two hydrogen atoms and every other to a hydrogen atom and a methyl group. The monomer formula is:



Graphically you describe polypropylene:



Polypropylene is a semi-crystalline commodity, denoted by— and commonly referred to as—PP. It is also known as “polypropylene.” It is the second-largest plastic on the market, after LDPE.

Polypropylene was discovered in 1954, almost simultaneously by two independent researchers Ziegler and Natta, who went on to share the Nobel Prize in 1963.

The Italian chemical company Montecatini launched the material on the market in 1957.

The polymerization of polypropylene can control both crystallinity and molecule size. One can also copolymerize polypropylene with other monomers (e.g. ethylene).

Polypropylene can occur as a homopolymer, random or block copolymer depending on the polymerization method. Polypropylene can also be mixed with elastomers (e.g. EPDM), filled with talc (chalk), or reinforced with glass fiber. In this way it is possible to obtain more grades with widely differing characteristics than can be achieved for any other plastic. Certain grades of polypropylene can handle a continuous temperature of 100 °C plus peaks of up to 140 °C and can therefore be classified as engineering plastics.