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Paul A. Tres

Designing Plastic Parts for Assembly

10ᵗʰ Edition

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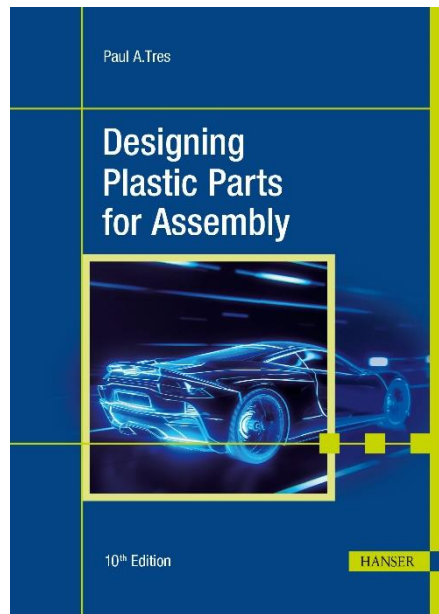
Sample Pages

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Print ISBN: 978-1-56990-912-6
E-Book ISBN: 978-1-56990-939-3

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Preface to the 10th Edition

The first edition of this book was released in 1994 and now, 30 years later, the 10th edition is available. Over the course of so many years many updates and additions have been included to each edition.

In part, this was possible because many design concerns and new ideas came to my attention, some from the readers of the previous textbook editions, but the bulk of new add-ons came from the participants to my seminars. More than 20,000 designers, engineers, and managers attended the seminars during the last 36 years. They came from many countries, including Canada, France, Germany, India, Korea, Malaysia, Mexico, Thailand, and the United States of America, among others.

There have also been many legal cases involving consumer products (among them: digital wrist watch made by MBZ, wheel barrel made by AMES Companies, snow thrower made by MTD Products, and Omnibook™ 300 notebook computer made by HP), medical devices (among them: dental applicator Icon® made by DMG of Hamburg, Germany, hospital beds made by Hill-Rom, surgery beds made by Stryker, and defibrillators made by Survivalink™), recreational products (among them: baby playpen made by Evenflo, swimming pool steps made by S. R. Smith, and paintball masks made by Save Phace™), and many boats and vehicles components (among them: 550i and 750i transmission holding bracket from BMW, Corvette C6 rear quarter side panel from GM, Dodge Nitro sports utility vehicle driver side airbag door made by Chrysler, Chrysler 300M air intake manifold, Ford heat ventilation and air conditioning unit, General Motors 3.5-liter engine cover, Honda Accord power lumbar support, Mercedes-Benz M-Class windshield washer bottle and engine cover and C-Class tumble valve, Mercury Marine V8 engine and Tesla Model 3 door panels), which failed one way or another, hurting or even killing people.

Over the years I included many examples on how the products failed and how they should have been designed to perform properly for the entire life span they were intended for.

In this latest edition some typos have been fixed and two new sections have been added. The first one, included in the first chapter, describes the important role that the coefficients of linear thermal expansion and contraction play in the performance of the component for the duration of its entire lifespan when large temperature gradients are present while the product is in use.

The second addition is in Chapter 5. It describes a rather new thermoplastic welding process for assembling polymeric components, called hot gas welding. The joint design is also discussed in this section, so that if this novel manufacturing process is selected by a designer or engineer, the suggested joint design, fully explained in the chapter, can be easily and productively used.

The World Wide Web References, related to the Plastic Part Design section at the end of the textbook, have also been updated, covering: Associations and Organizations, Books and Magazines, Consulting Companies, Forums, Material Databases, Material Suppliers, Museums, Rapid Prototyping, Testing and Research, Tips on Design and Processing, Tooling, and Universities.

Bloomfield Hills, Michigan *Paul A. Tres*

Fellow of the Society of Plastics Engineers

Foreword to the First Edition

Knowing well the work and many special talents of Paul A. Tres, I take delight in the opportunity to introduce his new book, Designing Plastic Parts for Assembly, and recommend it to a broad range of readers. Material engineers, design and manufacturing engineers, graduate and under-graduate students, and all others with an interest in design for assembly or plastic components development now have a clearly written, method-oriented resource.

This practical book is an outgrowth of the like-named University of Wisconsin–Madison course which is being offered nationally and internationally. Just as his lectures in the course provide a detailed yet simplified discussion of material selection, manufacturing techniques, and assembly procedures, this book will make his unique expertise and effective teaching method available to a much larger audience.

Mr. Tres' highly successful instructional approach is evident throughout the book. Combining fundamental facts with practical techniques and a down-to-earth philosophy, he discusses in detail joint design and joint purpose, the geometry and nature of the component parts, the type of loads involved, and other vital information crucial to success in this dynamic field. Treatment of this material is at all times practice-oriented and focuses on everyday problems and situations.

In addition to plastics, Mr. Tres has expert knowledge in computer software, having directed the development of DuPont's design software. The course at the University of Wisconsin–Madison is indirectly an outgrowth of the software he designed for living hinges and snap fits at DuPont.

Mr. Tres holds numerous patents in the plastics field. He is known worldwide for his expertise in computer programming, manufacturing processes, material selection and project management on both a national and international scale.

Most recently, Mr. Tres' accomplishments have earned him the DuPont Automotive Marketing Excellence Award as well as recognition in the 1994–1995 edition of Who's Who Worldwide.

Whether you are just entering the field, or are a seasoned plastic parts designer, Designing Plastic Parts for Assembly is an excellent tool that will facilitate cost-effective design decisions, and help to ensure that the plastic parts and products you design stand up under use.

Madison, WI   *Dr. Donald E. Baxa*

University of Wisconsin-Madison

Preface to the First Edition

It gives me great pleasure to write this preface for such an important contribution to engineering design. It is rather sad fact that while the creative use of plastics has changed the very structure of consumer products over the past decade, many engineering students graduate with very little knowledge of polymer engineering or plastic design principles. This book written by a recognized expert and practitioner in the field of plastic component design is both a valuable text for engineering courses and a resource for practicing design engineers.

The full potential for the use of plastics in consumer products became recognized in the mid 1980s through the pioneering development of the IBM ProPrinter. The ProPrinter destroyed the myth, prevalent amongst product engineers at that time, that such design elements as plastic springs, plastic bearings, plastic securing elements, etc., lacked the structural integrity of their more common metal counterparts. In the ProPrinter, not only were these plastic design features shown to have the required reliability in regular use and abuse, they were combined into single parts to produce a new level of design elegance. For example, the injection molded side-frames of the ProPrinter, which support the rollers and lead screw, incorporated bearings for all of these rotating members, springs to maintain the required paper pressure, and cantilever securing elements to allow the frames to be snap fitted into the base. The result of such innovative design details produced a desktop printer which could be assembled in only 32 final assembly steps compared to the 185 steps required to assemble its main competitor in the marketplace.

Since the emergence of the ProPrinter, smart plastic design has become an essential tool in the competitive battle to produce products which have simpler structures with smaller numbers of discrete parts. Part count reduction, in particular, has been shown, through numerous case studies published over the past five years, to have a ripple effect on product manufacture which improves the efficiency of the entire organization. Fewer parts mean fewer manufacturing and assembly steps, and fewer

joints and interfaces, all of which have a positive effect on quality and reliability. Moreover, a reduction in the number of the parts results in a direct attack on the hidden or overhead cost of an organization. Thus, fewer parts also mean fewer vendors for purchasing to deal with, less documentation, smaller inventory levels, less inspection, simpler production scheduling and so on.

Designing Plastic Parts for Assembly tackles all of the important issues to be faced in designing multi-feature complex plastic parts. The book is thus much more than its title suggests. It deals with essential fundamentals for the development of competitive consumer products.

Providence, Rhode Island   *Dr. Peter Dewhurst*
Department of Industrial and Manufacturing Engineering
University of Rhode Island

Acknowledgments

Contents

1 Understanding Plastic Materials

■ 1.1 Basic Resins

Polymers are divided into two major groups: *thermoplastics* and *thermosets*.

Thermoplastic resins are formed from individual molecular chains, which have a linear structure and exhibit no chemical linkage between the individual molecules.

Thermoset resins have molecules that are chemically linked together by crosslinks and form a sort of network structure.

1.1.1 Thermoplastics

A major characteristic of *thermoplastic* polymers is that they repeatedly soften when heated and harden when cooled. The molecules are held together by intermolecular forces, such as van der Waals. During the molding process, when heat and pressure are applied to the thermoplastic resin, the intermolecular joints break and the molecules move, changing positions in relation to one another. In the holding phase of the molding cycle, the molecules are allowed to cool, doing so in their new locations. The intermolecular bonds are restored in the new shape.

Thermoplastic polymers are ideal for recycling purposes because of their ability to rebond many times over (Fig. 1.1).
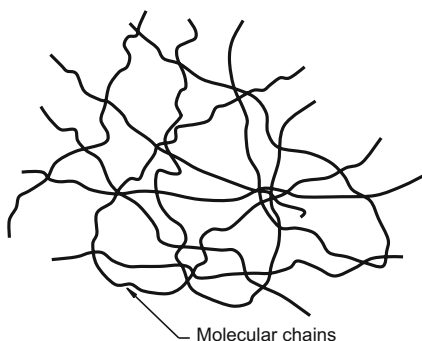
Molecular chains

Figure 1.1
Thermoplastics: molecular chains

When heated, the individual chains slip, causing plastics to flow. When cooled, the molecular chains are strongly held together once again. There are practical limitations to the number of times the material can be heated and cooled, depending upon the thermoplastic being used.

Polycarbonate, nylon, acetal, acrylic, thermoplastic elastomers (TPEs), and polyethylene are examples of thermoplastics.

1.1.2 Thermosets

Thermoset polymers undergo chemical change during processing.

During the molding process, when thermoset resins are heated and cured, crosslinks form between molecular chains (Fig. 1.2). This reaction is also called a *polymerization reaction*. When reheated, these cross bonds prevent individual chains from slipping. Chemical degradation occurs if more heat is added after the cross bonding is complete. Therefore, applying heat and pressure cannot remelt thermosets, and they cannot be recycled.
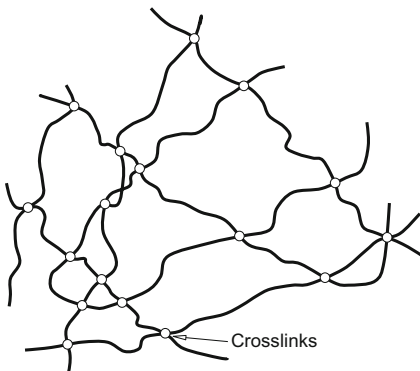
Crosslinks

Figure 1.2
Thermosets: crosslinks

■ 1.2 Basic Structures

1.2.1 Crystalline

Crystalline polymers are orderly, densely packed arrangements of molecular chains (see Fig. 1.3). These molecular chains have the appearance of a shoestring when magnified many times under a microscope. The highly organized regions show the behavioral characteristics of crystals.
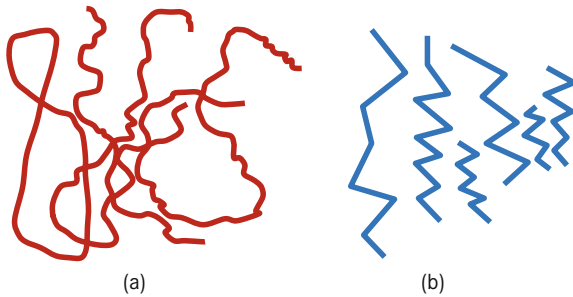
Figure 1.3
Molecular chains for crystalline polymers: (a) melt; (b) solid

It should be noted that complete crystallinity is seldom achieved during polymer processing. There will almost always be some amorphous areas left in the part. During processing, parts cool from the outside in, so the skin of the part is the area most likely to lack the necessary crystallinity. Many crystalline polymers achieve a degree of crystallinity of only 35 to 40%, even under ideal processing conditions. That means that slightly more than one-third of the component structure becomes self-organized.

Some typical examples of crystalline polymers include acetal, polyamide (nylon), polyethylene (PE), polypropylene (PP), polyester (PET, PBT), and polyphenylene sulfide (PPS).

1.2.2 Amorphous

Polymers having *amorphous* structures represent a disordered or random mass of molecules (Fig. 1.4). A typical noncrystalline or amorphous structure tends to give the resin a higher elongation and flexibility. It will also exhibit higher impact strength than would a crystalline structure.
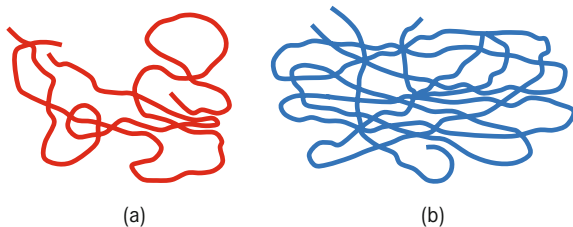
Figure 1.4
Molecular chains for amorphous polymers: (a) melt; (b) solid

Some examples of amorphous polymers are acrylonitrile-butadiene-styrene (ABS), styrene-acrylonitrile copolymer (SAN), polyvinyl chloride (PVC), polycarbonate (PC), and polystyrene (PS). Table 1.1 highlights various properties of semicrystalline polymers compared to amorphous polymers.

Table 1.1 Comparison of Typical Properties between Amorphous and Semicrystalline Polymers

Properties	Amorphous	Semicrystalline
Chemical resistance	Poor	Very good
Creep capabilities	Very good	Good
Elongation at yield	Average 0.4–0.8%	Average 0.5–0.8%
Fatigue strength	Poor	Very good
Mechanical properties	Good	Very good
Temperature	Softening range	Defined point
Notch sensitivity	Poor	Good
Service temperature	Good	Very good
Shrinkage	Very good	Poor

1.2.3 Liquid Crystal Polymer (LCP)

Liquid crystal polymers (LCP) are generally considered a separate and unique class of polymers. Their molecules are stiff, rod-like structures that are organized in large parallel arrays in both the molten and solid state (see Fig. 1.5). This parallel organization of molecules gives LCP characteristics similar to both crystalline and amorphous materials.

(a)   (b)
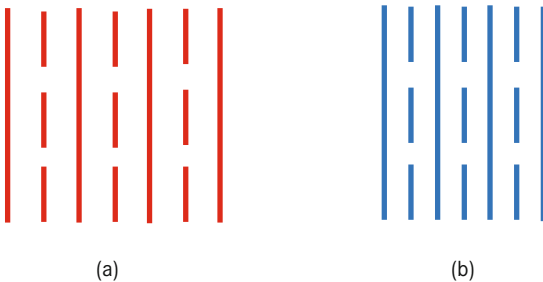
Figure 1.5
Molecular chains for liquid crystal polymers: (a) melt; (b) solid

1.2.4 New Polymer Technologies

1.2.4.1 Inherently Conductive Polymers (ICP)

Polymers, since their inception, have been known as insulators both electrically and thermally. In the last few decades a number of suppliers have tried to make polymers conductive by using metal fillers or reinforcements. The result of improving polymer conductivity has been marginal.

The discovery of inherently conductive polymers (ICP) has changed all that. Alan Heeger, Alan MacDiarmid, and Hideki Shirakawa were awarded the Nobel Prize for Chemistry in 2000 for their pioneering work related to ICPs.

The above scientists, as well as many others, discovered that adding or subtracting atoms to or from polymers allows the plastic to become electrically or thermally conductive. This process, known as doping, typically removes or adds conducting electrons, leaving a polymer with some positive or negative charges. Dopants are chemical substances that either supply additional electrons to conduct a charge or, alternatively, take electrons away to create what are known as holes or places in a molecule that conduct the charge by accepting electrons. Having fewer electrons that remain in the polymer, they will be capable of moving more openly, allowing conduction.

The most promising ICPs are polyacetylene, polyaniline (PAni), and polypyrrole (PPY). They can be added to known polymers, such as acrylics (known as poly methyl methacrylate or PMMA), poly vinyl chloride (PVC), polypropylene (PP), and others, to make them conductive.

1.2.4.2 Electro-Optic Polymers (EOP)

Electro-optic polymers (EOP) are distinct resins, but they do have some overlapping characteristics with ICPs (inherently conductive polymers). Upon the application of an electric field, EOPs exhibit optical characteristics: they glow. The effect is due to the large molecules making up the polymers. When voltage is applied it raises the molecules' electrons to higher energy levels, after which they drop back to their original energy levels, emitting light in the process (electroluminescence). Richard Friend and Jeremy Burroughes from Cambridge University, England, developed the first electroluminescent polymer, PPV (polyphenylene vinylene). They showed that sandwiching a thin layer of resin between a pair of electrodes—one of which was transparent—made the polymer glow.

There are a number of polymers emitting various colors. For example, green is emitted by PPV, red by PT (polythiophene), and blue by PF (polyfluorene). When an electric charge (typically low voltage of 3 to 5 volts) is applied, the benzene electrons of each polymer are excited. Then the benzene electrons, returning to their original state of energy levels, emit light in a color specific to their resin, which is vibrant and soft.

The simplified manufacturing process consists of an electrical conductor laid down on a carrier foil, glass, or plastic. Then a thin LEP (light-emitting polymer) layer is applied, which is less than 1 μm (0.00004 in.) thick. Finally, another electrode is deposited on top and the display is realized (see Fig. 1.6).
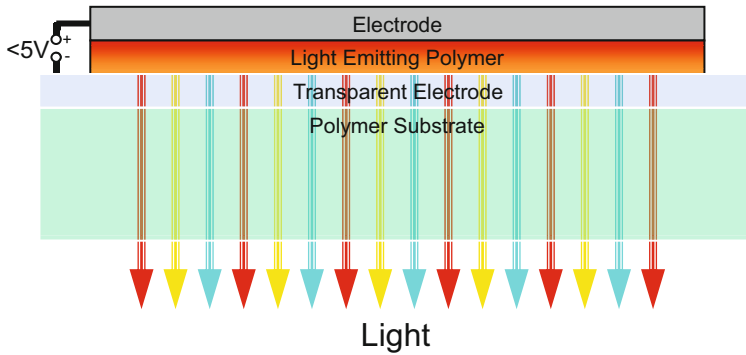
Figure 1.6 Cross section through a light–emitting display (LED) containing a thin layer of light-emitting polymer (LEP)

It should be noted that display stability and performance is greatly improved when sealing techniques are used to prevent air and moisture from reaching the LEP sandwiched between the two electrodes. Certain LEDs (light-emitting displays) have reached continuous working lifetimes exceeding 50,000 hours.

1.2.4.3 Biopolymers

Polylactic (PLA) polymers are one type of biopolymers that consists of rather long chains of lactic acid. The lactic acid is manufactured from fermented and polymerized sugars extracted from starch-producing plants, such as corn and potatoes.

Table 1.2 Physical and Mechanical Property Comparison between PLA, PET, and PS Polymers

Property	ASTM Method	PLA (Polylactide)	PET (Polyethylene Terephthalate)	PS (Polystyrene)
Specific gravity	D792	1.21	1.37	1.05
Melt index (g/min @ 190°C)	D1238	10–30	1–10	1–25
Clarity	15	Transparent	Opaque	Transparent
Tensile yield strength (psi)	D638	7,000	9,000	6,000
Tensile strain (%)	D638	2.5	3	1.5
Notched Izod impact (ft-lb/in.)	D790	0.3	0.7	0.01
Flexural strength (psi)	D790	12,000	16,000	11,500
Flexural modulus (psi)	D790	555,000	500,000	430,000

The PLAs have mechanical properties, such as tensile strength and elastic modulus, comparable to PET (polyethylene terephthalate), while their appearance is comparable to polystyrene clarity and gloss.

■ 1.3 Homopolymer vs. Copolymer

Homopolymers have a single type of repeating unit throughout the molecular chain. All monomer links in the chain are of the same type (Fig. 1.7).
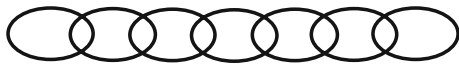
Figure 1.7
Molecular chain for homopolymer resins

A *copolymer* is a polymer with links of more than one kind, which are randomly placed in the chain. Copolymers have different properties from homopolymers because they have different repeating units. When the base unit is altered, its physical and mechanical properties change in different areas (Fig. 1.8).
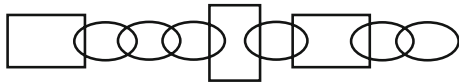
Figure 1.8
Molecular chain for copolymer resins

■ 1.4 Reinforcements

Reinforcing fibers significantly improve most mechanical and thermal properties of thermoplastic and thermoset materials. Glass fibers, carbon fibers, and aramid fibers are some typical reinforcements for plastic materials.

Glass fiber reinforcements are strands of thin filaments drawn from glass furnaces. They are often coated with polymeric films that hold glass strands together. Typical fiber diameters are between 0.002 and 0.02 mm (0.0001 to 0.001 in.). The coated fibers with polymeric films are used as intermediate products or are directly processed into reinforced resins.

The glass fibers have a tensile strength that varies between 3,000 and 5,000 MPa (435,000 to 725,000 psi), have a Young's modulus (see Section 3.8) in the range of 70,000 to 90,000 MPa (10 to 13 million psi), and have an ultimate strain between 4 and 5%.

Reinforcements are available in different forms, such as continuous strand, woven, roving, or chopped fiber. Continuous strands are mostly used in processes like sheet

molding compounding (SMC). Chopped fibers are used to reinforce a variety of resins used in processes such as injection molding and compression molding. These fibers usually range from 3 to 12 mm (0.125 to 0.5 in.) or more.

The carbon fibers have a tensile strength of 340 to 5,500 MPa (50,000 psi to 800,000 psi) and a Young's modulus of 35,000 MPa to 700,000 MPa (5 to 100 million psi). The aramid fibers have a tensile strength of 3,500 to 5,000 MPa (508,000 to 725,000 psi) and a Young's modulus of 80,000 to 175,000 MPa (11.6 to 25.4 million psi).

■ 1.5 Fillers

Fillers affect the physical nature of the material without significantly improving the mechanical properties. Some examples of materials used as fillers are talc, wollastonite, mica, glass spheres, silica, and calcium carbonate.

There are two basic types of micas: phlogopite and muscovite. Their size varies between 325 and 40 mesh in particle size (MPS).

Glass spheres can be solid or hollow. Their size varies between 0.005 and 5 mm (0.0002 to 0.2 in. or 5 μm to 5,000 μm). Both solid and hollow glass spheres can be covered with special coatings to improve the bonding between the filler and the matrix.

Nanocomposites are a new technology. Clay additive particles or nanofillers that are added to the polymer matrix are extremely small, having a thickness of about one-millionth of a millimeter (one twenty-five millionth of an inch). In comparison, the filler in conventional thermoplastic polymers—polyolefins, for example—is usually about 1,000 or more times thicker. A polyolefin polymer having as little as 2.5% nanoclay additive filler can be as stiff and at the same time much lighter than parts with 10 times the amount of conventional talc filler. The weight savings can reach 20%, depending on the part and the material that is being replaced by the nanocomposite polymer.

1.5.1 Glass Spheres

Glass bubbles are hollow, spherical particles typically in the range of 10 μm to 200 μm, which can be used to reduce the weight of components made of thermoplastic polymers [196]. They are known by a variety of names, including glass microballoons and hollow glass microspheres. On a per-pound basis, glass spheres are more expensive than conventional fillers such as talc and calcium carbonate. However,

most glass bubbles are sold on a volumetric basis with loading levels of 3–5%, making cost less of a concern. The most common glass bubbles for thermoplastic applications are made by a high-temperature melt process and are a borosilicate glass composition. Figures 1.9 and 1.10 show some scanning electron microscopy (SEM) micrographs of glass bubbles.
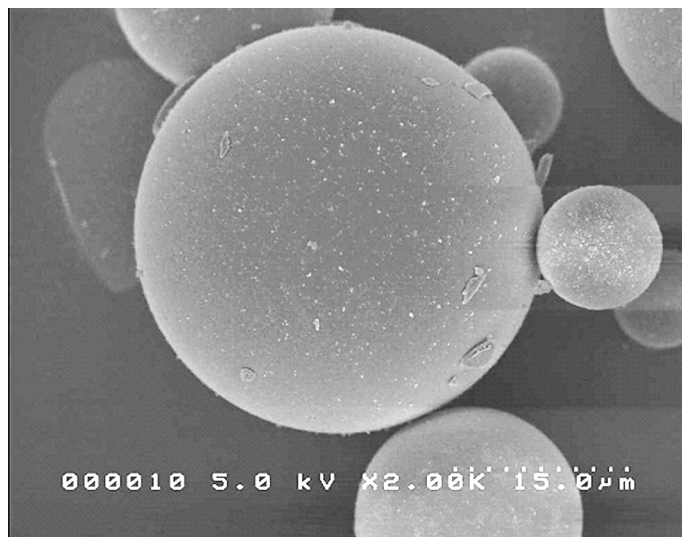

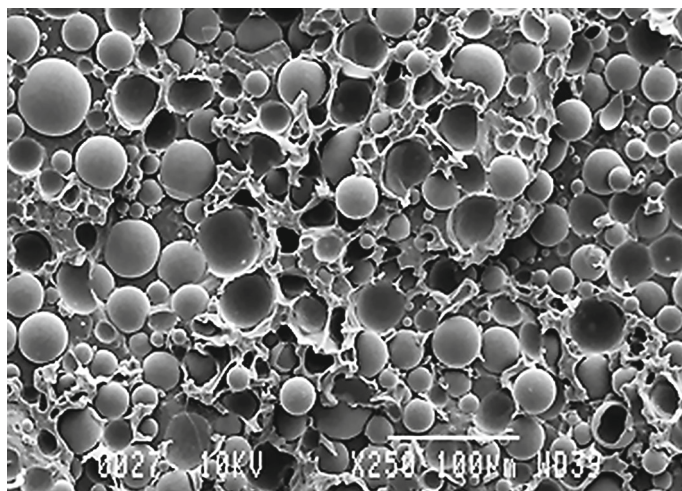**Figure 1.9** SEM micrograph of hollow glass microsphere, grade S60HS *(Courtesy of 3M Company)*

Figure 1.10 SEM micrograph of the fracture surface of S60HS in polypropylene at 40% by volume loading *(Courtesy of 3M Company)*

The microspheres are available in a wide range of densities, ranging from 0.1 grams per cubic centimeter to over 1.0 g/cc [198]. The higher density microspheres have higher compressive strengths due to their increased wall thickness. This strength-to-density correlation is an important consideration when choosing a hollow microsphere for a particular application, since most end users desire the lowest density microspheres that can survive their processing conditions.

1.5.1.1 Microsphere Properties

The most common use for glass bubbles in thermoplastics is as lightweight filler. In addition to providing the benefit of light weight, glass bubbles also provide attributes similar to those of other traditional fillers, such as reduced mold shrinkage, warpage, and coefficient of linear thermal expansion. Other attributes unique to glass bubbles are their low thermal conductivity and improved cycle times because materials containing hollow glass bubbles have less mass to heat and cool.

The downside to using hollow glass bubbles is that they are more expensive than traditional fillers. Their reduced density compared to solid fillers mitigates some of the cost imbalance. These issues are discussed in more detail in the following sections.

1.5.1.2 Compounding

In order to survive the hydrostatic and shear forces experienced during compounding and injection molding, glass bubbles with strengths greater than about 3,500 psi are recommended for extrusion processes; glass bubbles with strengths greater than 10,000–15,000 psi are recommended for injection-molding processes. The exact grade of bubble that should be used depends on the formulation and processing conditions. Heavily filled systems require stronger bubbles, as do high screw speeds, high extruder outlet pressures, and aggressive mixing elements in the extruder.

To minimize bubble breakage it is imperative to use a twin-screw extruder or a Buss kneader equipped with a downstream feed port for adding the glass bubbles. Extruder screw flights beyond this point should be set up to impart a minimum amount of shear stress. Distributive mixing elements, such as gear mixers, are preferred. Aggressive dispersive mixing elements, such as reverse flight elements and kneading blocks, are not recommended. Single-screw extruders are also not recommended, as they typically do not have a downstream port and often contain "barrier" designs or other narrow tolerance/high shear features. A system designed for adding chopped fiberglass to a polymer would be a suitable starting point when developing a low shear extrusion system for glass bubbles.

Glass bubbles can be fed with a volumetric feeder, although a gravimetric feeder—ideally one equipped with a twin shaft—is the preferred method. An auger-driven side feeder at the downstream port, rather than a simple open hopper, will provide

the most consistent feeding behavior. Glass bubbles will become fluidized when aerated (which often occurs when initially filling a hopper), and this may lead to flooding of the hopper. To prevent this possibility, it is recommended that the feeder discharge be covered until the hopper is filled with glass bubbles.

Any pelletizing method suitable for the polymer of choice is suitable for a system containing glass bubbles. For highly bubble-filled polymers, it is advisable to use an underwater strand pelletizer or water-slide pelletizer.

1.5.1.3 Injection Molding

A general-purpose, three-zone screw (feed, compression, and metering) is suitable for processing glass bubbles. As mentioned in the previous section, dispersive mixing screws, such as barrier, vented, or double wave, are not recommended. Distributive mixers will give acceptable results.

A generous nozzle/sprue orifice dimension should be used. Additionally, it is best not to use internally tapered tips or tips without a constant-diameter pathway, as they can cause additional stress on the glass bubbles. For optimum mold filling, gate designs should incorporate full, round runners and sprues that are as short as possible.

1.5.1.4 Mechanical Properties in Injection-Molded Thermoplastic Applications

Although hollow microspheres are not considered to be reinforcing due to their $1:1$ aspect ratio, careful control of the formulation can minimize the negative effect of the microspheres on mechanical properties. In 1995, Trexel became sole licensee of MuCell® technology (see Fig. 1.11), which was developed by Massachusetts Institute of Technology. The technology uses nitrogen and sometimes carbon dioxide as the foaming agent. Figure 1.12 shows an engine cover made from thermoplastic polyamide 6,6 using 18% glass fibers and 8% glass microspheres as filler content. The cover is molded using the MuCell® microcellular foam injection-molding process, which employs the controlled use of gas in its supercritical state to create the foamed part.
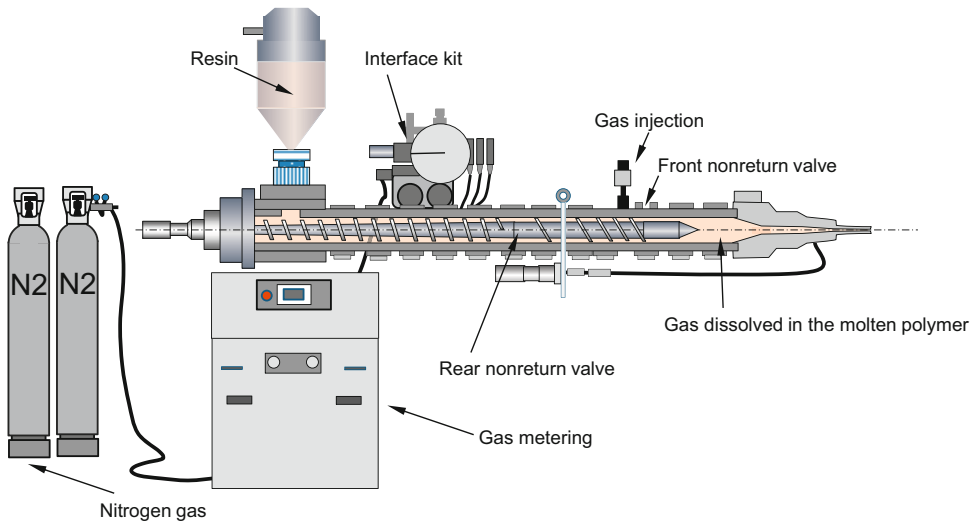
Figure 1.11 Schematic of MuCell® technology

Figure 1.12
Engine cover for 3.5 liter, six-cylinder engine made using 18% glass-reinforced fibers and 8% glass microspheres reinforced thermoplastic polyamide 6,6 *(Courtesy of ETS Inc.)*

The polymer is melted prior to gas introduction in the injection-molding barrel. Then the gas is injected into the polymer during the screw rotation. The nitrogen or carbon dioxide gas dissolves in the molten polymer. After it is fully dissolved, it is kept under pressure by controlling the screw position and by shutting off the nozzle of the injection-molding press and by employing valve gates when hot runner tools are used. The next step includes nucleation, where a large number of nucleation sites are formed throughout the resin during the injection-molding process. A substantial and rapid pressure drop is necessary to create the large number of uniform sites. Thereafter, cell growth is controlled by processing conditions, including precise control of the molding pressure and temperature.

The process generally offers a 50–75% improvement in key quality measures such as flatness, roundness, and warpage while also eliminating all sink marks. Sink marks result when uniform stress patterns, rather than a nonuniform stress characteristic, are created in the molded part in a solid part that was not foamed. Parts produced in this way tend to comply better with the dimensional specifications as a direct result of the uniform stress and shrinkage that occurs because the pack-and-hold phase of the molding cycle is eliminated. Table 1.3 shows the weight reduction achieved using the MuCell® for an engine cover used in a 3.5 liter V-6 engine.

Similar weight saving was realized for the OM651 diesel engine by Daimler, replacing 10% by weight glass fiber reinforced and 20% by weight mineral filled, heat stabilized polyamide 6 with 10% by weight glass fiber and 10% by weight iM16K glass bubbles (see Figs. 1.13 and 1.14). Also, the for new passenger side rear quarter panel for General Motors' Chevrolet Corvette C7 molded by Continental Structural Plastics, a Teijin Holdings USA company using Class A compatible Tough Class A (TCA) Ultra Lite sheet molding compound reinforced with 3M iM16K glass bubbles reduced the panel weight by 35% (see Fig. 1.15).

Table 1.3 Weight Reduction Achieved Using Glass Microspheres in Combination with Glass Fibers for the Polyamide 6,6 Used in the Engine Cover versus 20% Glass Reinforced PA 6,6 *(Courtesy of 3M Company)*

Polymer	20% Glass Reinforced Polyamide 6,6	18% Glass Reinforced + 8% Glass Microsphere Polyamide 6,6	Change (%)
Process	Classic injection molding	MuCell® injection molding	
Flexural Modulus (MPa)	4,233	3,712	−12
Flexural Strength (MPa)	158	128.5	−18
Tensile Strength (MPa)	88	66.2	−25
Elongation (%)	4.9	5.7	+16
Notched Izod (J/m^2)	3,962	3,046	−23
Density (g/cm^3)	1.27	1.029	−
Weight Reduction			+19

Glass bubbles have the ability to produce lightweight thermoplastic parts with improved dimensional stability.

Figure 1.13 Mercedes-Benz engine cover for in-line four-cylinder diesel engine OM651 molded using a polyamide 6 reinforced with glass fibers and iM16K glass bubbles PA6 achieving a weight reduction of 20% versus the previous polyamide reinforced with glass fibers only *(Courtesy of 3M Company)*

Figure 1.14 Mercedes-Benz engine cover assembled on OM651 engine *(Courtesy of 3M Company)*

Figure 1.15 Passenger side rear quarter panel for Chevrolet Corvette C7, fabricated by Continental Structural Plastics, a Teijin Holdings USA company, using Class A compatible TCA (Tough Class A) ultra lite sheet molding compound reinforced with 3M iM16K glass bubbles *(Courtesy of 3M Company)*

■ 1.6 Additives

Additives are used to improve specific properties of the plastic material. Flame retardants, thermal stabilizers, and UV stabilizers are some examples (Table 1.4).

Table 1.4 The Influence Additives Have on Polymer Properties

Additive Type	Max Content	Modulus	Impact	Strain	Dimensional Stability	Flammability
Aramid fibers	20	Better	Lower	Lower	Lower	Better
Antistatic agents	5	Lower	Much lower	Much lower	No effect	No effect
Elastomers	15	Lower	Excellent	Much better	Lower	Lower
Glass fibers	60	Excellent	Lower	Much lower	Lower	Better
Inorganic flame retardants	40	Lower	Worst	Much lower	Better	Excellent
Minerals	40	Better	Lower	Lower	Much better	Better
Organic flame retardants	20	Lower	Much lower	Much lower	Better	Excellent
UV stabilizers	1	Lower	Lower	Lower	No effect	No effect

■ 1.7 Physical Properties

Density, specific gravity, elasticity, plasticity, ductility, toughness, brittleness, notch sensitivity, isotropy, anisotropy, water absorption, and mold shrinkage are important physical properties we will be exploring.

1.7.1 Density and Specific Gravity

Density is a measure of the mass per unit volume, expressed in pounds per cubic inch or grams per cubic centimeter. Table 1.5 shows densities for various polymers.

Table 1.5 Typical Density Values for Polymers

Material	Density (g/cm³)	Density (lb/in³)
ABS	1.05	0.0382
ABS GR	1.2	0.0433
Acetal	1.4	0.051
Acetal GR	1.6	0.0582
Acrylic	1.2	0.0433
Cast epoxy	1.8	0.0655
Phenolic	1.85	0.0673
Polyamide (PA)	1.15	0.0415
Polyamide (PA) GR	1.35	0.0487
Polyamide imide	1.55	0.0564
Polycarbonate (PC)	1.2	0.0433
Polycarbonate GR	1.45	0.0523
Polyester (PET, PBT)	1.14	0.0415
Polyester GR	1.63	0.0588
Polyethylene	0.9	0.0325
Polyphenylene oxide (PPO)	1.08	0.0393
Polyphenylene sulfide (PPS)	1.55	0.0564
Polypropylene (PP)	0.9	0.0325

Material	Density (g/cm³)	Density (lb/in³)
Polypropylene (PP) GR	1.1	0.0397
Polysulfone (PSU)	1.25	0.0451
Polystyrene (PS)	1.05	0.0382
Polyvinyl chloride (PVC), rigid	1.35	0.491
Polyvinyl chloride (PVC), flexible	1.25	0.0451
Styrene acrylonitrile (SAN)	1.07	0.0389
Styrene acrylonitrile (SAN) GR	1.28	0.4657

Specific gravity is the density of a material divided by the density of water. This is a dimensionless measurement.

Both density and specific gravity are used in determining part weight and cost (Fig. 1.16).
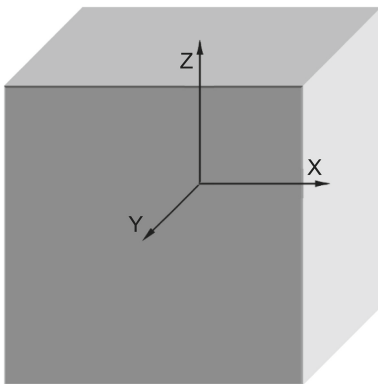
Figure 1.16
Unit volume to calculate density and specific gravity

1.7.2 Elasticity

Elasticity is the ability of a material to return, partially or completely, to its original size and shape after being deformed (Fig. 1.17). Materials that recover fully to their initial size are perfectly elastic. Those that partially recover are partially elastic.
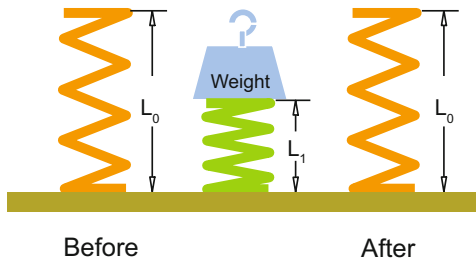
Figure 1.17
Elasticity

Before   After

The elastic region for thermoplastic or thermoset material is a very important domain for linear analysis. Brittle materials show generally reduced elastic domains. Rubber and thermoplastic elastomers have excellent elasticity.

1.7.2.1 Case History: Elasticity and Denier

Denier is a term derived from the old French word *denier*, which stands for silver or copper coins that were used in France until 1794. It also represents the measurement that is used to identify the *fiber thickness* or diameter of individual filaments used in the creation of textiles. Initially, the term was applied mainly to natural fibers, such as silk and then cotton. Over time, the unit of thickness for synthetic fibers such as polyester and nylon also came to be identified with the same term. The denier, used as textile unit, describes the density of yarn. A 9,000-meter strand of yard that weighs exactly a gram has a density of one denier.

A company from the state of Ohio manufactures playpens for infants (see Fig. 1.18). The playpen incorporates a baby mattress which originally used a 300 denier fabric to cover it. Then later, to save money during the manufacturing process (a few pennies per yard or meter of the finished fabric), it reduced the 70/30 polyester-cotton filament blend used to weave the fabric from 300 to 100 denier, thus making the covering mattress material non-breathable.

A baby girl, Abigail, was dropped off in 2010 by her grandparents to a day-care center in the morning. Later that morning, the seven-month-old infant was placed into a playpen to rest. About an hour later, the day-care personnel found Abigail dead, face down, in the playpen. Later, during the civil court trial, it was determined that the baby girl suffocated on the mattress (see Fig. 1.19).

Figure 1.18 Playpen
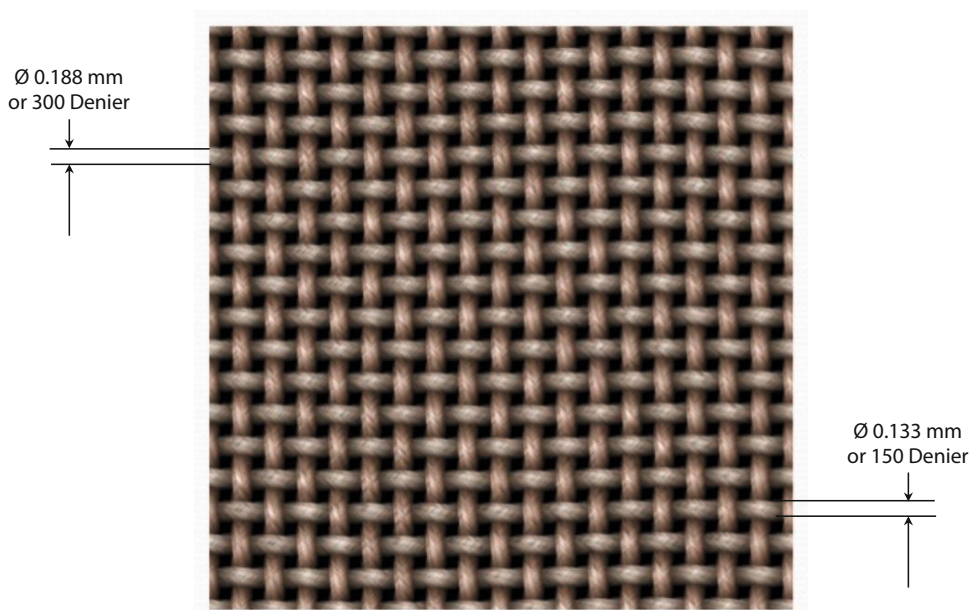
Figure 1.19 Detail of playpen mattress fabric

The 100 denier fabric uses a very thin diameter yarn, comparable to the yarn used to manufacture cargo parachutes for the U.S. Army, as specified in the Parachute Industry Association commercial specification 7350 from April 2007. The 100 denier fabric is very elastic because its fibers have small diameter, allowing a much tighter weaving process as compared with 300 denier filaments. However, this fabric quality was decreased because the manufacturing company chose to place an im-

print on the material which covered the interfilament spaces between fibers (see Fig. 1.20) [207].
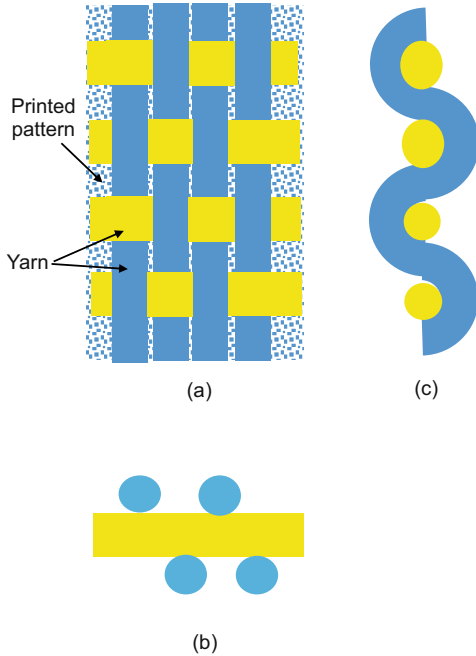
Figure 1.20
Ink printed fabric: (a) top view;
(b) perpendicular cross-section;
(c) parallel cross-section

At the end of the civil trial the jury found the mattress pad defective and the manufacturer of the playpen guilty for the wrongful death, awarding Abigail's parents a multimillion dollar verdict. Now her parents' goal is that no other baby should have the same fate; they are lobbying to change the law so that all playpen manufacturers use only breathable fabrics for their mattresses.

1.7.3 Plasticity

Plasticity is the property of a material to preserve the shape or size to which it is deformed (Fig. 1.21). Plasticity occurs when the stress goes beyond the yield point on the stress-strain curve for any given material.
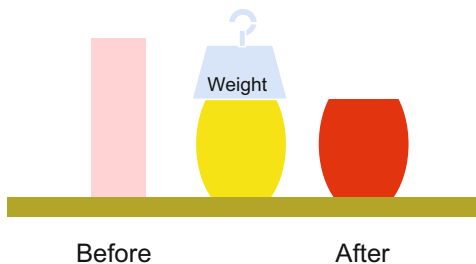
Figure 1.21
Plasticity

This material property can be utilized in cold-forming processes for some plastics. Increases in temperature greatly affect plasticity, especially in thermoplastic resins.

1.7.4 Ductility

The material's ability to be stretched, pulled, or rolled into shape without destroying its integrity is called *ductility* (Fig. 1.22). Polymers are categorized as ductile or brittle at a given temperature. Typical failure of ductile polymers occurs when molecules slide along or over each other. This causes large elongation, usually with necking down of the cross-sectional area, and breakage.
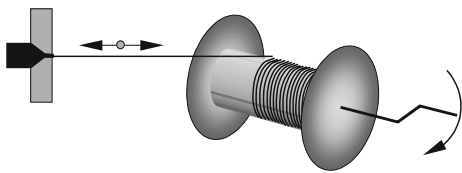
Figure 1.22
Ductility

1.7.5 Toughness

Toughness is the ability of polymeric materials to absorb mechanical energy without fracturing. This is done with either elastic or plastic deformation. Toughness is often measured as the area under the stress-strain curve, as in Fig. 1.23.

(a)

(b)
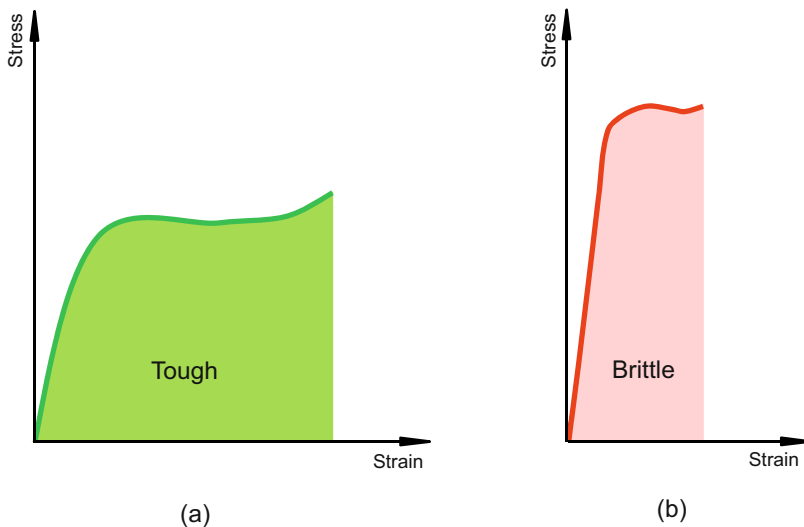
Figure 1.23 Toughness: (a) tough material; (b) brittle material

1.7.6 Brittleness

Brittleness is the property of polymeric materials that fracture easily when absorbing mechanical energy (Fig. 1.24). Many reinforced plastics are brittle and therefore show lower impact and higher stiffness properties.
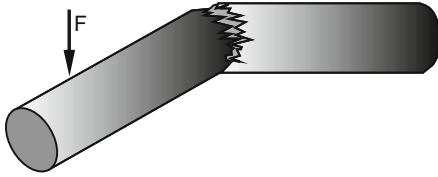
Figure 1.24
Brittleness

1.7.7 Notch Sensitivity

Notch sensitivity is the ease of crack propagation through a material from a preexisting notch, crack, or sharp corner (Fig. 1.25). Excessive stress concentrations can occur as a result of three types of conditions: grooves and holes, changes in the cross-sectional area brought about by shoulders or offsets, and various mounting methods. To account for stress concentration areas, a stress concentration factor k has been established.
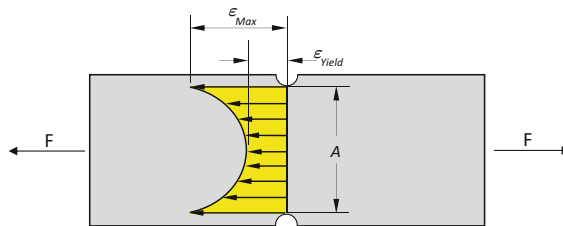
Figure 1.25 Notch sensitivity created by grooves and holes

For example, let's consider a plate as shown in Fig. 1.26. In the course of designing a part, we need to determine the ideal fillet between two right-angle surfaces that will allow us to avoid a sharp corner. In order to determine the transition radius r the following steps should be followed.

Let's assume that D is the part thickness and d is the thickness of the thinner portion. Then d/D is the ratio of the two thicknesses. The appropriate curve d/D should be selected from the lower graph (Fig. 1.26). If none is available in Fig. 1.26, a d/D curve is established by graphic interpolation. Then a fillet radius, r, is selected.

Next, the ratio r/d is calculated.

The calculated ratio r/d is then located on the horizontal axis (Fig. 1.26, lower). A vertical line from that point is drawn to intersect with the corresponding d/D curve.

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