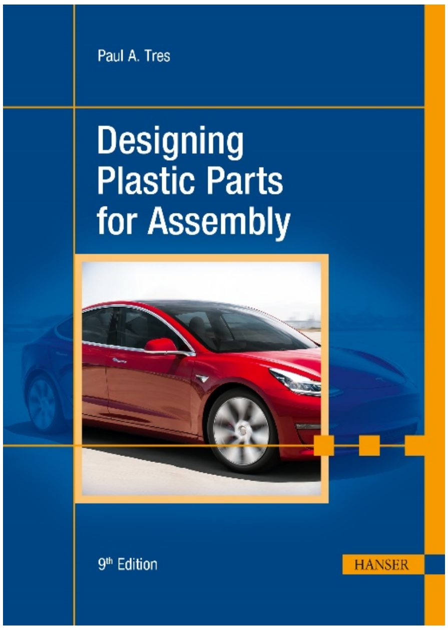
HANSER



Sample Pages

Designing Plastic Parts for Assembly

Paul A. Tres

ISBN (Book): 978-1-56990-820-4
ISBN (E-Book): 978-1-56990-821-1

For further information and order see

www.hanserpublications.com (in the Americas)

www.hanser-fachbuch.de (outside the Americas)

Foreword to the Ninth Edition

Our use of plastic parts and assemblies continues to grow as the properties of the material grow and as the creativity of their designers generate new innovations. Innovation relies on a solid foundation of knowledge and concepts and *Designing Plastic Parts for Assembly* is a key element of this foundation for the engineer designing in plastic. In the 9th edition Paul Tres adds useful information to keep the reliable reference book up to date with these changes, including detailed failure analysis to avoid future incidents.

In my own company, we have over 30 engineers trained in Mr. Tres' courses and keep several copies of the book on hand. This has served us well as we developed one of the newest plastic assemblies: the Thermal Management Module. This unit involves several types of plastic and fastening methods in a mechatronic assembly that controls the flow of coolant to up to five areas of the car, including cylinder head, engine block, heater, and turbo charger. This allows for a faster warm-up of the engine, improving fuel economy and bringing heat to the passenger compartment quickly in winter!

As you can imagine, such a device has numerous design challenges: all joints and parts must be leak free, the sealing surfaces of the valves are critical, and it must survive wild swings in temperature. It has a challenge for every chapter of *Designing Plastic Parts for Assembly*! As industry continues to advance, it is critical to have resources such as this on which to rely.

Wooster, Ohio *Jeff Hemphill*

2020–2021 President Society of Automotive Engineers (SAE)
Chief Technical Officer, Schaeffler Group USA Inc.

Preface to the Ninth Edition

From the invention of Bakelite to very recent natural fiber-reinforced polymers or wood-reinforced plastics, our life is filled with plastics. Plastics have found their way into our daily life so much that it has become difficult to imagine the world without their presence. From tapes to bottles, pens to books, bicycles to spacecraft, plastics have invaded the way we think about technology and have expanded our horizons of invention, discoveries, and design. With plastics, a strong base has undoubtedly been built for upcoming technologies to survive.

Plastics have shaped many careers, including mine. I am currently working with Tesla Motors Inc. with 14 years of experience as a Mechanical Design Engineer on a Product Launch Team specializing in interiors of vehicles.

Plastics have varied applications. Students and engineers from various fields, wherever plastics are used and applied, and industrial design engineers from every industry would find this book useful as a guide and source of plastic design and assembly knowledge. Understanding the physiology of plastics, the structure of the polymers at a molecular level, their physical, mechanical, thermal, and chemical properties, the effect of different factors like humidity, temperature, chemicals, and UV radiation, etc., is extremely important to obtain the desired results after the parts have been assembled, and for the assembly to function as intended.

This book summarizes various methods of critical plastic assembly like snap-fit design, various types of welding, adhesive bonding, fastening, living hinges, in-mold assemblies, and mating the parts using press fit, etc. The bottom-up approach of creating the machine-assemblies for varied applications has always been the methodology of design and manufacturing. Achieving the correct fit and finish of intended assembly of plastic components for elegance, perceived quality, and ergonomic usage requires in-depth knowledge of the behavioral science of plastics, and the effect of their additives and impurities on the manufacturing process capabilities of the plastics parts. Repeatability and reproducibility are of essence for any manufacturing and assembly process too. This book also covers the statistical and calculative part.

Case studies discussed in this book demonstrate the importance of applications of basic mechanics and first principles. They will guide readers into a world of design applications, the mistakes that industries have committed, and how designers would have been able to avoid those. Appropriate root-cause analyses of the issues lead to improved design iterations. Detailed observations and analysis of design failure cases is exactly what sets this book series apart from any other plastic design book or guides available elsewhere.

Mr. Tres, being an industry veteran, is extremely knowledgeable about plastic molding and assembly processes himself. I've attended his seminar and 3-day course for *"Automotive Plastic Part Design"*. Receiving guidance via his book on the topic is a shear privilege for anyone who wants to work with plastics and their applications. It gives me immense sense of pride to have received guidance from Mr. Tres via his part design courses and books.

I look forward to more of his books on plastic design, manufacturing, and assembly.

Fremont, CA

Neelam Kaswa
Staff Mechanical Design Engineer
Tesla Inc.

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

6 Press Fitting 187

7 Living Hinges 237

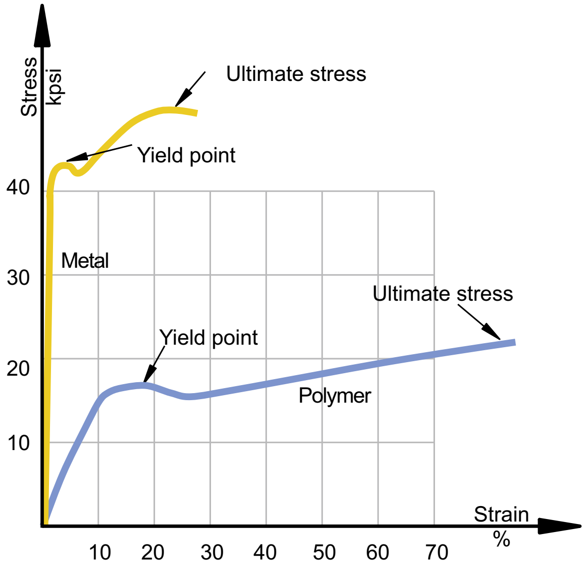


Figure 1.38 Stress-strain curve, metal vs. plastic

1.9 Creep

Plastic parts exhibit two important properties that can occur over long-term loading: creep and stress relaxation.

1.9.1 Introduction

When a constant load is applied to a plastic part, it induces an internal stress. Over time, the plastic will slowly deform to redistribute the internal energy within the part. A test that measures this change is performed by applying a constant stress over time. This time-related flow is called *creep*.

1.9.2 Creep Experiments

Figure 1.39 shows a creep experiment in which a specimen bar is held vertically from one end. The original length of the bar is L. When a weight is hooked at the free end of the bar, the load will immediately increase the length by an amount expressed as ΔL at time = 0.

If the weight is left on the part for some time–for example, 1 year or 5 years–the end of this time period is called time = end. During this time the specimen bar will elongate further. This further increase in length, which is brought about by the time factor rather than the weight, is called *creep.*

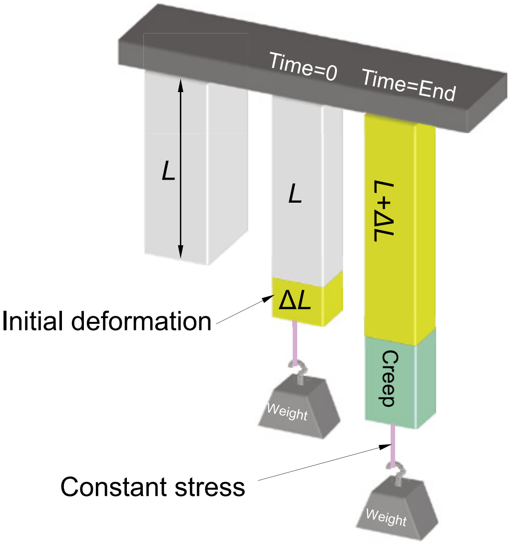


Figure 1.39 Creep experiment

1.9.3 Creep Curves

One of the best ways to demonstrate creep properties is through the use of isochronous stress-strain curves (Fig. 1.40). Most of these are generated from several test samples, each under a different degree of constant stress. After the appropriate load is applied, the elongation of each sample is measured at various time intervals. The data points for each time interval are connected to create isochronous stress-strain curves. Because material properties are also temperature dependent, the temperature must be kept constant throughout the experiment.

Creep modulus is the modulus of a material at a given stress level and temperature over a specified period of time. Creep modulus is expressed as

$$E_C = \frac{\text{Stress}}{\text{Total Strain at time} = \text{end}} \tag{1.4}$$

Creep modulus is also called *apparent modulus* [188, 189]. These curves are usually derived from constant-stress isochronous stress-strain curves. The curves are plots of the creep (apparent) modulus of the resin as a function of time (Figs. 1.41 and 1.42).

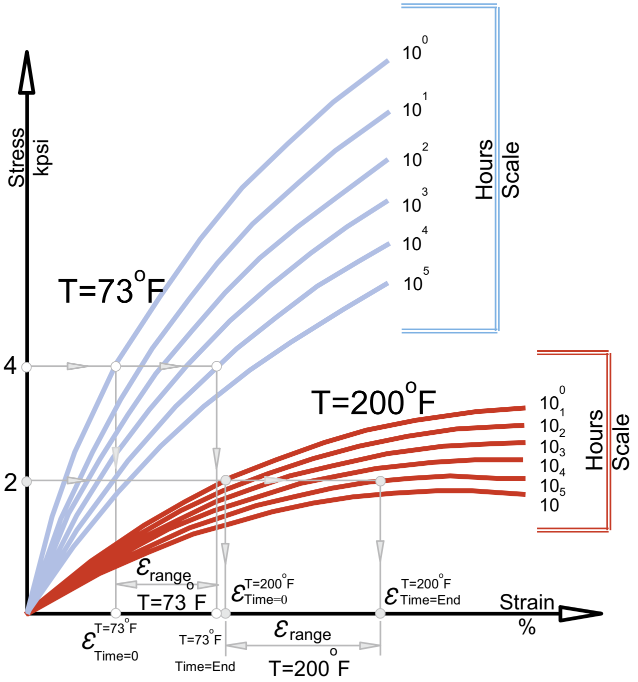


Figure 1.40 Isochronous stress-strain curves

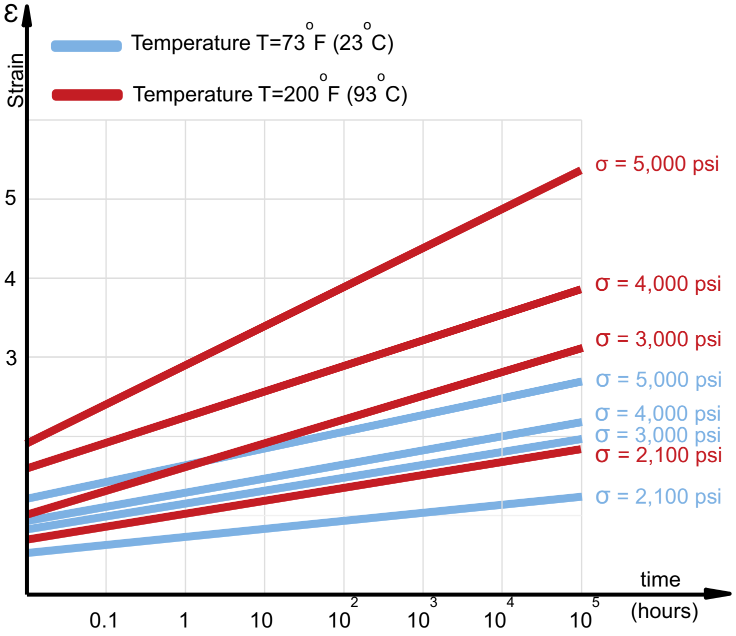


Figure 1.41 Constant stress, strain vs. logarithmic time

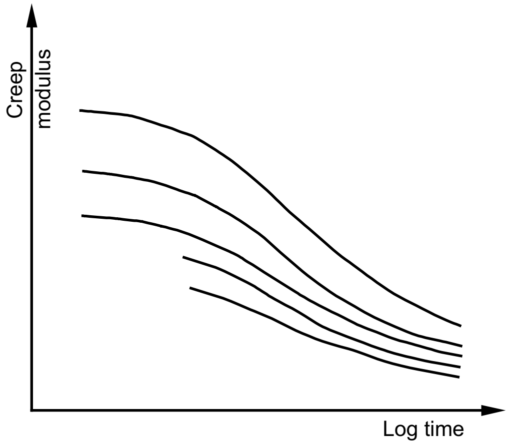


Figure 1.42
Apparent (creep) modulus

1.9.4 Stress-Relaxation

If the plastic part is subjected to a constant strain (or elongation) over time, the amount of stress necessary to maintain that constant elongation will decrease. This phenomenon is known as *stress-relaxation*.

Figure 1.43 shows a stress-relaxation experiment. It is very similar to the creep experiment except that the weight of the load varies, decreasing over time as needed to maintain $L + \Delta L$ at a constant length. The variance of the weight in an idealized case should be continuous with instantaneous measurements. Because this is not always possible, creep curves can be used if stress-relaxation curves are not available. In most cases a margin of error of 5–10% is acceptable.

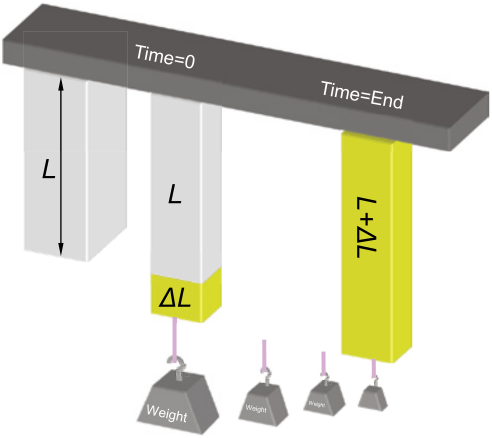


Figure 1.43
Stress-relaxation experiment

Stress-relaxation can be described as a gradual decrease in stress levels with time, under a constant deformation or strain.

2

Understanding Safety Factors

2.1 What Is a Safety Factor

The safety factor is a measurement of a product's ability to perform throughout its life expectancy. Ideally, after the life expectancy has been reached, the product should fail.

The safety factor of a bridge, for example, might be quantified with the number 10, while the safety factor of an aircraft could be 4. A bridge might be expected to perform over hundreds or even thousands of years, while an airplane's life expectancy is considerably less. It should be noted that an aircraft with a safety factor of 10 would never leave the ground. Also, the precision of the product must be taken into account. Aircraft parts are built to very precise tolerances, while a bridge's tolerances are comparatively high.

The safety factor is a coefficient the wise engineer has to take into consideration when designing a part. This coefficient gives assurance that a part will not fail under any operating conditions. In addition, it is proof that the material has been chosen correctly for those operating conditions. It also covers imperfections from processing of this material until it becomes a finished part. Safety factors can be divided into several categories:

- design factor
- material property safety factor
- processing safety factor
- operating condition safety factor

It is important to note that these categories are interrelated, and that continuing feedback to the design stage with regard to these safety factors is necessary.

2.2 Using the Safety Factors

2.2.1 Design Safety Factors

This is the most important category, largely because the designer requires input from all other categories. Material properties, processing, and operating conditions must all be considered by the designer.

At the design stage the engineer will start by choosing a material and designing the part to withstand external loading. If the finished product is expected to work under various adverse operating conditions, the engineer will perform stress-analysis calculus in order to ensure that the finished part will not fail throughout its life cycle. Depending upon the type of loading that will be applied to the finished part, design safety factors can be broken down into the following categories:

- design static safety factor
- design dynamic safety factor
- design time-related safety factor

Safety factors from other categories can be added at this stage.

NOTE: In the following design factor formulae, stress was chosen for convenience. Related strain or forces can also be used.

2.2.1.1 Design Static Safety Factor

When external loads are applied statically, a relatively simple calculation is performed and the safety factor is related to material allowable/permissible stress.

2.2.1.2 Design Dynamic Safety Factor

For cases where external loads are applied intermittently or in cycles, and the material is subjected to fatigue, safety factors will be higher than static ones and design stresses will be lower.

2.2.1.3 Design Time-Related Safety Factor

Creep and stress-relaxation are the most common time-related effects on thermoplastic polymers and are a major factor in determining the life expectancy of the product. In order to forecast the life expectancy, we can apply the theory that *initial design safety factor decreases with time.*

$$n = \frac{\sigma_{\text{Ultimate}_{\text{time=end}}}}{\sigma_{\text{Allowable}_{\text{time=end}}}} \tag{2.1}$$

In Fig. 2.1 the initial design (time = 0) safety factor n is greater than 1. Safety factor n reaches 1 when the product fails (time = end).

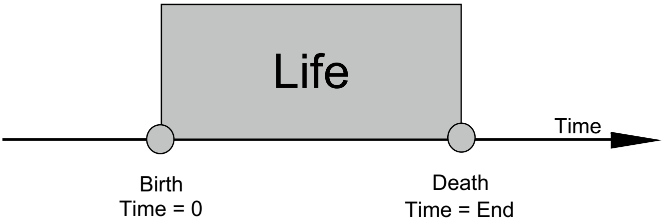


Figure 2.1 Creep

Product life expectancies vary between industries. Some products are expected to be completely rebuilt or replaced after 10 years; others may be replaced after less than one year. The safety factor is therefore determined by the norms (specifications) of the industry.

For a new product in a new industry with no established product life expectancies, testing the product and measuring the stress level for failure can determine a safety factor. These values, measured against original material properties, will provide a good starting point for establishing time-related safety factors.

2.2.2 Material Properties Safety Factor

If a safety factor can be estimated from experience, testing, or any other reliable means, then the maximum allowable stress is defined as:

$$\sigma_{\text{Allowable}} = \frac{\sigma_{\text{Yield}}}{n} \tag{2.2}$$

For snap-fitting and press-fitting calculations the material safety factor is based on yield stress (or strain) because it is more accurate for the elastic region.

$$n_{\text{SnapFit/PressFit}} = \frac{\sigma_{\text{Yield}}}{\sigma_{\text{Allowable}}} \tag{2.3}$$

For living-hinge calculations the material safety factor is based on ultimate stress.

$$n_{\text{Living Hinge}} = \frac{\sigma_{\text{Ultimate}}}{\sigma_{\text{Allowable}}} \tag{2.4}$$

This is more accurate for visco-elastic properties where large displacements and plastic deformation often occur.

The two safety factors mentioned take into account the following characteristics:

- imperfections of the material
- inclusions
- voids
- RH content

3.7 Poisson's Ratio

Provided the material deformation is within the elastic range, the ratio of lateral to longitudinal strains is constant, and the coefficient is called *Poisson's ratio* (v, nu).

$$\nu = \frac{\text{Lateral strain}}{\text{Longitudinal strain}} \tag{3.11}$$

In other words, stretching produces an elastic contraction in the two lateral directions. If an elastic strain produces no change in volume, the two lateral strains will be equal to half the tensile strain times minus one (–1).

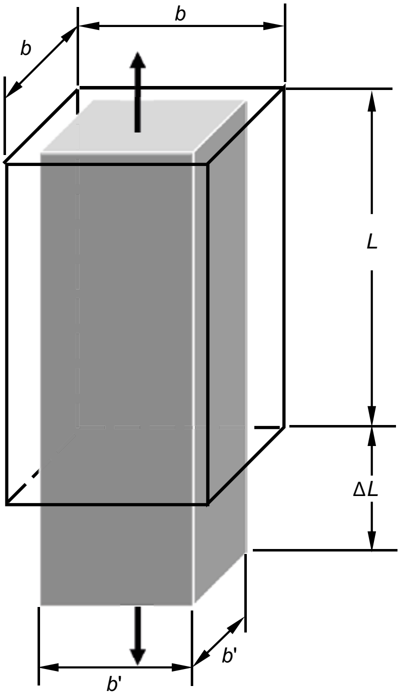


Figure 3.10
Dimensional change in only two of three directions

Under a tensile load, a test specimen increases (decreases for a compressive test) in length by the amount ΔL and decreases in width (increases for a compressive test) by the amount Δb. The related strains are:

$$\varepsilon_{\text{Longitudinal}} = \frac{\Delta L}{L}$$

$$\varepsilon_{\text{Lateral}} = \frac{\Delta b}{b} \tag{3.12}$$

Poisson’s ratio varies between zero (0), where no lateral contraction is present, to half (0.5) for which the contraction in width equals the elongation. In practice there are no materials with Poisson’s ratio zero or half.

Table 3.1 Typical Poisson’s Ratio Values for Different Materials

Material Type	Poisson’s Ratio at 0.2 in./min (5 mm/min) Strain Rate
ABS	0.4155
Aluminum	0.34
Brass	0.37
Cast iron	0.25
Copper	0.35
High-density polyethylene	0.35
Lead	0.45
Polyamide	0.38
Polycarbonate	0.38
13% glass-reinforced polyamide	0.347
Polypropylene	0.431
Polysulfone	0.37
Steel	0.29

The lateral variation in dimensions during the pull-down test is

$$\Delta b = b - b' \tag{3.13}$$

Therefore, the ratio of lateral dimensional change to the longitudinal dimensional change is

$$\nu = \frac{\frac{\Delta b}{b}}{\frac{\Delta L}{L}} \tag{3.14}$$

Or, by rewriting, the Poisson’s ratio is

$$\nu = \frac{\varepsilon_{\text{Lateral}}}{\varepsilon_{\text{Longitudinal}}} \tag{3.15}$$

3.8 Modulus of Elasticity

3.8.1 Young's Modulus

The *Young's modulus* or *elastic modulus* is typically defined as the slope of the stress/strain curve at the origin.

The ratio between stress and strain is constant, obeying Hooke's Law, within the elasticity range of any material. This ratio is called Young's modulus and is measured in MPa or psi.

$$E = \frac{\sigma}{\varepsilon} = \frac{\text{Stress}}{\text{Strain}} = \text{Constant} \tag{3.16}$$

Hooke's Law is generally applicable for most metals, thermoplastics, and thermosets, within the limit of proportionality.

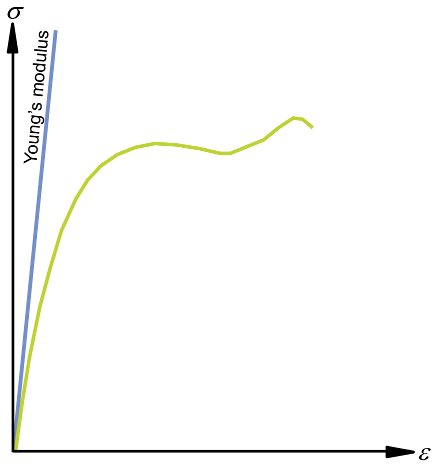


Figure 3.11
Young's modulus

3.8.2 Tangent Modulus

The instantaneous tangent over the elasticity range of a stress/strain curve for a thermoplastic or thermoset material gives a better approximation of the relation between stress and strain. The stress/strain curve of most plastic materials has a curved, elastic range (see Fig. 3.12). In these cases, the use of Young's modulus is difficult and less accurate.

5

Welding Techniques for Plastics

There are many different methods for welding two parts together. All variables, such as materials, design, and conditions under which the finished product will be used, including cost of the process, must be considered when deciding which welding technique should be employed.

Polymers can be melted, and therefore welded, using relatively little energy. Heat, friction—even ultrasonic vibrations and radio frequencies—can be used to create the melting necessary for a polymer weld. Welding methods include ultrasonic welding, ultrasonic heat staking, hot plate welding, spin welding, vibration welding, and laser welding. Welding requires no additional materials with one exception: electromagnetic welding, which requires bonding agent consumables.

5.1 Ultrasonic Welding

The principle behind ultrasonic welding technology is based on vibration. One of the parts being assembled is vibrated against the other, stationary one. Heat generated through vibration melts the materials at the joint interface to accomplish the weld.

Thermoplastics are the only polymers suited for this process. Thermoset materials do not melt when reheated because of their intermolecular cross-links.

5.1.1 Ultrasonic Equipment

The type of equipment required for an ultrasonic welding process depends upon the size of the manufacturing operation. The ultrasonic welding equipment requirements of a large-volume production environment will be different from those of a small prototype operation. They will, however, be very similar in principle.

A typical ultrasonic welding system consists of a power supply, also referred to as an *ultrasonic generator*; a *converter*, also known as a *transducer*; a *booster*; and a *horn* (see Fig. 5.1). The horn is a metal bar designed to resonate at a certain frequency, delivering the actual energy to the parts to be welded. The converter, booster, and horn are mounted inside a frame, which can slide along the stand, allowing them to travel vertically under the power of a pneumatic cylinder. The pressure applied by the air cylinder can be preset for manual systems or fully controlled by a computer for automatic systems. The pressure, trigger pressure, stroke speed, and stroke travel are all adjustable through the control panel or by the computer. The two palm buttons are used by the operator to activate the machine.

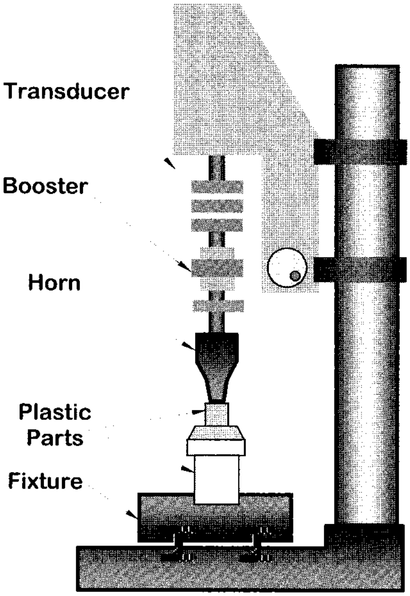


Figure 5.1
Ultrasonic welder

To generate the necessary amount of vibration required for a particular assembly, an electrical current is passed through a stack of crystalline ceramic material that possesses *piezoelectric* properties, which allow the material to change its size. The electric power supply has a frequency of 50 to 60 Hz. Once an electric current is applied, the material expands and contracts at a very high frequency, converting the electrical energy into mechanical energy or vibrations. These vibrations occur with frequencies ranging from 15 to 70 kHz. The most common output in ultrasonic welding systems provides frequencies of 20 to 40 kHz.

The distance the mechanical vibrations travel back and forth is called the *amplitude*. A typical converter of 20 kHz could have amplitudes of 0.013 to 0.02 mm (0.0006 to 0.0008 in.) between its maximum expansions and contractions.

Figure 5.2 Ultrasonic welder HiQ Dialog also includes software to control and operate the welding process and machine functions, having the additional capability of welding visualization in two graphic modes: EasySelect and Expert mode *(Courtesy of Herrmann Ultrasonics)*

There are different types of ultrasonic welding systems for different applications. An integrated welder (see Fig. 5.1) is a self-contained unit, which has a power supply, actuator, and the acoustic components packaged as a stand-alone system. Advantages of this type of system include low investment cost and ease of service.

Modular systems include, in addition to the welder, a rotary indexing table and an in-line conveyor. These systems are ideal for assembling large numbers of parts. Also, their components are interchangeable and easy to upgrade.

For the torsional ultrasonic welding process, the cycle times are comparable to regular axial welding. The system is used for sensitive components such as electronic assemblies, in which integrated circuits are enclosed polymer components assembled with a very thin film or membrane, and automotive crankshaft pulse sensors.

Components designed for this new process can use thinner wall thicknesses because no marks will permeate to the show surface. Typically, the design should incorporate an energy-director joint design even for crystalline polymers. For automotive components such as bumpers, fascias, and even cowl vents, the wall thickness of the actual part can be reduced by as much as 20% when compared to classic axial ultrasonic welding, without marking the automotive painted class-A surfaces, or even molded-in color class-A surfaces.

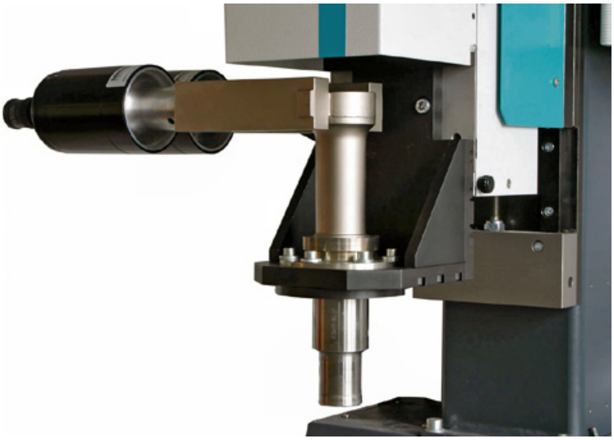


Figure 5.24 Detail of torsional ultrasonic sonotrode

The reduced wall stock results in significant reductions in weight—which nowadays is a major driver in the automotive marketplace due to electrification efforts and the overall injection-molding cycle time necessary to manufacture the part.

Figure 5.25
Painted automotive rocker panels having assembly locators mounted using the Soniqtwist® torsional ultrasonic machine

5.1.4.6 Case History: Welding Dissimilar Polymers

Going to the dentist is an unappealing task for most people, especially those prone to cavities. Cavities mean getting fillings, which traditionally entail a large injection in the gums and then a scary and noisy drill filing away at the molars. German dental equipment manufacturer DMG has developed the dental applicator (Fig. 5.26) called Icon® that should calm many people's fear of going to the dentist.

Figure 5.26 Dental applicator Icon® made by DMG of Hamburg, Germany

DMG's Icon product applies hydrochloric acid directly onto the weak area of the tooth and eats away at the enamel until it reaches the cavity. The therapy uses a light-cured resin that fills the enamel cavities and then is activated by blue light and seals the tooth surface. The technique works very well for early-stage cavities and makes the trip to the dentist a little more appealing.

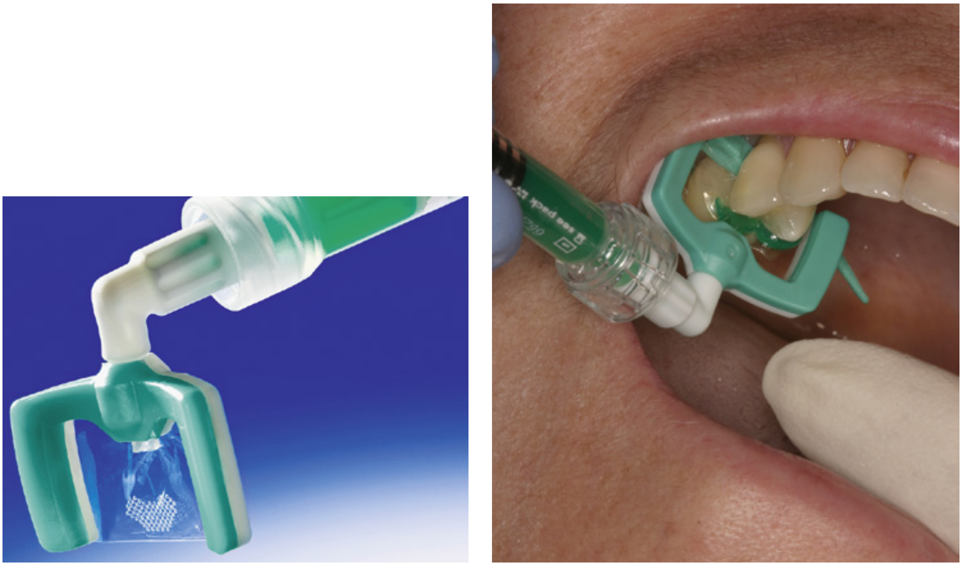


Figure 5.27 Dental applicator (a) detail, (b) detail in use *(Courtesy of Herrmann Ultrasonics)*

The dental applicator uses three polymers assembled with an axial ultrasonic welder. A semicrystalline polyethylene terephthalate (PET) double-layered PET film (called

Hostaphan® and manufactured by Mitsubishi Polyester Film), partially perforated and with a wall stock of about 0.05 mm, is clamped between two halves of a U-shaped frame made of amorphous polystyrene (PS), called Polystyrol®, from BASF (Fig. 5.27(a)).

Figure 5.28 U-shaped frame having four studs and four energy directors *(Courtesy of Herrmann Ultrasonics)*

Ultrasonic welding produces a controlled melt built up to ensure a tight bond with minimal thermal load. The key to properly welding dissimilar crystalline-amorphous polymers (PET/PS) into a homogenous assembly is to program the weld force required to uphold the desired joining velocity. Amorphous resins, like polystyrene in general, are hard and rigid. They require low specific heat and small welding amplitudes, between 10 and 25 microns at a 35,000 cycles per second (Hz) frequency.

Figure 5.29 Frame assembly *(Courtesy of Herrmann Ultrasonics)*

On the other hand, crystalline polymers—like PET film—are softer, tougher, and can generally withstand higher temperatures, thus requiring higher specific heat to disrupt the resin structure. This is accomplished by employing larger amplitudes in the welding cycle.

The major components of the vibrator are shown in Fig. 5.61. They are a set of flat springs, two electromagnets, a vibrating element (drive platen), and a clamping mechanism. The springs have three functions: to act as resonating members, to support the vibrating element against vertical welding pressures, and to return the vibrating element to the aligned position when the magnets are de-energized.

The vibrating element engages and holds the plastic part to be vibrated; the stationary element holds the other part of the assembly. Pressure is applied to the parts by a pneumatically operated clamping mechanism that engages the stationary element or tray. This locks onto the vibrator housing and pulls the part against the vibrating element during the welding cycle.

The vibrator is mounted on a frame that incorporates a power supply and a tray lift mechanism, forming a complete plastic assembly system. The modular construction of the vibration welder also allows the individual components to be used in a variety of automated systems.

Fixtures for vibration welding are usually simple and inexpensive. They generally consist of aluminum plates with cutouts that conform to the geometry of the part or countered cavities of cast urethane. Depending on the part size, two or more parts can be welded at the same time using a multicavity fixture.

5.8.3 Joint Design

Vibration welding calls for some specific design requirements. Two of the most important are that the parts be free to vibrate relative to one another in the plane of the joint and that the joint can be supported during welding.

The basic joint design for vibration welding is the simple butt joint (Fig. 5.62). A flange is generally desirable unless the wall is sufficiently rigid or supported to prevent flexure. A flange also makes it easier to grip the parts and apply uniform pressure close to the weld.

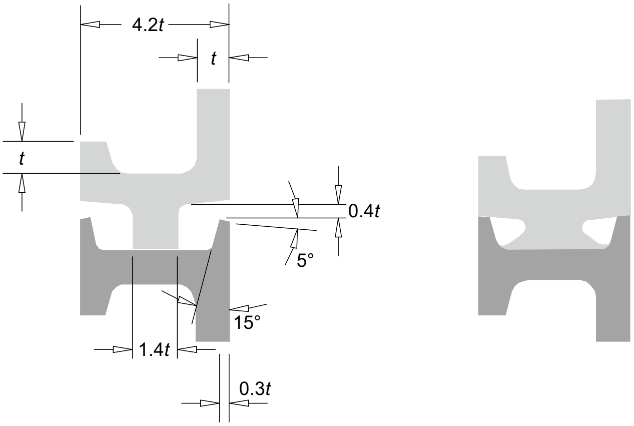


Figure 5.62
Vibration welding joint design detail: (a) before, and (b) after assembly

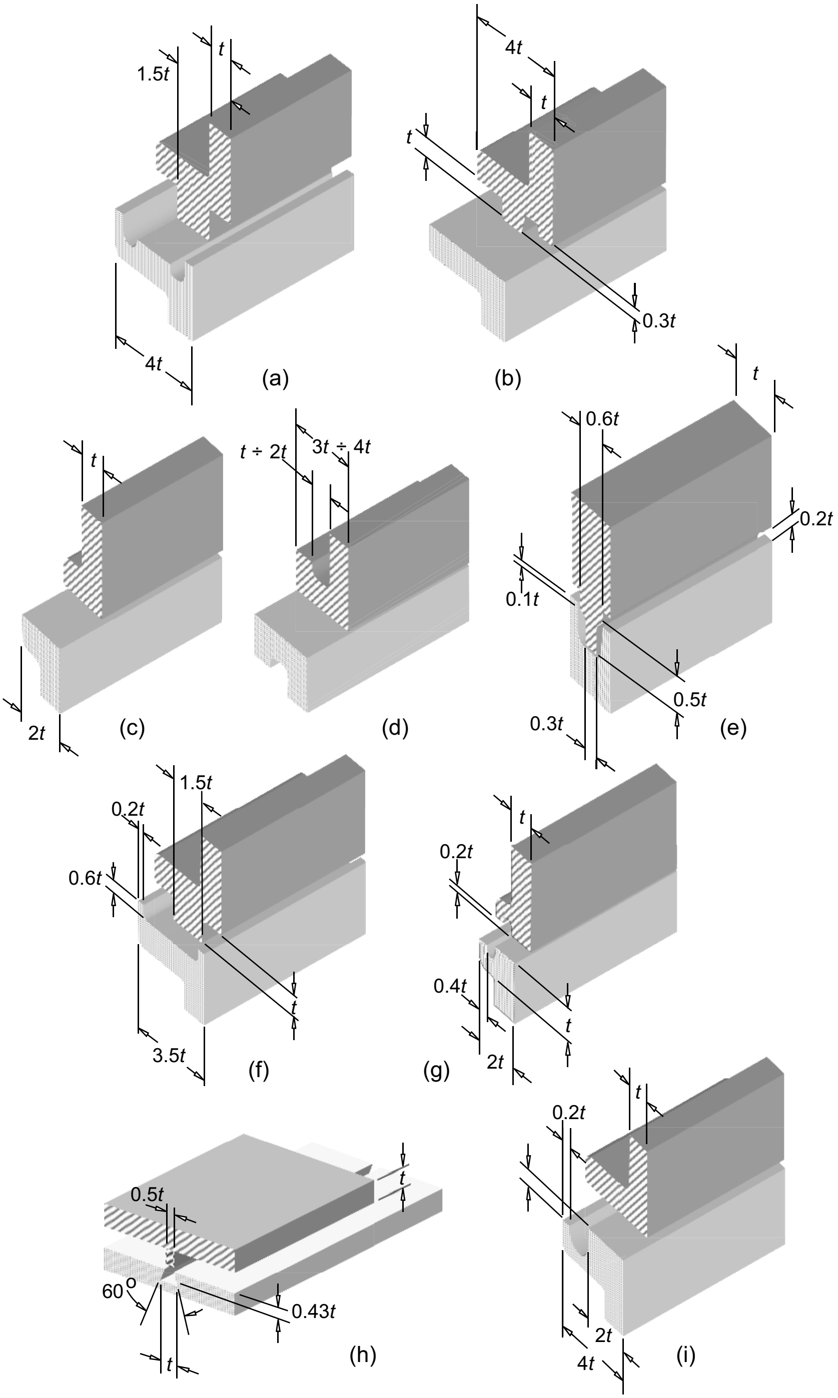


Figure 5.63 Vibration welding joint designs: (a) bench with flash traps; (b) straight bench; (c) tongue-and-groove; (d) double L; (e) ridged double L; (f) grooved bench; (g) double L with flash traps; (h) dovetail; (I) double L with single flash trap.

6.7 Press Fit Theory

Equations developed by the French mathematician Lamé are used to define the contact pressure at the interface between the assembled parts. These equations apply specifically to thick-wall cylinders.

A. In a room temperature 23°C (73°F) case, the surface contact pressure at the interface is

$$p_c = \frac{i}{\frac{R_i}{E_{\text{Hub}}}\left(\beta + \nu_{\text{Hub}}\right) + \frac{R_i}{E_{\text{Shaft}}}\left(1 - \nu_{\text{Shaft}}\right)} \tag{6.4}$$

The insertion force required to assemble the components is

$$\mathrm{F}_{\text{In}} = 2\pi\mu h R_{\text{Shaft}}\, p_c = \mathrm{F}_{\text{Out}} \tag{6.5}$$

Transmitted torque is determined as a function of the insertion force (6.5) as

$$M = \mathrm{F}_{\text{In}} R_{\text{Shaft}} = 2\pi\mu h R_{\text{Shaft}}^2\, p_c \tag{6.6}$$

It is important to recall that p_c is normal to the shaft and hub surfaces. Therefore,

$$\sigma_{\text{Normal}} = p_c \tag{6.7}$$

The maximum stress, however, is tangential to the surface:

$$\sigma_{\text{Tangential}} = \beta p_c \tag{6.8}$$

where β is the geometric factor described in 6.1.

The condition required to have a proper press fit assembly is that the yield strength of the polymer should be greater than the tangential stress present at the common surface between the two parts, i.e.:

$$\sigma_{\text{Yield}} > \sigma_{\text{Tangential}} \tag{6.9}$$

In 6.9 when the *greater than* sign is replaced with the *equal* sign, the maximum interference is determined:

$$i_{\text{Maximum}} = 2R_{\text{Shaft}} \frac{\sigma_{\text{Yield}}}{\beta}\left[\frac{\beta + \nu_{\text{Hub}}}{E_{\text{Hub}}} + \frac{1 - \nu_{\text{Shaft}}}{E_{\text{Shaft}}}\right] \tag{6.10}$$

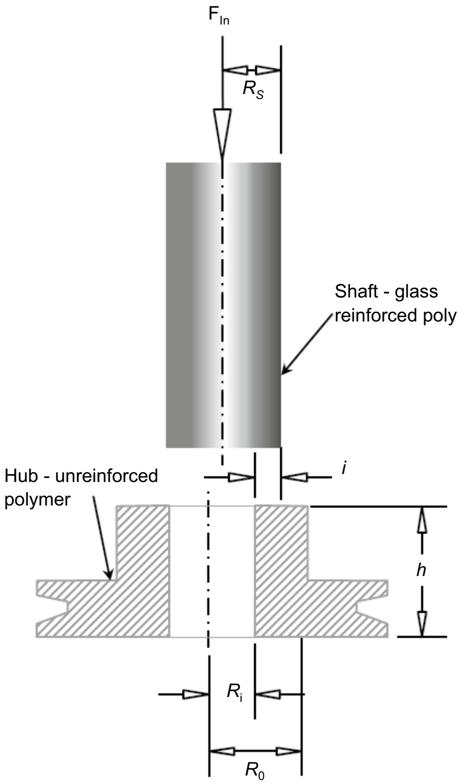


Figure 6.2
Shaft and hub before assembly

B. During operation, the temperature increases due mostly to friction. The interference will vary with the operating temperature. Above room temperature the total interference is

$$i^T = 2\left(R_o^T + R_i^T\right) \tag{6.11}$$

The shaft radius will change with temperature. So R_{Shaft}^T becomes

$$R_{\text{Shaft}}^T = R_{\text{Shaft}}\left(1+\alpha_{\text{Shaft}}\Delta T\right) \tag{6.12}$$

The hub radius will experience similar change:

$$R_{\text{Hub}}^T = R_{\text{Hub}}\left(1+\alpha_{\text{Hub}}\Delta T\right) \tag{6.13}$$

The initial interference was

$$i = 2\left(R_s - R_i\right) \tag{6.14}$$

Using 6.12, 6.13, and 6.14, the total interference required at a given temperature T (6.11) becomes:

$$i^T = i - 2R_{\text{Shaft}}\Delta T\left(\alpha_{\text{hub}} - \alpha_{\text{Shaft}}\right) \tag{6.15}$$

Elastic strain

$$W = \frac{2\left[2t\left(1-\nu\varepsilon_{\text{Tension}}\right)-h\right]\sigma_{\text{Yield}}}{\left[\pi t\left(2-\nu\varepsilon_{\text{Tension}}+l\right)-Y\right]E} \tag{7.95}$$

7.8 Example: Case History

This section will examine the actual cases of two plastic components that use living hinges. The first is a world-class connector, an automotive under-hood component that connects the onboard computer to the engine controls. The second case involves a bracket that organizes ignition cables between the spark plugs and the distributor. Two materials and designs will be analyzed for each case.

7.8.1 World-Class Connector

The original design consisted of three parts assembled. To reduce assembly labor costs, inventory, handling, and shipping costs, a new design was considered using living hinges, so that the three former components could be molded as one piece.

The material with the best properties for living hinges is PP. But this material is not able to survive the under-the-hood environment where temperatures of 250 to 300°F and possible spills of various chemicals such as gasoline and oil are commonplace. Therefore, the designer had to consider other plastic materials. The first to be considered was polyamide, which can withstand the temperatures and chemicals of the under-the-hood environment.

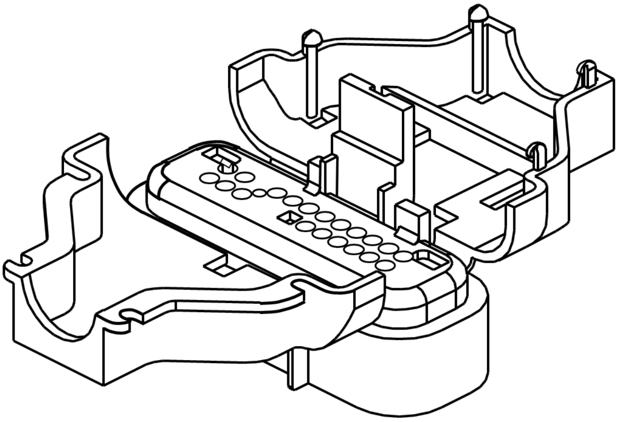


Figure 7.14
World-class connector (axonometric view)

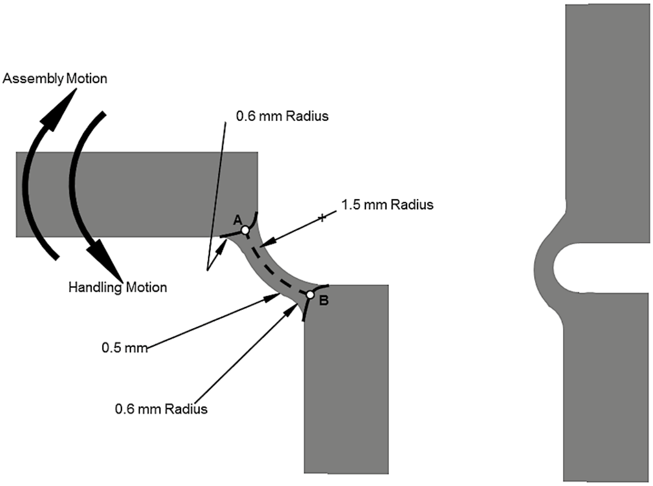
Another requirement of the connector was that it withstand packing and transportation from the molding facility to the final electric component assembly. In transit, some connectors suffered breakage. Panels broke from the component when hinges cracked as a result of asymmetrical hinge design. The polyamide material was failing in this application because the panels, by moving through different positions during shipping, were causing the material to reach its elongation-at-break point.

A new material had to be considered. Polyester elastomer thermoplastic was chosen.

7.8.1.1 Calculations for the "Right Way" Assembly

To examine the details of the living hinge design and the materials used in this analysis, we will begin with what is called the "right way" assembly. The two panels in Fig. 7.15 are moved in the direction designated "right way" in Fig. 7.16. The panels rotate 90°, but point A on the hinge only needs to rotate 45°.

The analysis of the hinge in the example that follows begins by using the thermoplastic elastomer properties. Next, the polyamide case will be reviewed.



(a) (b)

Figure 7.15 Hinge design detail: (a) as molded; (b) as assembled

Material properties for a PET elastomer are

σ_{Ultimate} = 50 MPa Tensile strength at break

σ_{Yield} = 40 MPa Tensile strength at yield

$E_{\text{Secant Yield}}$ = 236.5 MPa Secant modulus for the yield point ($E_{S_{\text{Yield}}}$)

$\varepsilon_{\text{Ultimate}}$ = 39.7% Ultimate strain (elongation at break)

$\varepsilon_{\text{Yield}}$ = 9.1% Yield strain

ν = 0.45 Poisson's ratio

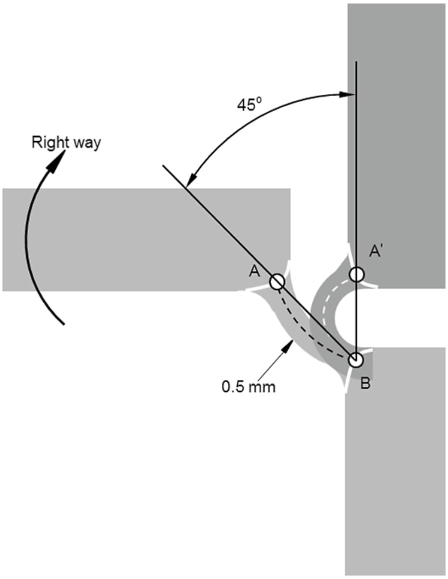


Figure 7.16
"Right way" assembly hinge detail

The values for hinge thickness, length, and recess for this design are

$X = 0.5$ mm	Hinge thickness
$Y = 2.748$ mm	Hinge length
$Z = 0.0$ mm	Hinge offset or recess

The aim of the analysis that follows is to determine if the design is robust or not. To initiate the analysis, A is calculated, which represents the length of a fully elastic hinge. If $A < Y$, we will have a total elastic hinge. For a 45° bend angle ("right way" assembly), the value for A is

$$A = \frac{\pi t E_{S_{\text{Yield}}}}{4\sigma_{\text{Yield}}} = 1.16 \text{ mm} \tag{7.96}$$

$$A < Y \tag{7.97}$$

The 1.16 mm is the length necessary to have a completely elastic hinge.

Once a pure elastic hinge has been established, other hinge properties can be calculated:

Hinge radius

$$R = \frac{\pi t}{\sigma_{\text{Yield}}} = 2.74 \text{ mm} \tag{7.98}$$

Hinge maximum strain takes place in bending:

$$\varepsilon_{\text{Bending}} = \frac{\pi t}{L_1} = 0.071 = 7.1\% \tag{7.99}$$

9 Bonding

There are bonding techniques employing two types of consumables: adhesives and solvents.

Adhesive bonding is an assembly process by which two parts are held together through surface attraction, also known as mechanical interlocking. The adhesive itself is a substance capable of adhering to the surface of the parts being bonded, developing strength after it has been applied and, afterwards, remaining stable. It can be described as a specific interfacial tension phenomenon. A useful way to classify adhesives is by the way they react chemically after they have been applied to the surfaces to be joined.

The principle of *solvent* bonding, on the other hand, consists of applying a liquid solvent that dissolves the surfaces of the joint area. Once the solvent evaporates, the parts are assembled by applying a small pressure in the joint area.

There are many adhesives and solvents available. The task of selecting the best adhesive or solvent for any given bonding application is a difficult one.

9.1 Failure Theories

There are two types of failure for bonded joints: adhesive failure and cohesive failure.

Adhesive failure refers to a bonded assembly that fails because the adhesive peels away from one or both of the surfaces it was supposed to hold together (Fig. 9.1(b)). In most bonded applications it is an unacceptable failure. It can also be defined the same way when both the substrate and the bonded joint would fail at the same time.

Cohesive failure represents the breakage of the adhesive used for the bonded joint. On both components, the surface of the bonded joint after failure would have adhesive remnants visible. Cohesive failure also refers to the dual failure of the polymer being bonded and the adhesive—both failures occuring at the same time (Fig. 9.1 (a)). While adhesive failure is considered unacceptable, cohesive failure is the preferred failure.

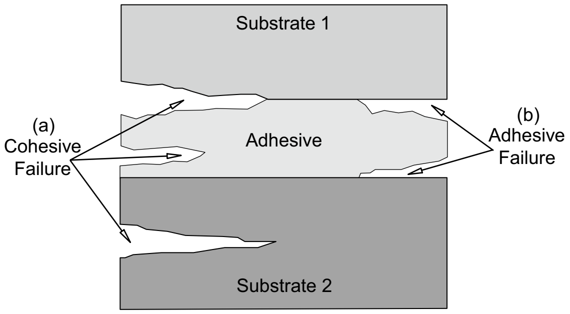


Figure 9.1
Failure theories: (a) cohesive, (b) adhesive

9.2 Surface Energy

A characteristic called *wetting* is an important element in both the adhesive and solvent bonding processes. Wetting refers to the intimate contact between the liquid solvent or adhesive consumables and the surface of the polymer. Good wetting occurs when there is strong attraction between the parts and the liquid.

Table 9.1 Surface Energy of Various Materials (Expressed in dynes/cm or 0.001 N/m)

SOLIDS (dynes/cm)	LIQUIDS	SURFACE TENSION (dynes/cm)
100+ (metals, glass, ceramics)		100
80	Water	72
	Glycerol	63
	Formamide	58
47	Phenolic	
46 (PA)		
43 (PET)		
42 (PC, ABS)		
39 (PVC)		
38 (PMMA)		
37 (PVA)		
36 (POM)		
33 (PS, EVA)		

SOLIDS (dynes/cm)	LIQUIDS	SURFACE TENSION (dynes/cm)
31 (PE)	Cellosolve	30
29 (PP)	Toluene	29
	N-Butanol	25
	Alcohol	22
18	Fluoropolymer	

Polymers in general are difficult to bond. As Table 9.1 shows, metals, ceramics, and glass are the materials that are easiest to bond succssssfully. Plastics, on the other hand, have surface energies required for bonding much lower than metals, glass, and ceramics. Thermoplastic nylon, also known as polyamide (PA), exhibits the highest *surface energy,* of 46 dynes/cm. Polypropylene (PP) is the worst thermoplastic polymer to bond–nothing sticks to it. Its surface energy is less than 30 dynes/cm.

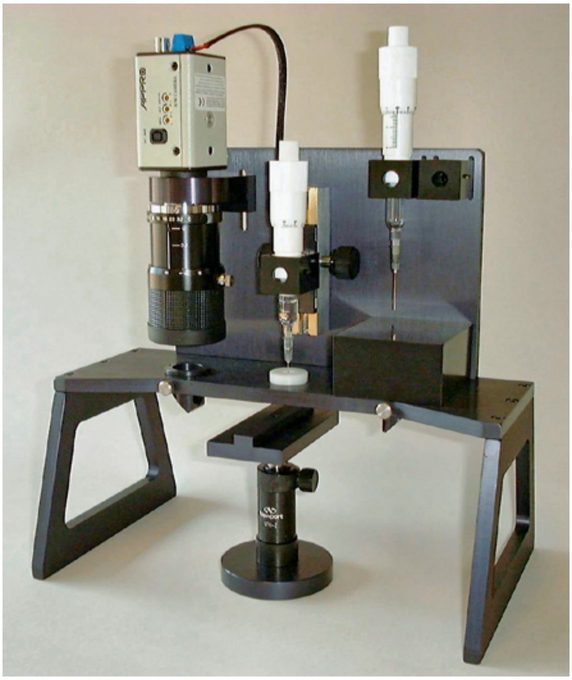


Figure 9.2
Contact angle goniometer instrument

Reinforcements, fillers, additives, pigments, dyes, and flame retardants all play a role in modifying the polymer surface energy. To properly measure the exact surface energy of the polymer, an instrument called the “contact angle *goniometer*” (see Fig. 9.2) can be used. The device measures the angle between the tangent to surface of the thermoplastic material and the tangent to the curvature of a drop of distillated water placed on the polymer surface. If the angle between the two tangents is less than 60°, then the surface energy of the thermoplastic to be bonded is excellent (see Fig. 9.3(b)). However, if the same angle is greater than 90°, that means that the surface of the polymer being bonded has extremely low surface energy and additional steps to improve it are required, as will be discussed in Section 9.3.

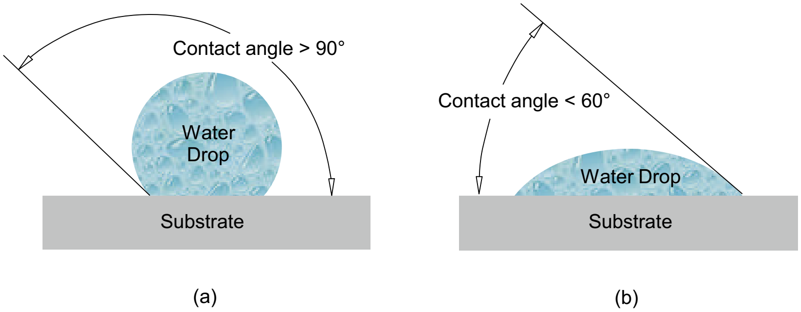


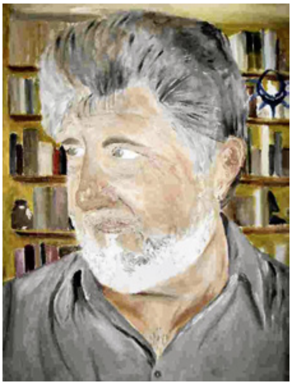
Figure 9.3 Surface energy: (a) poor surface energy (wettability), and (b) good wettability

Another technique for determining precisely the surface energy of the thermoplastic polymer, when a contact angle *goniometer* instrument is unavailable, involves a liquid ink set. The test liquids come in sets from as little as six to as many as 24 small bottles, each with a specific dynes per centimeter label designation.

Fluid from the bottle is applied to the surface of the thermoplastic material to be bonded, with the small brush mounted inside the cap (Fig. 9.4). If the test liquid draws back into droplets in less than 1 second after it has been applied, then the surface energy of the polymer substrate is lower than that of the fluid itself. The exact surface energy *(dyne level)* is determined by subsequently applying a range of increasing or decreasing values of dyne test inks until the fluid spreads like a film over the plastic surface. The label designation on the bottle will indicate the polymer surface energy level.

Figure 9.4 Set of dyne test liquids containing 12 fluid bottles ranging from 30 to 72 dynes/cm

About the Author
Paul A. Tres



Serving the plastics and automotive industries for over 40 years, Mr. Paul A. Tres, a Senior Consultant with ETS, Inc. *(www.ets-corp.com)* in Bloomfield Hills, Michigan, has provided consulting services to global companies, expert witness services for attorneys, and also trained over the years in excess of 18,000 designers, engineers, and managers in the intricacies of plastic part design.

Some of the global companies served include: *Advanced Green Technologies* of Fort Lauderdale, FL; *Automotive Components Holding* of Dearborn, MI; *B/E Aerospace* of Lenexa, KS; *Belimo Holding AG* of Hinwil, Switzerland; *Briggs & Stratton* of Wauwatosa, WI; *Bombardier Recreational Products* of Valcourt, QC, Canada; *BorgWarner* of Warren, MI; *Caravan Global* of La Mirada, CA; *Conmed Corporation – Electrosurgery* of Utica, NY; *Continental Automotive Systems* of Auburn Hills, MI and Guadalajara, Jalisco, México; *Design Concepts of Niagara Ltd.* of Gasport, NY; *Dexterity Design* of Salt Lake City, UT; *Donaldson Company* of Bloomington, MN; *Dow Chemical* of Midland, MI; *Exide Technologies GmbH* of Büdingen, Germany; *Ford Motor Company* of Dearborn, MI; *General Motors Technical Center* of Warren, MI; *Georgia-Pacific LLC* of Atlanta, GA; *Hewlett-Packard* of Vancouver, WA and Corvalis, OR; *Honda of Canada Manufacturing* of Alliston, Ontario, Canada; *Honda R&D America* of Marysville, OH; *Hoosier Windows* of Fort Wayne, IN; *Hunt Manufacturing Company* of Statesville, NC; *Invest in France Agency* of Chicago, IL; *Johnson Controls* of Holland, MI and Madison, WI; *Kostal North America* of Troy, MI; *Leggett & Platt Automotive* of Lakeshore, Ontario, Canada; *Medallion Instrumentation System* of Spring Lake, MI; *Mercedes-Benz US International* of Tuscaloosa, AL; *Meritor* of Troy, MI; *Nyco Minerals* of Willsboro, NY, *Plastics Omnium* of Troy, MI and Anderson, SC; *Pelco by Schneider Electric* of Clovis, CA; *Philips Sonicare* of Bothell, WA; *Siemens* of Münich, Germany; *Solvay* of Brussels, Belgium and Adrian, MI; *Southco* of Concordville, PA; *Super Cool Products* of Elmhurst, IL; *TRW* of Washington, MI; *Tyco Electronics Corporation* of Menlo Park, CA; *Uni-Solar Ovonic* of Troy, MI; *Valeo* of Auburn Hills, MI; *Visteon* of Plymouth, MI; *WL Gore & Associates* of Newark, DE; and *Yazaki North America* of Monterrey, Nuevo Leon, México.

Some of the attorneys include: *Bamberger, Foreman, Oswald & Hahn, LLP* of Indianapolis, IN; *Bowmann and Brooke LLP* of San Jose, CA; *Brobeck, Phleger & Harrison LLP* of Washington, DC and Los Angeles, CA; *Cash, Krugler & Fredericks LLC* of Atlanta, GA; *Carcione, Cattermole, Dolinski, Stucky, Markowitz & Carcione, LLP* of San Mateo, CA; *Conroy, Simberg, Ganon, Krevans, Abel, Lurvey, Morrow & Scheffer, PA* of West Palm Beach, FL; *Cozen O'Connor* of Chicago, IL; *Dickinson-Wright PLLC* of Detroit, MI; *Finnegan, Henderson, Farabow, Garrett & Dunner, LLP* of Washington, DC; *Foley, Barron & Metzger PLLC* of Livonia, MI; *Fulmer & Fulmer PA* of Lakeland, FL; *Griffin & Szipl, PC* of Arlington, VA; *Kreis, Enderle, Callander & Hudgins PC* of Kalamazoo, MI; *Krupnick, Campbell, Malone, Buser, Slama, Hancock, Liberman & McKee* of Fort Lauderdale, FL; *Larkin, Axelrod, Ingrassia & Tetenbaum, LLP* of Newburgh, NY; *LeClair Ryan, PC* of San Francisco, CA; *Leydig, Voit & Mayer, Ltd.* of Chicago, IL; *Lynn, Jackson, Shultz & Lebrun, PC* of Sioux Falls, ND; *Morgan Lewis* of Washington, DC; *Notaro, Michalos & Zaccaria, PC* of New York, NY; *Nurenberg, Paris, Heller & McCarthy Co. LPA* of Cleveland, OH; *Ropers Majeski Kohn Bentley PC* of San Jose, CA; *Rymer Moore Jackson Echols, PC* of Houston, TX; *Sellars, Marion & Bachi, PA* of West Palm Beach, FL; *Slater & Zurz* of Akron, OH; *The Law Office of Clay M. Barnes, LLC* of Towson, MD; *Tierney Law Offices* of Philadelphia, PA; *VanAntwerp, Monge, Jones & Edwards, LLP* of Ashland, KY; *Weltman, Weinberg & Reis Co., LPA* of Cincinnati, OH; and *Wilson Kehoa Winingham LLC* of Indianapolis, IN.

Some of the companies which benefited from the plastics training provided include: *Alabama Industrial Development Training* of Montgomery, AL; *Alcatel Lucent* of Mesquite, TX; *BASF* of Wyandotte, MI; *Bombardier* of Valcourt, QC, Canada; *BorgWarner* of Auburn Hills, MI; *Briggs & Stratton* of Milwaukee, WI; *Brose North America* of Auburn Hills, MI; *Cobasys* of Springboro, OH; *Daimler Trucks North America* of Portland, OR; *FCI Automotive* of Westland, MI; *Ferro Corporation* of Evansville, IN; *FIK International* of Mumbai, India; *Hyundai America Technical Center Inc. (HATCI)* of Superior Township, MI; *Holley Performance Products* of Bowling Green, OH; *Honda of Canada Manufacturing* of Alliston, ON, Canada; *Inergy Automotive Systems* of Troy, MI; *Japanese Business Systems* of Torrance, CA; *Kostal North America* of Troy, MI; *Lutron Electronics* of Coopersburg, PA; *Maytag - subsidiary of Whirlpool Corporation* of Newton, IA; *Minnesota Mining and Manufacturing Company* of Saint Paul, MN; *Pall Gelman Laboratories* of Ann Arbor, MI; *Mann+Hummel Purolator Filters LLC* of Fayetteville, NC; *Sogefi Engine Systems USA Inc.* of Rochester Hills, MI; Technimark of Asheboro, NC; *The First Years* of Avon, MA; *TRW Vehicle Safety Systems* of Washington, MI, *Tyco Electronics* of Menlo Park, CA; *Unisys Corporation* of Plymouth, MI; *Valeo Thermal Systems Business Group* of Auburn Hills, MI and Paris, France; and *WL Gore and Associates* of Newark, DE. The plastic training was conducted in many countries, among them: Canada, France, Germany, India, Korea, Malaysia, México, Thailand, and United States of America.

Paul Tres is a Fellow of the Society of Plastics Engineers. He is also a member of the Society of Automotive Engineers, American Society of Mechanical Engineers, and Plastics Academy.

Index