Robert A. Malloy

Plastic Part Design for Injection Molding

An Introduction

2nd Edition

Sample Chapter 5:
Prototyping and Experimental Stress Analysis

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5 Prototyping and Experimental Stress Analysis

5.1 Prototyping Plastic Parts

It is generally best to develop both models and prototype parts during the plastics product development process. The prototyping stage of product development is crucial to the success of a project, yet this aspect of development is often hurried through or underfunded. Prototype parts are used for communications, engineering studies, market studies/promotions, to evaluate product manufacturability/assembly characteristics, and to verify CAD model or print accuracy. Regardless of the medium chosen, prototyping techniques generate physical models that act as a primary means of communication between Product Marketing, Product Engineering, Tooling and Product Manufacturing groups. The use of a prototype to describe the function, size, shape, feel and look of a part inevitably leads to a more productive environment and a higher degree of interaction between the members of the product design team.

5.1.1 Introduction

Prototype parts have been characterized as being either (i) facsimile prototypes, which can serve both marketing and perhaps limited engineering functions, or (ii) processing prototypes, (i.e., those produced using prototype injection molds or tools), which are used to evaluate both the molding process and the molded part properties, before production tooling is fully committed [1, 2]. It is likely that at least one, or perhaps a series of facsimile prototypes (i.e., form and limited fit/function prototype parts) would have been made before one commits to the cost of preproduction or prototype tooling. The latter step can add significant time and initial cost to the process of product development. However, this step is necessary when working with new and unfamiliar materials, complex product geometries, structural parts, or tighter tolerance applications, since the *function* and *fit* of a molded plastic product are strongly influenced by the tool design and the manufacturing and injection molding conditions. Preproduction tool trial results allow the mold designer to fine tune the production mold design, and provide the design team with a potentially large number of nearly real life prototype parts, which may be required for marketing or engineering studies. It is important to note here that the use of computer aided process simulation software for injection molding has reduced the need for prototype tooling to a significant degree. Filling, cooling, shrinkage and warpage analysis packages are providing answers that were previously available only through actual molding trials [3]. A well designed simulation study will provide information on weld line locations and potential part weaknesses, possible gas traps, part warpage or internal (molding) stress levels as described in Chapter 2. The results obtained using this approach are of course simulated, and are often used in concert with prototype tooling to optimize the design of the process and product. The simulation packages, at a minimum, reduce the need for major production tool modifications.

Figure 5.1 shows the relative cost of a design change with time. Design changes made early in the product design cycle have minimal impact on overall cost. Design changes made late in the product development cycle can be extremely expensive and increase time to market.

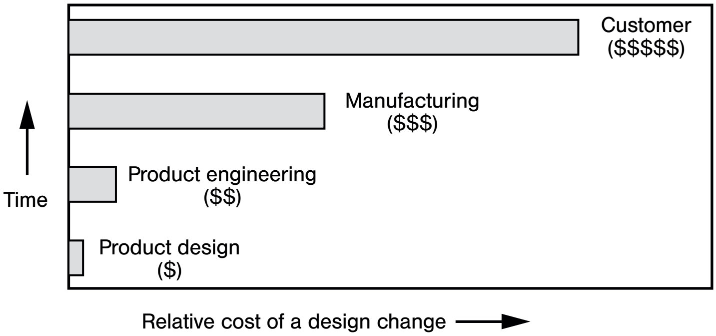


Figure 5.1 Relative cost of a design change with time

There are literally dozens of methods that can be used to produce prototype plastic parts or assemblies. The method(s) that is best for a given application depends on the quantity of prototype parts required, the size of the parts, the budget and time available, and perhaps most importantly, on how true to life the prototype must be in terms of its engineering functions. Common plastic prototype part production techniques include:

- Hand fabrication and machining of prototypes
- Photo polymerization prototyping
- Laser sintering
- Automated filament extrusion
- Laminated object manufacturing
- 3 D printing
- Polymer casting
- Molding prototypes using die cast tooling
- Molding prototypes using soft tooling
- Molding prototypes using pre-production tooling
- Structural foam prototyping

Virtually any prototyping technique can be used to produce a part that is esthetically pleasing, however, only pre-production or prototype molding techniques provide true to life information on product performance, moldability, and dimensional tolerances. The chemical, mechanical, electrical, thermal, and dimensional characteristics of molded plastic parts are influenced by both the primary and secondary processing operations, indicating that product performance should ideally be evaluated using the production material formulation and the primary/secondary operations to be used in production. At some point, the costs and time associated with prototype development work of this type can exceed realistic levels, and one must generally rely on simulations or less realistic prototyping methods. The safety factors used in design are directly influenced by the confidence the designer has in the prototyping and experimental test methods that have been used over the course of the product development cycle.

5.1.2 Machined and Fabricated Plastic Prototypes

Conventional machining operations such as drilling, sawing, milling or turning, and to a lesser extent grinding, are commonly used to produce prototype plastic parts. Cast, laminated or extruded plastic rod, sheet, or bar stock (i.e., semi-finished goods) can be machined to produce a plastic part or component. In many cases, these plastic parts are assembled, bonded, or in some way merged with other plastic, wood, or metal parts before they are decorated and finished to produce a final product assembly [1, 4–6].

Machined plastic prototypes can be produced to high degrees to an accuracy of ±0.025 mm or better can be achieved, provided one follows proper machining practices for plastic materials [1]. Suggested machining practices for various plastic materials are given in Table 5.1 [7]. Several general concepts should also be taken into consideration when machining plastic materials since the machining characteristics of plastic materials are very different than those of metallic materials. Some of these considerations include:

- Plastics are good insulators, and the work pieces can become hot during machining. The hot part's dimensions can be significantly different from the final equilibrium values, since many plastics have high thermal expansion coefficients. Localized heat causes expansion in the cutting area and can result in overcuts, undercuts, and even degradation.

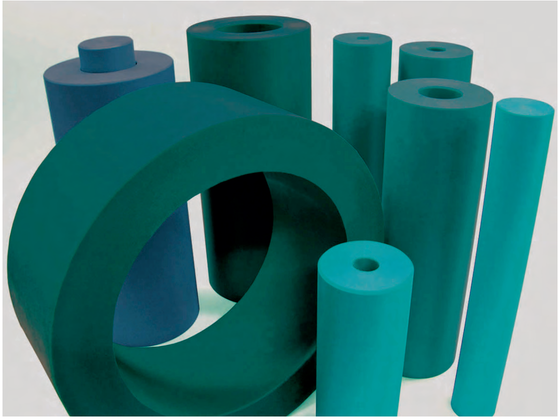


Figure 5.2 Semi-finished thermoplastic rod and sheet stock serve as the raw material for machined plastic prototypes

Table 5.1 Machining variables for some common thermoplastics

Material	Variable	Sawing (Circular)	Sawing (Band)	Lathe (Turn)	Lathe (Cutoff)	Drilling	Milling	Reaming
Acetals	Speed (sfpm)	4000–6000	600–2000	450–600	600	300–600	1000–3000	350–450
	Feed (in/rev)	Fast,smooth	Fast,smooth	0.0045–0.010	0.003–0.004	0.004–0.015	0.004–0.016	0.0055–0.015
	Tool	HSS,carbide	HSS	HSS,carbide	HSS,carbide	HSS,carbide	HSS,carbide	HSS,carbide
	Clearance(deg)	20 to 30		10 to 25	10 to 25	10 to 25	10 to 20	
	Rake (deg)	0 (positve)	0 to 15 (positive)	0 to 5 (positive)	0 to 15 (negative)	0 to 10 (positive)	0 to 5	0 to 10
	Point (deg)					90 to 118		
	Cooling	Dry, air jet vapor	Dry, air jet	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor
Acrylics	Speed(sfpm)	8000–12000	8000–12000	300–600	450–500	200–400	300–600	250–400
	Feed (in/rev)	Fast,smooth	Fast,smooth	0.003–0.008	0.003–0.004	Slow,steady	0.003–0.010	0.006–0.012
	Tool	HSS,carbide	HSS	HSS,carbide	HSS,carbide	HSS,carbide	HSS,carbide	HSS,carbide
	Clearance (deg)	10 to 20		10 to 20	10 to 20	12 to 15	15	
	Rake (deg)	0 to 10 (positive)	0 to 10 (positive)	0 to 5	0 to 15 (negative)	0 to 5 (negative)	0 to 5 (negative)	0 to 10 (negative)
	Point (deg)					118		
	Cooling	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet water solution	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor
Fluoroplastics	Speed(sfpm)	8000–12000	5000–7000	400–700	425–475	200–500	1000–3000	300–600
	Feed(in/rev)	Fast,smooth	Fast,smooth	0.002–0.010	0.003–0.004	0.002–0.010	0.004–0.016	0.006–0.015
	Tool	HSS,carbide	HSS	HSS,carbide	HSS,carbide	HSS,carbide	HSS,carbide	HSS,carbide
	Clearance (deg)	20 to 30		15 to 30	10 to 25	20	7 to 15	10 to 20
	Rake (deg)	0 to 5 (positive)	0 to 10 (positive)	0 to 5	3 to 15 (positive)	0 to 10 (negative)	3 to 15 (positive)	0 to 10 (negative)
	Point (deg)					90 to 118		
	Cooling	Dry, air jet, vapor	Dry, air jet	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor
Nylons	Speed(sfpm)	4000–6000	4000–6000	500–700	700	180–450	1000–3000	300–450
	Feed(in/rev)	Fast,smooth	Fast,smooth	0.002–0.016	0.002–0.016	0.004–0.015	0.004–0.016	0.005–0.015
	Tool	HSS,carbide	HSS	HSS,carbide	HSS,carbide	HSS,carbide	HSS,carbide	HSS,carbide
	Clearance (deg)	20 to 30		5 to 10	7 to 15	10 to 15	7 to 15	
	Rake (deg)	15 (positive)	0 to 15 (positive)	0 to 5	0 to 5 (positive)	0 to 5 (positive)	0 to 5 (negative)	0 to 10 (positive)
	Point (deg)					90 to 110 (under 1/2”) 118 over 1/2”		
	Cooling	Dry, air jet, vapor	Dry, air jet	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor
Polyolefins	Speed (sfpm)	1650–5000	3900–5000	600–800	425–475	200–600	1000–3000	280–600
	Feed (in/rev)	Fast,smooth	Fast,smooth	0.0015–0.025	0.003–0.004	0.004–0.020	0.06–0.020	0.006–0.012
	Tool	HSS,carbide	HSS,carbide	HSS,carbide	HSS,carbide	HSS,carbide	HSS,carbide	HSS,carbide
	Clearance (deg)	15		15 to 25	15 to 25	10 to 20	10 to 20	10 to 20
	Rake (deg)	0 to 8 (positive)	0 to 10 (positive)	0 to 15	3 to 15 (positive)	0 to 5 (positive)	0 to 10 (positive)	0 to 10 (negative)
	Point (deg)					90 to 118		
	Cooling	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor	Dry, air jet, vapor

This information is designed as a guideline and is not to be construed as absolute. Because of the variety of work and diversity of finishes required, it may be necessary to depart from the suggestions in the table.

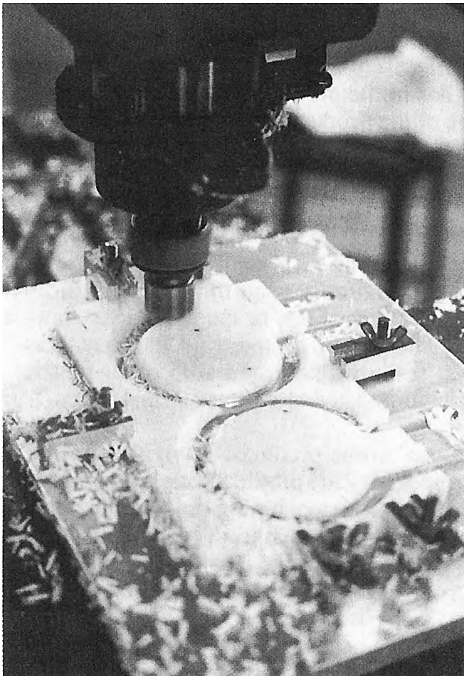


Figure 5.3 CNC machining of prototype plastic parts

- It can also be good practice to stress-relieve the blank or the workpiece at an intermediate stage of machining to relieve any internal extrusion or machining related stresses which could result in part dimensional changes over time or at elevated temperature.
- Heat generated in the workpiece does not dissipate through the piece as quickly as it would with metals, and part temperatures can reach the softening point of the material. However, the use of aggressive coolants should be avoided with some polymers since they could result in stress cracking. Air jets, water mist or spray, water/soap solutions, or water soluble oils may be used cautiously (parts should be examined for evidence of stress cracking). Compressed air cooling offers the additional advantage of avoiding the need for part cleaning after machining.
- It is important to avoid high local stresses and deformation of the workpiece caused by part fixturing and clamping since many plastic materials are relatively soft, while others can be brittle. In some cases, custom fixtures may need to be machined in order to support the plastic part during the machining operation. Double sided tape is sometimes used to fixture the plastic stock.
- Regular high speed tools with sharp cutting edges are acceptable for short runs, however, wide flute tungsten carbide or diamond bit tools are recommended for longer runs. Tools should be kept extremely sharp and have appropriate cutting clearances. All contact surfaces should be highly polished.

Only a limited number of types or grades of plastic materials (perhaps only several dozen) are available in a form that is suitable for machining. Generic groups of materials that are widely available in rod or bar stock include acetals, nylons, flexible and rigid PVC, polycarbonate, ABS, fluoropolymers, and some higher temperature, higher modulus materials such as polyimide and reinforced phenolic laminates. Unfortunately, prototype parts machined from these materials provide no information on processing (i. e., molding) effects. While the machined parts may be geometrically equivalent, they may not perform in the same manner as the production part [4, 5].

The properties of the machined parts are most likely different than their molded counterparts, even when they are made using the same base polymer, since the additives, molecular weights, morphology, processing stresses and orientation levels in the machined part will not be equivalent to those of the molded part. In certain instances, it may be possible to machine or fabricate prototype parts using injection or compression molded plaques produced from the production polymer. While this is a step in the right direction, orientation levels, weld lines, surface characteristics, and other processing related effects will not be equivalent to those of molded prototypes [5]. It suffices to say that the choice of material for the machined prototype is critical and should reflect, as closely as possible, the properties of the polymer to be used in production, however, even then, the results of any test may be misleading since processing related effects are not considered.

Machined prototypes may or may not be expensive depending on the complexity, quality, and quantity required. In some instances, such as when the model will serve as the pattern for a casting mold, only one prototype is required, and machining is a likely candidate process. For simple parts, it may be less expensive to machine even hundreds of units before reaching the breakeven cost for an acceptable quality prototype tool, while more complex parts may break even at fewer than a dozen parts. Computer numerical control (CNC) machining equipment and CAD techniques help reduce the labor costs associated with higher production runs or for parts having complicated geometry, such as the prototype prosthetic part shown in Fig. 5.4. A significant amount of set-up, fixturing, and hand finishing or decorating labor may still be required for each individual part, even when automated machining equipment is used. The method of producing prototype plastic parts by machining dimensional plastic stock for the production of one or more facsimile prototype parts is still used, it is less common compared to the other RP techniques. The technique offers versatility and utilizes raw materials and conventional machining equipment that are readily available.

5.1.3 Some Rapid Prototyping Technologies

There are several technologies available for the manufacturing of prototype plastic parts. These so called *Rapid Prototyping Technologies* are attractive since they link CAD part geometries directly with the prototype part production equipment. These prototyping methods have also been described as *Desktop Manufacturing, Solid Object Manufacturing, Solid Imaging, Free-Form Manufacturing or Automated Fabrication.* The rapid prototyping techniques can produce prototype plastic parts or models in a matter of hours. These processes use a

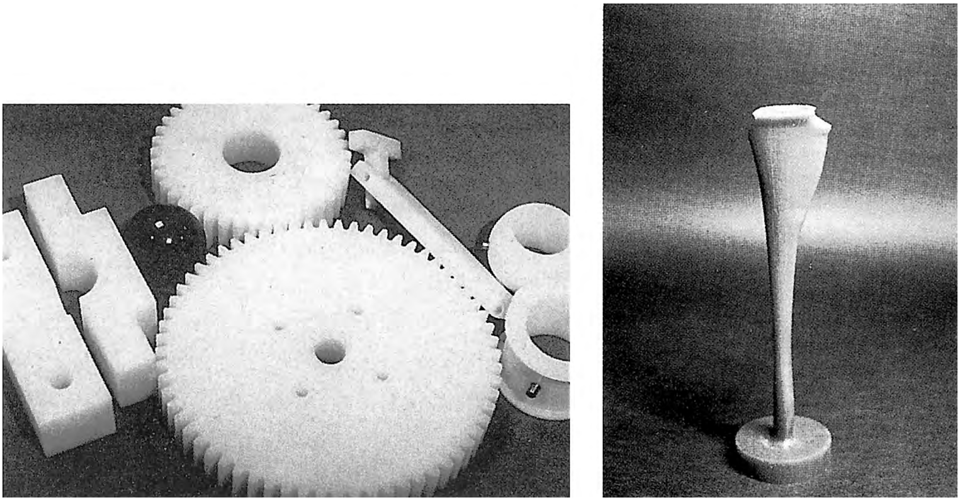


Figure 5.4 (left) Machined plastic parts for a prototype drive assembly, and (right) prosthetic part machined from plastic stock

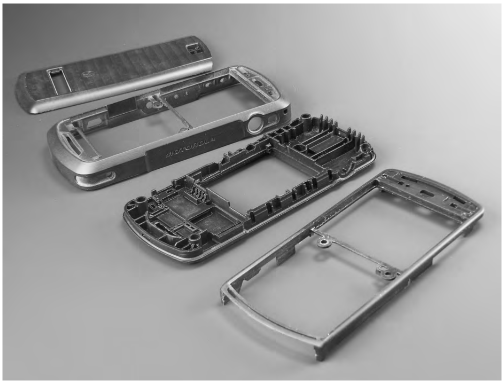


Figure 5.5 Prototype housings for a Motorola smart phone machined from molded blocks of 30 % glass-filled polycarbonate (Courtesy Motorola Rapid Prototyping Services)

variety of different technologies for part production, however, each of these processes have several fundamental concepts in common:

- Defining the part geometry on a CAD system (solid model)
- Slicing the geometric model into discrete 2D slices
- Production of a physical 3D model of product, layer by layer

These prototyping methods can bring an extremely complex design to life as a conceptual facsimile prototype in a relatively short period of time. The rapid prototyping technologies eliminate the potential for misinterpretation (by the model maker), and eliminate the tool

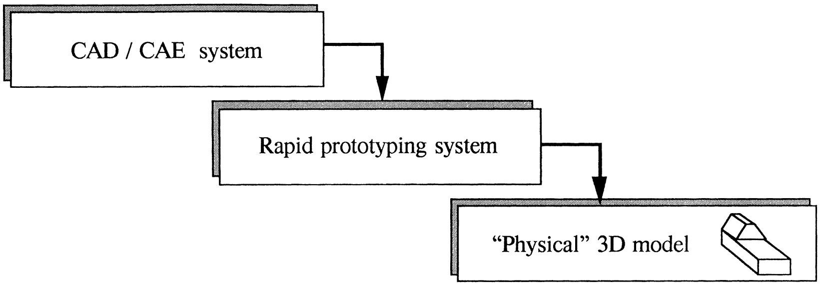


Figure 5.6 Flow chart for rapid prototyping technologies

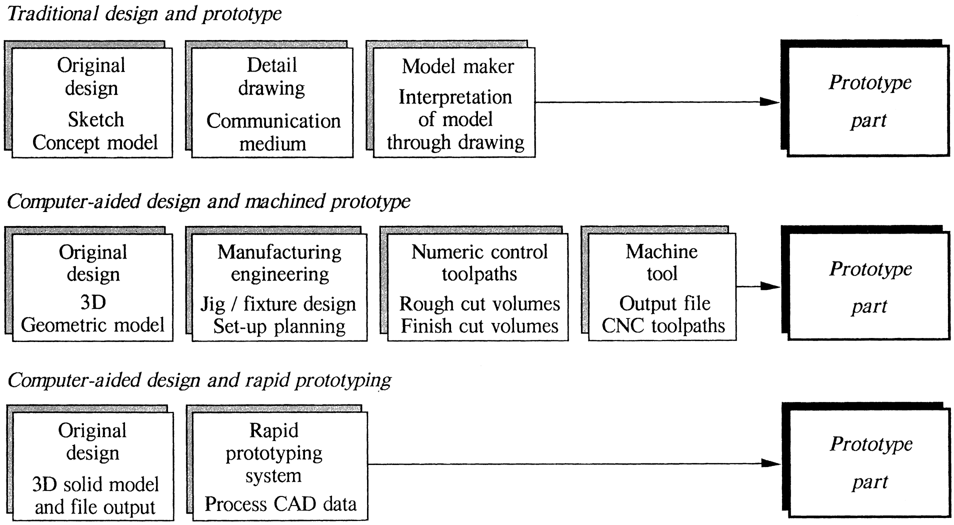


Figure 5.7 Comparison of the procedures associated with conventional model making, computer aided machining of prototypes and rapid prototyping techniques

selection/set-up planning, and the fixturing steps necessary in manual or CNC machining operations. Models can be produced in a matter of hours, providing a valuable communication link for concurrent product engineering. The rapid prototype models can also serve as the pattern for other plastic part prototyping techniques that may be used to provide larger part quantities or more realistic prototype parts. Rapid prototype parts can also serve as the pattern for an investment or lost wax type metal casting operation (processes which can be used for the production of cast metal cavity and core inserts).

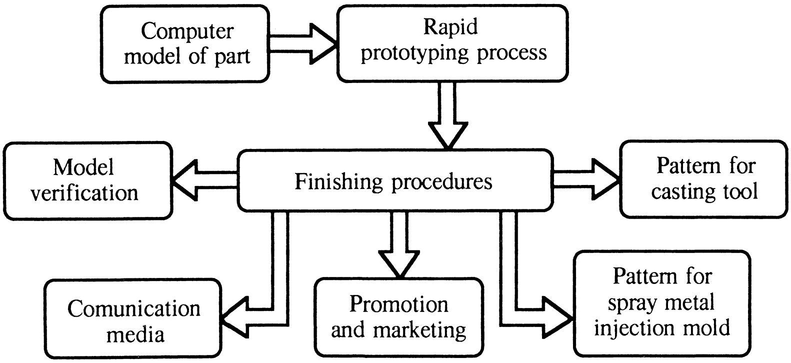
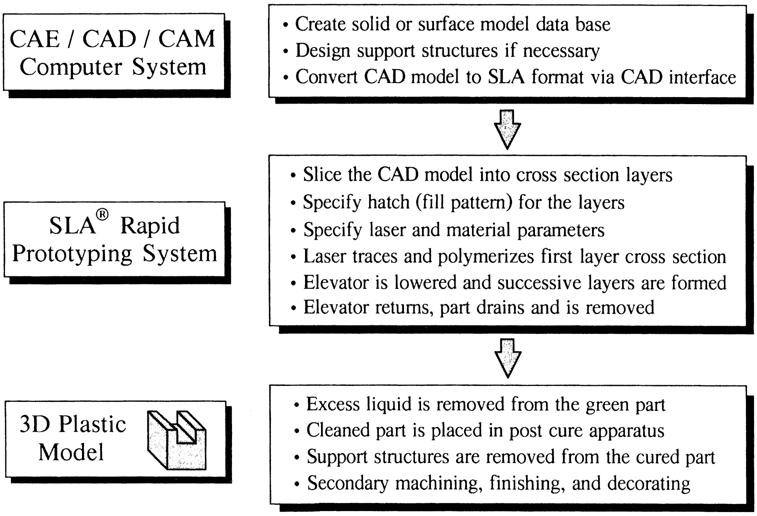


Figure 5.8 Both machined and rapid prototype parts can be used in a variety of different ways

5.1.3.1 Photopolymerization of Prototype Parts

The first commercial Desktop Plastics Prototyping System links CAD design information with a photopolymerization process to produce prototype plastic parts [8–19]. The technique deemed *Stereo Lithography®* by the system manufacturer [20] is capable of producing complicated prototype parts at rapid turnaround times. The process has evolved to the point where a comprehensive text has been written on the subject [21].



- Create solid or surface model data base
- Design support structures if necessary
- Convert CAD model to SLA format via CAD interface

- Slice the CAD model into cross section layers
- Specify hatch (fill pattern) for the layers
- Specify laser and material parameters
- Laser traces and polymerizes first layer cross section
- Elevator is lowered and successive layers are formed
- Elevator returns, part drains and is removed

- Excess liquid is removed from the green part
- Cleaned part is placed in post cure apparatus
- Support structures are removed from the cured part
- Secondary machining, finishing, and decorating

Figure 5.9 Steps associated with the production of a photopolymerized rapid prototype model. (Courtesy Computervision, Bedford, MA)

This rapid prototyping process begins by taking a CAD model, either a 3-D surfaced model or a solid model, and slicing the model into layers having thicknesses in the 0.005–0.020 in

(0.013–0.51 mm) range. These layers will ultimately be fabricated one at a time, starting from the bottom, to produce a solid, three dimensional prototype part. While the capital costs associated with this technique are relatively high (greater than the cost of CNC machining equipment), the process is capable of producing extremely complex, medium size parts in a fraction of the time required for the production of conventional prototype parts via conventional CNC machining, since set-up operations are eliminated [8]. Over the years, a number of service bureaus, firms that hire out their prototyping systems and expertise, have been established for those that wish to make use of the process but cannot justify the capital expenditure.

Figure 5.10 An SLA rapid prototyping system. (Courtesy 3D Systems, Rock Hill, SC)

A schematic of a typical photopolymerization model building process is shown in Figure 5.12. The rapid prototyping apparatus consists of an ultraviolet laser source and associated optics, a beam directing mirror, a vat of photopolymerizable material, a liquid leveling wiper, and an elevator, capable of Z axis movement at digital increments equal to the thickness of the CAD slices (the apparatus is linked with the sliced CAD model). The Helium-Cadmium or ionized Argon UV laser apparatus generate and focus a beam of ultraviolet light, which is directed by a movable mirror to various locations across the X-Y surface of the resin vat [19]. The elevator table sits just below the liquid surface, at a distance equal to the thickness of the "slice" (i.e., the thickness of the layer being formed). The activated laser scans the thin 2D liquid surface, in a complex manner, curing the appropriate areas (i.e., those associated

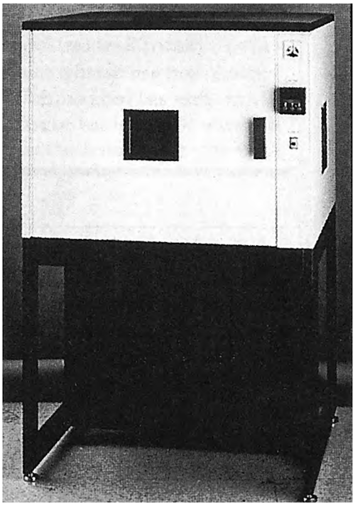


Figure 5.11 Post cure apparatus used with the SLA system (Courtesy 3D Systems, Rock Hill, SC)

with that particular layer). The ultraviolet light initiates the polymerization process which occurs only in areas exposed to the UV light.

A variety of photocurable liquids are available for use with the process. Once cured, the polymeric parts can have properties that range from brittle and glassy, to ductile, or even rubbery [21, 22]. The degree of polymerization is determined by variables such as the total amount of light energy absorbed by the photocurable liquid. Once the curing of a layer (or slice) is complete, the elevator drops, the surface is leveled, and the process repeats itself. To prevent overshooting of the laser into the lower, previously scanned layers, the light must not be allowed to penetrate beyond a certain depth. This is accomplished by controlling the laser process conditions. The elevator continues to descend, layer by layer, until the uppermost layer of the part has been formed, at which time the elevator rises to the top of the bath and the part (or group of parts) is removed, drained and cleaned of surface liquids via blotting, alcohol or solvent rinse, or ultrasonic cleaning [8, 9]. Drains can be incorporated into the part to facilitate movement through the bath during the build. After removal from the bath, the part is described as being in the "green" state (like any partially cured material) and must be handled carefully. The green part is then placed on a rotary table inside a high-intensity U.V. light post-curing apparatus for a short period of time to complete the cure [22]. The very earliest materials developed for use with the SLA process tended to be higher shrinkage, brittle materials, but newer, low shrinkage, more ductile, or even rubbery materials grades have become available. One of the more flexible materials is described as having the properties of medium impact ABS [11, 18]. In addition, new epoxy based resins are available with shrinkages that are an order of magnitude lower than the more conventional acrylic based resins. The lower shrinkage translates to significantly improved accuracy [11].

The initial part CAD model is usually modified to provide an assisting support structure for the part as it is being produced (or "built") to ensure layer registration and structural integrity.

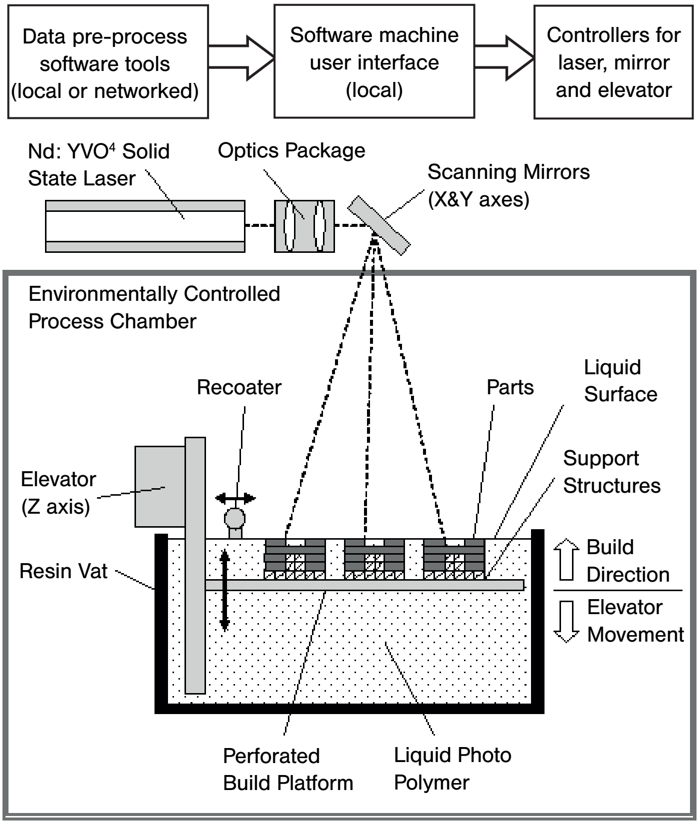


Figure 5.12 Basic schematic of a computer aided photopolymerization prototyping process (Courtesy Motorola Rapid Prototyping Services)

Support structures are required when the part cross section contains islands of unsupported material. These legs or thin vertical strips or webs (as one might use to support the ends of a cantilever fan blade section) are carefully removed as part of the finishing operation.

The time required to construct or build a model varies with the complexity of the part and the tolerances required. Layer formation times can be decreased by creating an integral honeycomb like cross hatching structure between the inner and outer surface boundaries (vertical walls). The liquid entrapped between the walls is polymerized during the post cure [9]. The operator can control the degree of cure during the building of the part. Parts that are cured using the standard technique of hatching leave as much as 40–60 % uncured liquid between the thin solid cell walls. This can result in part warpage or internal stress during/after the post cure since there is a large volumetric shrinkage associated with the polymerization. Some degree of shrinkage and warpage can continue to occur even after the part has been removed from the post cure apparatus. Advanced weave techniques have been developed which permits "in vat" cure levels as high as 96–98 % within a reasonable period of time,

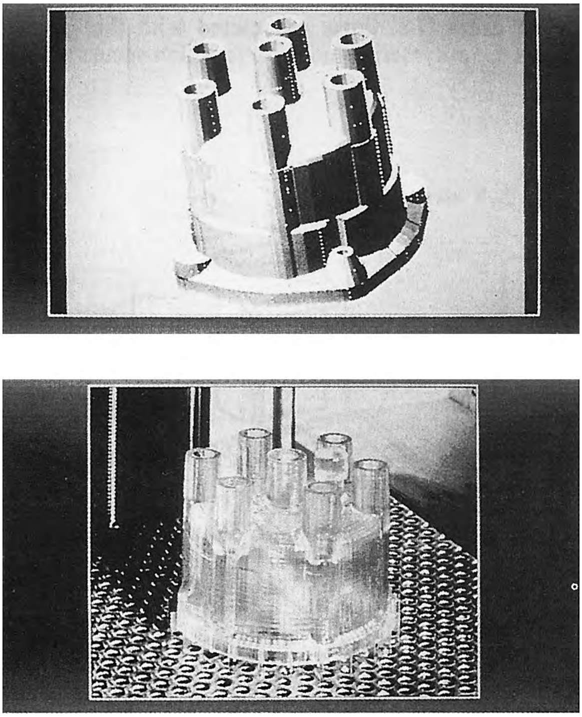


Figure 5.13 (top) Solid CAD model of an automotive distributor cap, and (bottom) prototype part produced using the SLA process (Courtesy of 3D Systems, Rock Hill, SC)

resulting in a major reduction in the potential for warpage [19]. Part sizes up to 20 in × 20 in × 24 in (51 cm × 51 cm × 61 cm) can be produced using the SLA process (on the larger equipment models). Production times are highly dependent on part size and tolerance requirements, although a typical medium size part of moderate to extreme complexity can reportedly be prototyped in several hours [8, 13]. Very large parts can be produced as several sub-components keyed, dove tailed and bonded together.

A key step in the process is the initial part orientation decision. The primary appearance side of the part is often placed on top. The tolerances associated with the process vary and depend upon the CAD model, and the build parameters used. The incremental nature of this process also produces layered, step-like vertical walls for drafted or sculptured surfaces. Smaller elevation increments improve the surface for drafted, rounded and sculptured surfaces, although this does increase build time. Flat or perpendicular surfaces minimize layer roughness compared to drafted or contoured surfaces.

Cured parts require removal of the support structure and surface finishing by hand sanding, bead blasting, or machining. Depending on the part size and complexity, the cured parts can have tolerances that approach those attainable by machining (if warpage is not a problem) while tighter tolerances can be obtained with additional machining after cure [11, 19]. Machining, however, is an operation that may require fixturing, and to a large degree, defeats

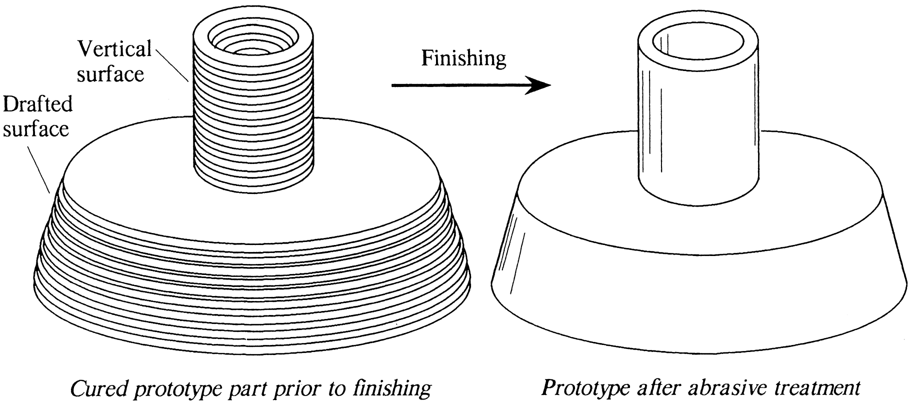


Figure 5.14 (left) Prototype part before and (right) after finishing

the purpose of the rapid prototyping technology. The finished parts can then be painted, dyed, or decorated to produce the desired effect [8–10].

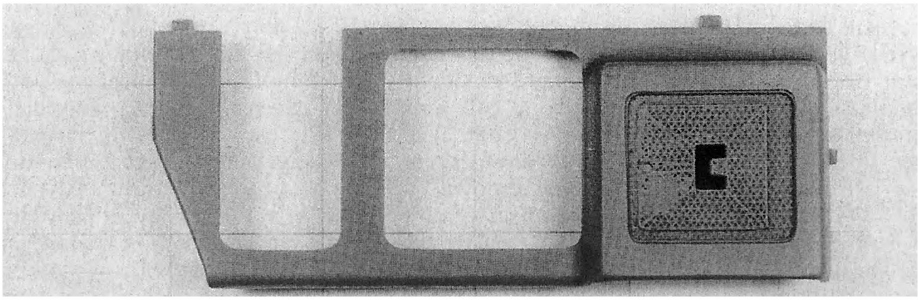


Figure 5.15 Rapid prototype part that has been finished and painted to produce the desired appearance (Courtesy Santin Engineering, Inc., Beverly, MA)

Another technique that uses photopolymerization process is Rapid Micro Product Development (RMPD®) which only uses other polymeric materials. The photo sensitive monomer, oligomer, and hybrid materials as sol-gel can be used in this equipment, which are polimerized by the UV-light to create the parts. FDA approved materials are available for this process as well. The component is built up in layers up to 1 μm and a resolution in any direction of up to 10 μm. The minimum component size can be 1 × 10 × 10 μm to a maximum of 50 × 50 × 50 mm. During the growth of the process mechanical parts can be inserted to achieve the desired functionality [23, 24]. Trends in this dynamic rapid prototyping area include larger scale production units, better tolerances, and development of new photopolymerizable resin grades spanning a wider range of properties.

5.1.3.2 Laser Sintering

Another technology in the rapid prototyping area is *Selective Laser Sintering*® [24–28]. This process is in some ways analogous to the photopolymerization/laser technique, as it uses a concentrated laser (carbon dioxide laser) to form a prototype plastic part, layer by layer. The similarities end there since this process uses powdered thermoplastic material rather than a chemically reactive liquid photopolymer. This technique is especially attractive since it may be possible to produce complex prototype parts directly out of the production material (or similar material) in a relatively short period of time directly from computer models [24, 29, 30]. In theory, prototypes produced using the anticipated production material for the powdered resin could have more engineering uses, however, there are very significant differences in the molding and sintering processes, an the sintered prototypes are not direct substitutes for injection molded prototype parts [31].

The *Selective Laser Sintering*® process shown schematically in Fig. 5.17 begins with a solid CAD model of the part. This CAD model is positioned or oriented appropriately and sliced into sections having thicknesses ranging from 0.005 in to 0.020 in (0.13 to 0.51 mm). The model is built up layer by layer in a bin of powdered thermoplastic or wax material. A stationary laser is reflected off of a beam directing mirror, and traces out the X-Y cross section of the part for that particular Z slice. The preheated thermoplastic powder is momentarily heated and softened by the laser to a point where welding or sintering of the particles takes place. In general terms, sintering is described as a process where the viscosity of the heated powdered polymer drops to the point where surface tension overcomes viscosity and fusion between neighboring particles occurs. The piston supporting the platform and part descends one Z-increment while the powder reservoir is raised. A new layer of powder is laid down with the leveling roller, and the process repeats until the model is complete. Another advantage of this process is that the unsintered powder surrounding the sintered part helps support structurally weak areas during the model building process [19]. In theory, any powdered material that softens or reduces its viscosity when heated can be used with this process, however, the sintering characteristics of each material must be matched with the power of the laser. Powdered thermoplastic materials such as polycarbonate, nylon, PVC and waxes have been used with this process [15, 19, 29, 30].

The interest level in this versatile rapid prototyping technology known as *Selective Laser Sintering*® is extremely high. Perhaps the greatest area of development for this process is in the area of *Rapid Tooling*. *Selective Laser Sintering*® has been used to produce cavity and core inserts for prototype injection molds. These cavity and core sets are created directly by sintering powdered metal in a polymer binder. The sintered parts are then heated in a furnace, producing a somewhat porous metal part. The porous part is then heated with a copper infiltrant (the copper is wicked up) to produce a dense, solid, machinable, steel alloy core/cavity that can be inserted into a standard mold frame [11, 12]. This process should have a huge impact in the area of plastic prototyping, since it will be possible to produce a prototype mold cavity/core sets directly from the metal powder and a CAD model, in a very short period of time [19]. Prototype (or possibly production parts) can then be molded

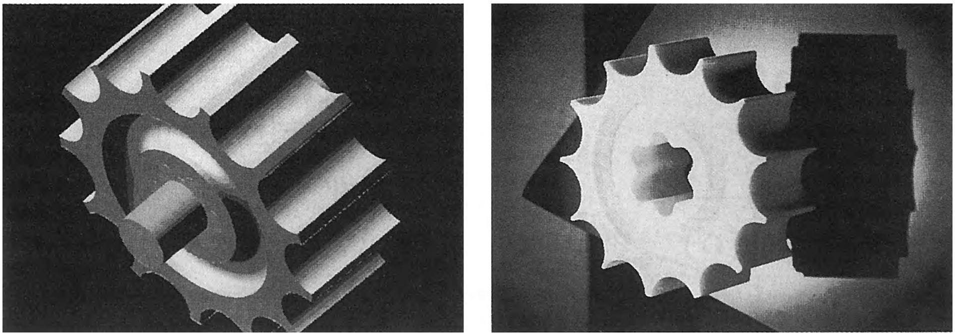


Figure 5.16 (left) Solid CAD model of a drive gear, and (right) prototype part produced using the selective laser sintering process (Courtesy 3D Systems, Rock Hill, SC)

in these "rapid tools" using the production material. This is an advantage for a number of reasons including:

- large quantities of prototypes can be molded at a low cost once the tool is built,
- realistic prototype parts can be obtained for engineering evaluation, and
- the processability (e.g., mold shrinkage, flow pattern, etc.) can be evaluated.

The durability of the rapid tools is described as being somewhere between aluminum and P-20 steel.

5.1.3.3 Automated Filament Extrusion Prototyping

Yet another rapid prototyping technology is based on the use of what is essentially a very small scale, computer controlled automated plastic wire fed extruder. The technique, *Fused Deposition Modeling®* [31], begins with a 3D surface or solid CAD model which is oriented in the same way it will be built in the machine. The orientation will affect the build time and strength of features as well. The program then continues to slice the model into layers having thicknesses ranging from 0.001–0.050 in (0.025–0.13 mm). Support structures can be used for more complex geometries. These support structures can be mechanically or chemically removed and are added to the model for any overhanging sections [31]. To actually build the model, thermoplastic filament, approximately 0.050 in (0.13 mm) in diameter, is automatically fed through an X-Y controlled electrically heated extruder head as shown in Fig. 5.18. The hot filament melt spreads over the previously formed layer, fuses to the surface, and quickly resolidifies. The model is created layer by layer from the bottom up and the machine controls what material to be used for the part and the support structures. When applicable, the part(s) will be placed in an alkaline water base solution bath to dissolve the support structures enabling complex geometries and multiple components to be created in a single build [31]. Materials that have been used with this prototyping process include ABS, PC, wax formulations for lost wax investment casting, machining wax and various proprietary thermoplastic formulations that can be used to build tougher prototype models [24, 31]. Parts

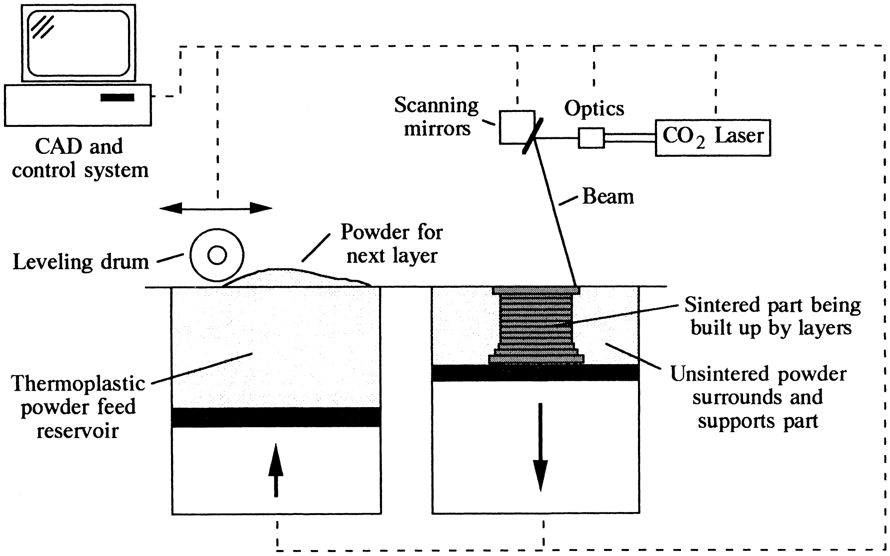


Figure 5.17 Basic schematic of the powdered polymer, selective laser sintering rapid prototyping process

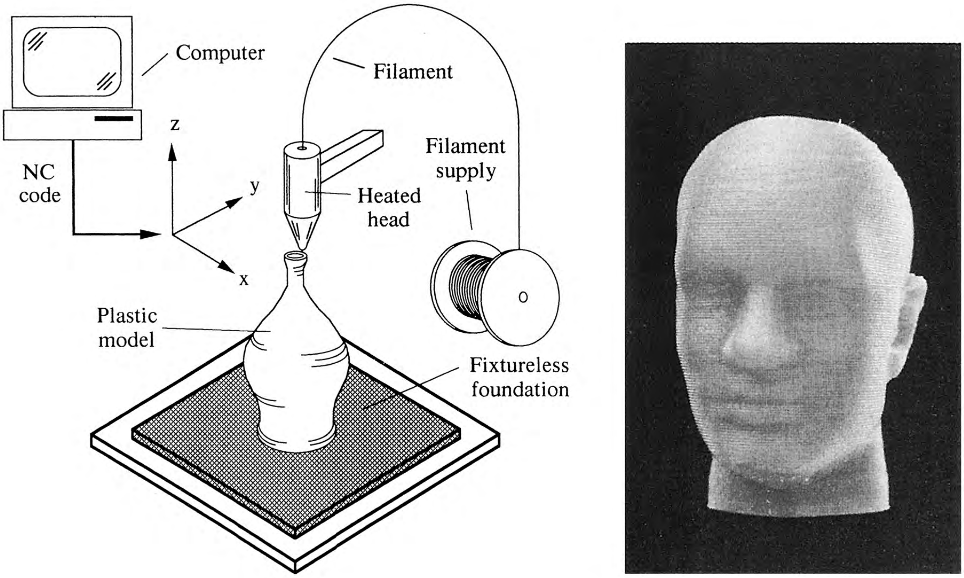


Figure 5.18 (left) Basic schematic of the automated filament extrusion prototyping process, and (right) part produced using the automated filament extrusion prototyping process. (Courtesy Stratasys, Inc., Eden Prairie, MN)

up to 24 × 24 × 20 in (600 × 600 × 500 mm) can be produced [24]. The *Fused Deposition Modeling®* systems are available as both a desktop and floor standing units. These prototyping systems are relatively simple and produce models quickly [11, 15, 19, 31, 32].

5.1.3.4 Laminated Object Manufacturing

Another laser based prototyping system capable of building 3D solid prototype plastic parts is known as *Laminated Object Manufacturing®* [33]. The process consists of layers of adhesive-coated paper, plastic or metal laminates that are continually glued together and cut to shape with a laser cutter. This unit uses a carbon dioxide laser tuned to a depth of one layer. Rolled sheets of pre-coated paper, plastic or composite material are fed into the unit where the laser traces and cuts out each cross sectional layer. The platform with the completed layer moves down. Then the sheet of material is rolled into position for the next cut. The platform moves back up to one layer below its previous position to receive the next layer as the roller bonds the second layer to the first and the process repeats itself [24, 34, 35]. Material cut from the central portions of the sheet can be removed using an automated vacuum system. Sheet thicknesses used for the laminated object manufacturing process are in the 0.002–0.010 in (0.051–0.25 mm) range. The model is built from bottom to top by laminating the stacked sheets. The individual sheets are stacked on top of one another in advancing order, and are sealed to each succeeding layer using a hot roller [17, 19]. Fig. 5.19 shows the setup for an LOM system.

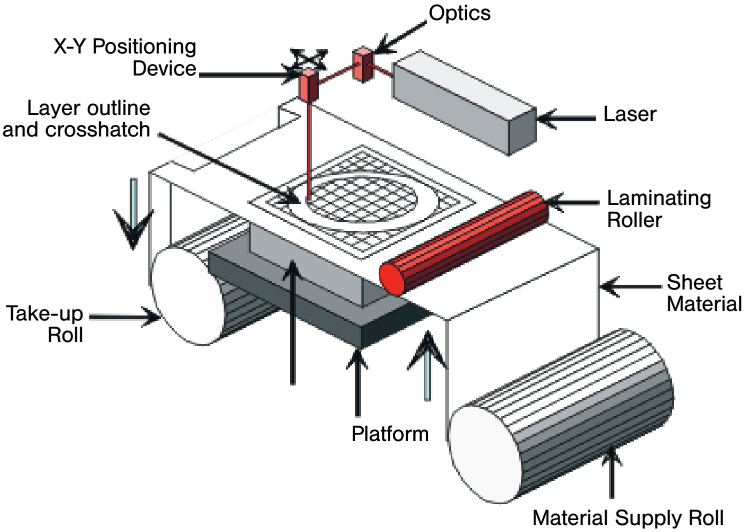


Figure 5.19 Schematic of an LOM setup (Courtesy www.Azom.com/)

5.1.3.5 3 D Printing

3D printing is another rapid prototyping process that allows for the production of 3D prototypes with good speed and accuracy [24–26]. 3D printers offer product developers the ability to print parts and assemblies made of several materials with different mechanical and physical properties in a single build process. The process starts, as for the other RP processes, with the CAD model which is transferred to the 3D printer and sliced into layers. The printer will deposit material (either liquid to solid or powder to solid form) in thing layers, some 3D printers uses the inkjet technology to create the 3D parts. Depending on the type of printer and material used, each layer could be as thin as 0.6 mm and the machines can use thermoplastics or wax materials. The main market for which this technique was developed is for an engineering office where the system must be non-toxic, quiet, small, and with minimal odor [34, 36]. Some processes combine the inkjet technique with the UV-lamp as in the case of Objet 3D-printer and the supporting structures can be removed with a water jet [23, 30, 37].

5.1.4 Simulating a Production Quality Appearance on Prototype Parts

In many cases machined or fabricated prototypes must look realistic in terms of their surface color, gloss and texture. Most molded production parts are colored throughout, and have a gloss and texture that are determined by the processing conditions, material flow characteristics, and by the surface topography of the tool (the part surface can be no better than that of the tool). It can therefore be difficult to simulate these surfaces using standard prototype decorating techniques. The final appearance of the production part is an important quality, especially when products are slated for consumer applications. A designer can obtain an estimate of the surface appearance that can be expected for a material by molding test plaques having different surface finish inserts. For conceptual or marketing prototypes, the designer can simulate molded in color and surface finish on the fabricated prototype parts using custom painting techniques [38].

5.1.4.1 Molded Surfaces/Color

Mold cavity and core finishes are generally described using SPI standards [39] or textured surface standards. A mold finish comparison kit or molded surface finish plaque can improve communication between the part designer and mold maker, since tool surface appearance and surface quality can be difficult to describe verbally or in a sketch.

The surface quality of a molded part does not necessarily mirror that of the tool, especially when higher viscosity or filled/reinforced polymers are used. In many cases, objectionable surface irregularities such as gate splay or weld lines are less pronounced when molded over matte, patterned, or textured surfaces. The polymeric material to be used in production (including all additives) can be molded in lab trials to evaluate the effect of tool surface finish, heat history or other process conditions, on the final color and surface quality of a molding part. Trials should take place over an extended period of time if plate-out or migration of additives is expected to be a problem. The tool can be an older production/prototype tool, or a standard test mold, preferably a multi-surface/multi-texture test plaque.

Table 5.2 Simulating molded surface appearance using hand finishing techniques

SPI/SPE Mold Finish Designation	Current SPI Surface Designation	RMS Surface Roughness Value (µm)	Method of Top Coat Surface Finishing
#1	A-1	0.5–1.0	Add clear lacquer to tinted color top coat. Wet sand 600 grit and polishing compound. Add several clear lacquer top coats. Immediate application of lacquer thinner mist to level surface.
#2	A-3	1.0–2.0	Add clear lacquer to tinted color top coat. Clear lacquer over tinted top coats. Surface is leveled with 600 grit dry/wet. Evenly stroked with polish compound in one direction to produce fine scratches.
#3	B-3	7.0–7.5	Clear lacquer added to tinted color top coat. Sand 600 grid dry/wet.
#4	C-3	12–15	Clear lacquer added to tinted color top coat. Sand 400 grid dry/wet.
#5	D-2	26–32	Flattening compounds added to tinted top coat.
#6	D-3	160–190	Suede compounds added to tinted top coat.

Ideally, the test mold should produce parts with a variety of standard and textured surface finishes for evaluation. The molded prototype test part/plaque will provide the designer with a visual indication of the final product's appearance for a number of different mold surface finishes. The prototype test part can also be used to provide a good indication of how the esthetics of the part will vary with changes in processing variables such as heat history. The parts can also be used to evaluate physical properties and material shrinkage. Molded plaques are easily distributed to each member of the product design team.

5.1.4.2 Molded Surface Simulation for Fabricated Prototype Parts

Smooth Surfaces: Machined prototypes or prototype parts generated using a rapid prototyping technology are usually given abrasive treatment and painted (or possibly dyed) to produce a visual effect that resembles the anticipated production look. Painting can be done using automotive repair finishes via spray application due to the availability of both the paints and the spray equipment, and the versatility and flexibility of the paint systems which are custom matched on a regular basis. Auto finishes are commonly available as lacquers, enamels, or urethanes, with lacquers being the most preferable for prototyping work due to their fast set up and excellent workability of the film. Enamels exhibit better gloss and flow as sprayed, but tend to show blemishes more than lacquers [38].

Michand [38] has outlined a series of lacquer finishing techniques that can be used to simulate various standard mold surfaces [39, 40], once one has obtained a lacquer of proper color and

Table 5.3 Current SPI mold surface designations

SPI Mold Finish	SPI/SPE (old)	Cavity finishing procedure
A-1	#1	#3 Diamond buff (1–5 μm/9 000–7 000 mesh equivalent)
A-2	—	# 6 diamond buff (4–8 μm/5 000–2 500 mesh equivalent)
A-3	#2	#15 diamond buff (8–22 μm/1300–900 mesh equivalent)
B-1	—	600 grit Paper
B-2	—	400 grit Paper
B-3	#3	320 grit Paper
C-1	—	600 abrasive stone
C-2	—	400 abrasive stone
C-3	approx #4 (280 stone)	320 abrasive stone
D-1	—	Dry glass bead blast (#11)
D-2	#5	Dry oxide blast (#240)
D-3	#6	Dry oxide blast (#24)

hue. The thermoplastic prototype part is first sprayed with a sealer to protect the part from the aggressive solvents in the lacquer. In the automotive area, sealers are used to protect enamel finishes from lacquer touch up. Next, a primer (a high solids paint) is sprayed to create a tooth for the base coat, and to provide enough buildup to cover up sanding/machining scratches and small imperfections. Light gray primers are recommended as they reflect more light than darker primers, assisting in surface inspection. Heavy scratches can be eliminated using filler compounds or several primer coats/sanding. Next, a lacquer base coat is applied to the primed surface. A white base coat is best for pastel top coat colors, while dark gray is used for solid color top coats. Finally, custom formulated tinted and clear lacquers are applied to the base coat. The standard mold finishes [39, 40] can be simulated by following the sanding and finishing procedures outlined in Table 5.2 [32].

Old SPI standards designate 12, rather than six different mold surface finishes. The mold surface designations and surface preparation procedures outlined in the current SPI standard are given in Table 5.3 [39].

Simulation of Textured Surfaces: Certain random textured surfaces can be obtained using pressure feed spray equipment (rather than siphon guns) where the fluid pressure can be increased beyond the capacity of the atomizing cap, producing small droplets or a course stipple. Alternatively, room temperature vulcanizing (RTV) or cure silicone castings of existing patterned or textured surfaces can be taken (as a negative) after which a positive RTV mold is cast. A viscous paint or coating is sprayed into the mold to produce a relatively flexible thin textured film, which can be bonded to the prototype part surface [38].

5.1.5 Prototype Part Casting Techniques

In situations where a few to as many as 50 prototype parts are required, low pressure casting is a potential prototyping method. Developments in both the areas of pattern manufacturing, tooling materials, and in the casting resin area, have led to the expanded use of this technique in recent years [1, 41, 42]. A relatively large number of prototype parts can be produced at an economical price using this technique, which is popular for electronic, communication, appliance, toy and automotive components.

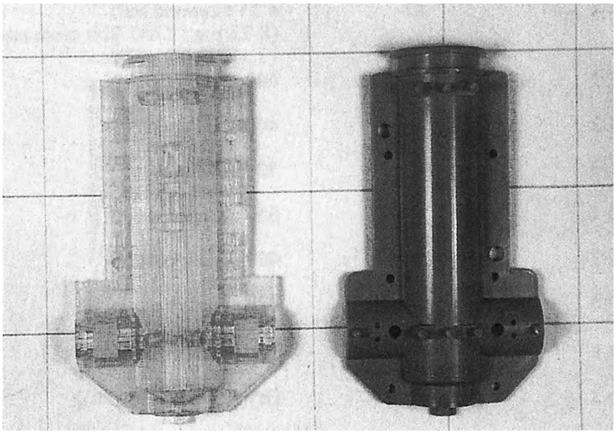


Figure 5.20 (left) Rapid prototype Stereolithography® part used as the pattern for a silicone casting mold, and (right) a colored, cast polyurethane part produced in the reusable, elastomeric silicone mold. (Courtesy Santin Engineering, Inc., Beverly, MA)

Casting can provide prototype parts in relatively large quantities (perhaps too many to fabricate via machining or rapid prototyping) that are often required for non-critical part field trials, package design programs, market studies or advertising campaigns. The cast prototyping process begins with the creation of a master pattern. The pattern can be produced from materials such as wood, plastic, soft metal or clay. Machined acrylic masters are commonly used due to the availability of acrylic stock, its good machinability/polishability, and its ability to be solvent cemented. Prototypes generated using one of the rapid prototyping technologies are also commonly used as masters for this type of casting process. This initial prototype part will be used as the master or pattern for a casting tool, typically produced using an RTV silicone resin. The tool will be in two or more parts, and it is therefore necessary to have well defined parting line locations and sprue/runner areas on the original master. Other common tooling materials that are used to a lesser extent include plaster and vinyl plastisol. Rigid plaster models may be adequate for a few simple, well drafted parts with no undercuts. One shot, water soluble plaster is available for more complicated geometries. Plaster has a relatively short set time, however, the tool should be completely dry before it is used, which could be as long as 72 hours for wall thicknesses in the 2–4 in (51–102 mm) range, in order to achieve maximum strength [43]. RTV is the most common choice for the mold material as it offers good release characteristics, excellent surface reproduction, durability (typically good for up to 25 castings), chemical resistance, flexibility (allows limited undercut), low shrinkage and good handling and cure characteristics. The mold can be cast using other, less flexible materials, however, additional part ejection mechanisms would need to be incorporated. Tools can also be machined directly from a block of cast material, but it is generally easier to produce a single master, which can be used for several cast molds, than to machine and finish both a cavity and a core.

The mold building process is fast, but labor intensive. Automated mold building/part casting equipment is also available to both speed the tool building/ art casting processes, and improve quality [42]. With this equipment, the mixing process is automated and is done under vacuum. Mold filling occurs under pressure, resulting in significant quality and surface finish improvements. The casting tool itself can be built in several ways. For the one shot mold tool building process, colored tape is used to identify and form the parting line on the pattern. The pattern is then coated with release agent, suspended in the center of a frame, and a transparent RTV silicone is then cast around the pattern as shown in Fig. 5.21. After cure, the one piece RTV molds are then cut open at the parting line using a razor knife. In a second tool building technique, a two-piece casting mold is constructed as separate halves. The cavity and core sides of the tool are poured separately (sequentially as shown in Fig. 5.22). To begin the tool building process, a wood, metal, plastic, or foam board frame (a few inches larger than the part) is fabricated. The pattern (sized with both the tool and casting resin shrinkage taken into consideration) is coated with a layer of release agent before the tool is cast. The parting line for a two-piece mold building process can be established using a pattern mounting board, or modeling clay. The clay or parting line mounting board form the proper parting line, the parting line location features, and support the pattern during the casting operation. The RTV resin is then de-aerated and/or vibrated and poured into the frame using a shaker table to facilitate flow. The rubbery material is allowed to cure, at which time the mold frame is inverted and the clay/mounting board are removed. The pattern is cleaned, coated with release, and the second half of the mold is poured and allowed to cure. Vents or risers and spree hole(s) can be directly cast-in or machined after the cast tool cures. Parts should be gated in such a way as to assist in the venting of the air when the part casting resin is poured [1].

Machined metal or plastic mold inserts are added top the casting tool when the part geometries become more complicated as shown in Fig. 5.23 and 5.24. While RTV silicones are tough materials, very thin sections or small holes can be produced more accurately with inserts due to the potential for core bending/deflection during the pour. The inserts also improve mold life for thin sections and can be used to assist in the ejection of deep undercuts such as the snap beam shown in Fig. 5.24. The parts themselves are typically cast using either epoxy, thermosetting polyester, or most commonly with thermoset polyurethane casting resins. The low viscosity resins are carefully mixed and vacuum de-aerated before being poured through the sprue (filling) hole. The mixing step is critical in terms of component concentrations (i. e., mixing ratio) and air entrapment. Mixing should be done by hand or with equipment that does not introduce air. The automated casting system mixes and casts the materials under vacuum.

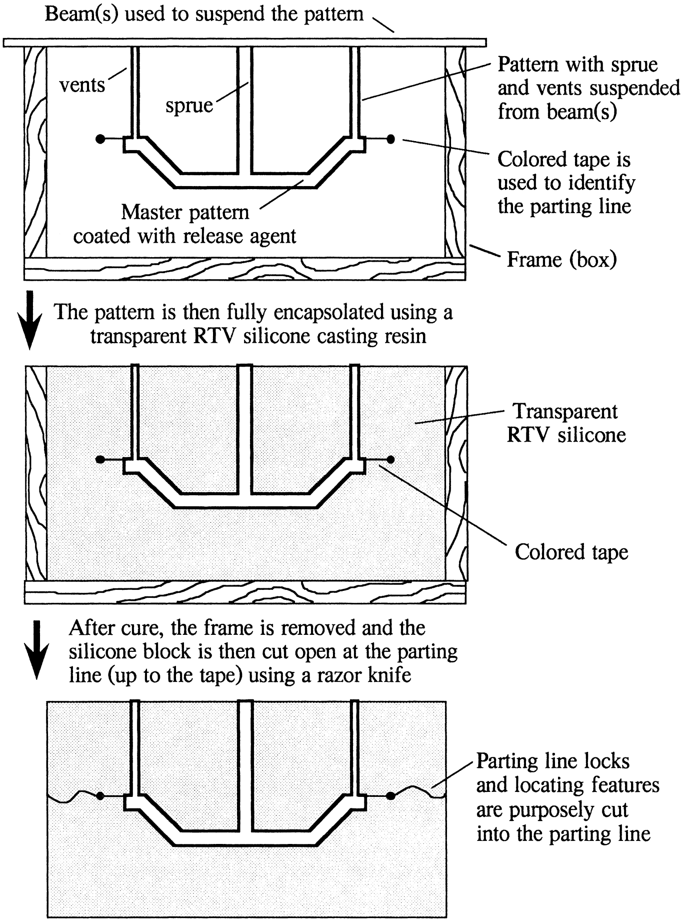


Figure 5.21 Steps associated with the construction of a one piece, transparent RTV silicone casting mold. The mold is cut open after the silicone cures to establish the parting line

All mixing utensils and containers should be clean and free of surface moisture, as this can affect the cure reaction [41]. Preheating the resin components or tool can temporarily reduce viscosity of the resin for hard to fill thin wall sections, however, this will also reduce pot life or working time. The cast parts are often cured in an autoclave to produce dense, void free parts [1], or using room or slightly elevated temperature cure cycles ranging from 1 to 24 hours depending on the resin grade.

Thermosetting polyurethane resins are most widely used as the casting resin because they are available in a number of grades, having a wide range of flow and toughness characteristics. Harder grades have mechanical characteristics similar to ABS (with somewhat reduced thermal properties). Additives can be mixed with the base resin formulation to produce materials

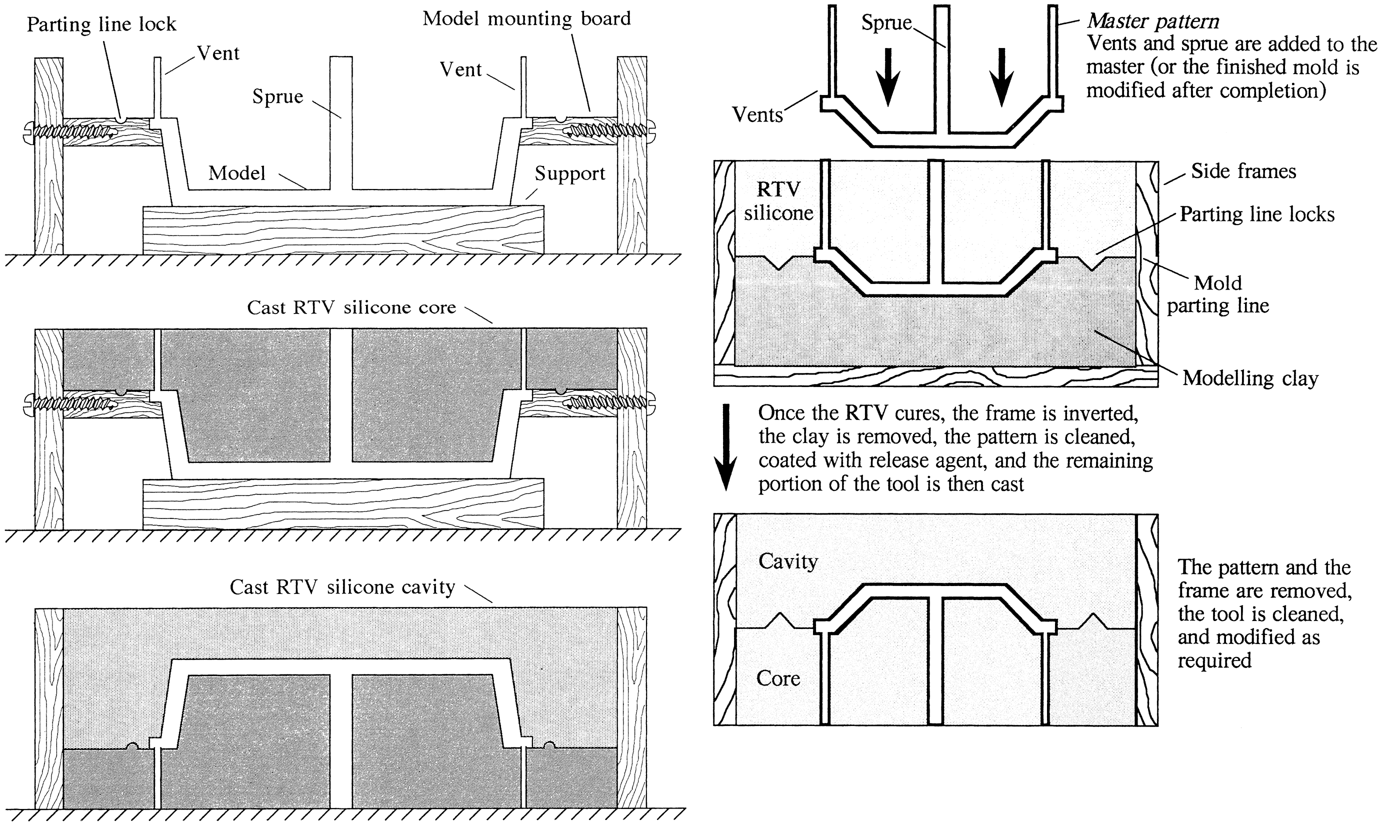


Figure 5.22 (left) Steps associated with the construction of a two-piece RTV Silicone casting mold, using a model mounting board to establish the parting line and (right) construction of a two-piece mold using modeling clay to support the pattern and establish the parting line

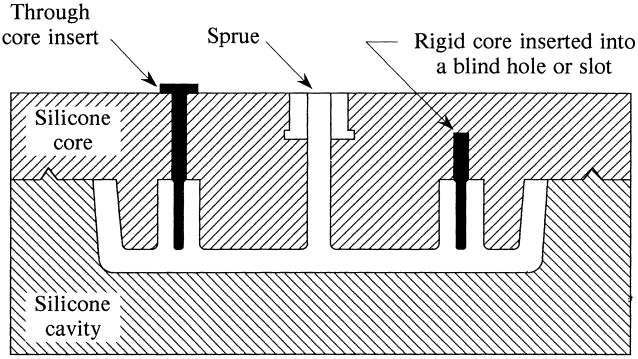


Figure 5.23 Removable metal inserts can be used to produce fine details such as the hole for a hollow boss. Alternatively, features such as holes can be machined in a secondary operation

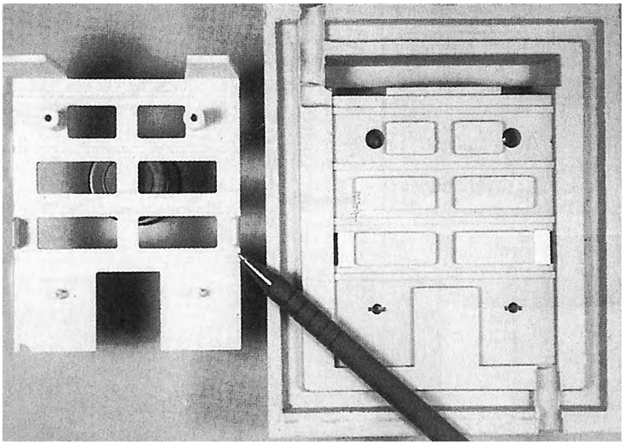


Figure 5.24 Cast polyurethane part (left) and silicone casting mold (right) used to produce the prototype part. The silicone mold contains removable aluminum inserts to assist in the production of the hollow bosses and the cantilever snap beam undercut (Courtesy Santin Engineering, Inc., Beverly, MA)

that more closely reflect the characteristics of the end-use material. Flame retardant grades having a U.L. 94 V-0 rating for ¼ in (5.4 mm) thick specimens and transparent grades are also available [1, 41, 44]. Colorants can be mixed in with the casting resin, or the cast parts can be painted or dyed after ejection. Shrinkages are relatively low for the polyurethane materials, however, it can be difficult to hit the target dimensions for higher tolerance items on the first attempt. In such cases, dimensional or styling changes can be made to the initial cast prototype, after which the modified model is used as a new pattern.

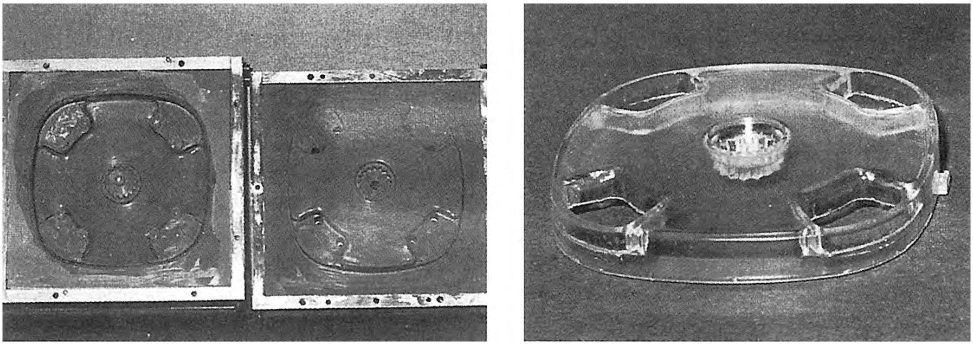


Figure 5.25 Prototype cover for an Oster Corporation part produced using a water-clear polyurethane casting resin, cast in a reusable RTV silicone mold (Courtesy Ciba-Geigy Tooling Systems)

Figure 5.26 Prototype keypad for a Motorola Talkabout Radio cast from 40 Shore A durometer RTV silicone using a casting mold printed on an Objet EDEN 500 polyjet printer (Courtesy Motorola Rapid Prototyping Services)

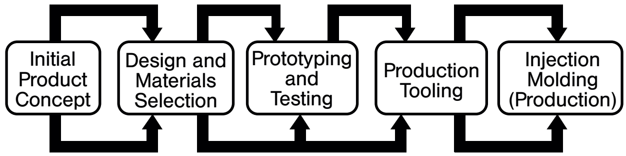
5.1.6 Prototype Injection Mold Tooling

The term "prototype tooling" is a term that can have different meanings to different people. To a part designer, it may indicate a relatively inexpensive, rapidly made non-production tool used to make a small number of prototype parts. To a toolmaker, it may be a tool that has been built to demonstrate whether a tool will perform as anticipated. The key points in either case are relatively low cost and relatively fast procurement as compared to production tools [43]. The SPI categorizes injection molds, or cavity inserts, according to their quality and service life (i. e., their production life in terms of the number of parts that can be produced). Prototype molds are described as molds that are constructed in the least expensive manner possible to produce a very limited quantity of prototype parts, based on the SPI's designation [45].

Table 5.4 SPI mold classification system

SPI class designation	Injection clamp size (ton)	Estimated number cycles	Mold description
101	< 400	$> 1 \times 10^6$	Extremely high production
102		$< 1 \times 10^6$	Medium to high production
103		$< 5 \times 10^5$	Medium production
104		$< 1 \times 10^5$	Low production
105		$< 5 \times 10^2$	*Prototype only*
401	> 400	$> 5 \times 10^5$	Extremely high production
402		$< 5 \times 10^5$	Medium to high production
403		$< 1 \times 10^5$	Low to medium production
404		$< 5 \times 10^2$	*Prototype only*

Prototype tooling budgets should include the costs of prototype tool modifications and the cost of 3D patterns, since a pattern is required for cast tooling (and at a minimum serves as an excellent communication aid). Even when molds are machined, models are extremely helpful. The money and time saved by skipping prototype molding steps may be small in comparison to the time and costs accrued when more expensive production tooling must be recut to accommodate the need for tool or part modifications [45]. Prototype tools are expected to produce parts that are very similar (identical would be optimum) to the expected production parts. The prototype part's production cycle time may be somewhat longer than that of the production tool due to reduced cooling capacity of prototype tooling or because the tool has manual inserts or slides. In the case of high quality aluminum prototype tools, cycles can be faster due to improved heat transfer. The parts produced in prototype tools may also require some additional secondary operations or hard finishing. Prototype tools are typically designed to produce a limited number of parts (a few to several hundred parts, even thousands of parts in some cases) although metal prototype or preproduction tooling often end up in production for one reason or another.


(a) Plastic Procuct Development Cycle *With* Prototyping

(a) Plastic Procuct Development Cycle *Without* Prototyping

Figure 5.27 The safest and best route in product development involves prototype part production and evaluations. While route b is initially more direct, problems are not detected until production begins. The solutions are likely to be expensive and time consuming

One of the major reasons for using prototype tools is to produce prototype parts for end-use or laboratory testing. Only injection molded samples manufacture using the production material will exhibit the true properties of the final product, because factors such as orientation, heat history, weld lines and other processing related effects are accounted for. While injection molded prototype parts and tools can be expensive relative to facsimile prototypes (especially when only a small number of parts are required), unforeseen manufacturing or processing related part performance problems are less likely to occur when manufacturing considerations are taken into account before one commits to production tooling.

The prototype tools may be single cavity (unit cavity insert) molds rather than multi-cavity, and may lack certain details such as trademarks or engravings. The unit cavity approach is common for smaller parts. However for larger parts, the decisions associated with prototype tooling are more difficult to make, because the cost of the prototype tool (relative to a production tool) becomes very significant. One solution is to target the problem areas. Potential problem areas for larger parts, such as the weld line on the exterior automotive panel shown in Fig. 5.28, can be evaluated using much simpler prototype tooling. In such a case, it is important to keep processing conditions and critical tooling geometry as realistic as possible. The prototype tools should be constructed in a manner similar to the production tool with respect to the number, type and location of the gate(s) and cooling layout whenever possible [3, 5]. In addition, it may be advantageous to design a prototype tool so that it is versatile. For example, a number of likely gating schemes could be incorporated into the tool in advance, if there is any question as to gate location as shown in Fig. 5.30 [3, 5].

In other cases, prototype parts are produced for non-engineering functions, such as those required for display, package design or marketing purposes. These parts might be produced using lower melting, non-production resins, along with softer, less expensive tooling and hand finishing, generating parts that are perfectly adequate as facsimile prototypes or models [43].

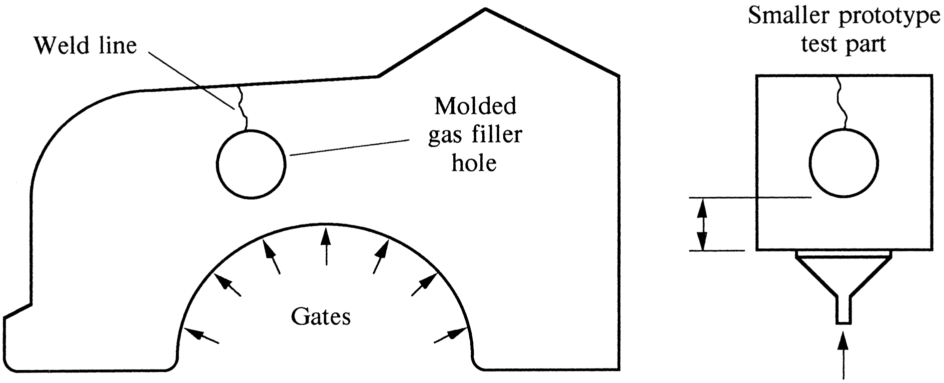


Figure 5.28 Example showing the simplification of part geometry, targeting a specific area of concern (a weld line in this case), in order to reduce cost and save time

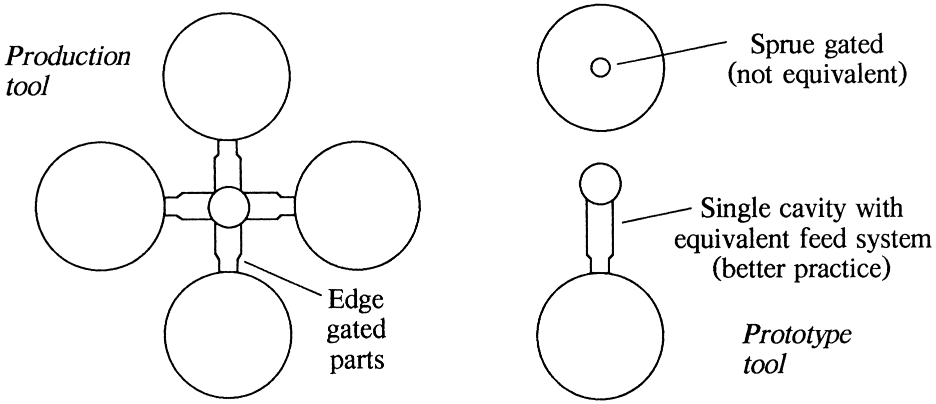


Figure 5.29 Molded prototype parts should be gated in the same manner that is planned for the production parts

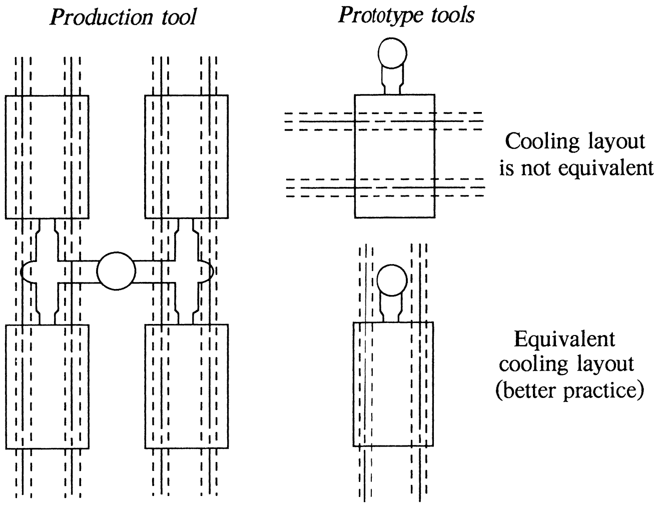


Figure 5.30 Cooling layouts for prototype molds should reflect the planned production cooling layout

Prototype molds can be categorized based on either their production characteristics [2, 4] or based on their materials of construction. The prototype injection molds can be cast, spray metal shells, sintered, or most commonly machined. Cast prototype tools require the use of a master(s) which can be made from sealed wood, plaster, plastic, wax or from a soft metal such as aluminum. The pattern material selection is dependent upon factors such as the temperature associated with the tool casting operation.

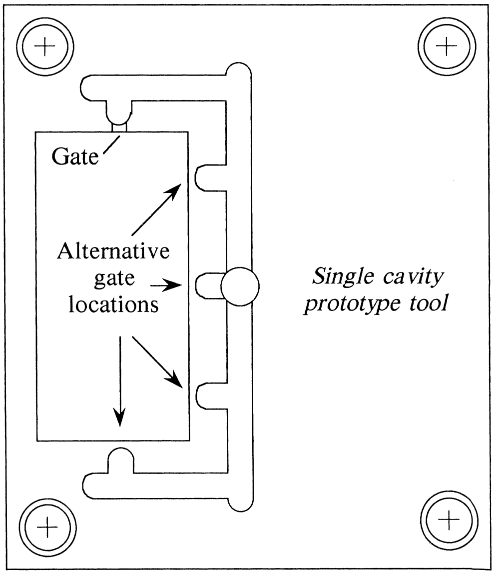


Figure 5.31 Prototype molds should be versatile. In this case, a number of possible gate locations have been incorporated into the prototype tool for potential evaluation

The decision to create a prototype versus a production tool depends on many variables, such as:

- Materials of construction to be used for the cavity/ core.
- Number of cavities of the tool, generally the prototype is made with one cavity only.
- Type of mold cooling to be used, if any in the prototype.
- Minimal automation in the prototype mold.
- Amount of polishing to be used
- Type of runner system, cold vs. hot system.
- Standard mold frames, etc.

Ideally you will want to make a prototype for small parts that will have high production since the cost will be easily justified. As the worst case scenario is to make a prototype mold for large parts that will have low production. The decision to make a prototype mold will depend on the expected problems to be identified, the budget, lead time, and how realistic will the part representation it will be.

Table 5.5 Prototype mold classification system [2]

Prototype tool type	Production characteristics	Materials of construction
Level I	Rough part, loose tolerances Standard geometry, a few simple features Secondary operations may be required Small number of parts for initial evaluation Shortest lead time Lowest capital cost Typically sprue gated	Cast epoxy, plaster Metal dip or metal spray
Level II	Relatively tight tolerances Some mold design evaluation Hand loaded inserts/core pulls	Cast or machined aluminum, brass, kirksite, soft steel or electroform
Level III	Relatively high volume prototype work Tight part tolerances Automated ejection/side action Duplicates production gating and cooling Tool design, part performance, mold design and process conditions can be evaluated Cycle time a production cycle	Machined aluminum or soft steel plate
Level IV	Single (unit) cavity preproduction mold Fully automated, production tolerances Useful as backup if production tool needs repair or doubles as production cavity insert	Hardenable steel Hardened before or after molding trials to accommodate design changes

5.1.6.1 Cast Epoxy Prototype Tools

Highly filled or reinforced epoxy casting resins can be used to produce very low cost prototype tool, of limited durability [4, 8, 43]. The casting resins are typically filled with aluminum, iron, or steel chips/powder to improve compressive properties, thermal conductivity, reduce shrinkage and reduce the coefficient of thermal expansion. The epoxy formulations exhibit low shrinkage and are generally room temperature cure systems, although a ramped elevated temperature post cure (for as long as two days) can be used to improve both the strength and high temperature properties of the final casting. Since the resin cures at room temperature, the pattern materials can be plastic, wood or even wax for low exotherm systems [43]. The process involves casting the filled liquid resin over a well drafted, well lubricated master, supported in a structural mold frame or chase. The frame must provide both the compressive clamping surface and be rigid enough to resist sidewall or support plate deflections due to cavity pressure. The surface quality of the tool is determined by the resin void content, filler content, pattern quality and resin viscosity. De-aeration, vibration and careful mixing will reduce void content. Some hand finishing and sealing may be required as undercuts should be avoided or filled to prevent tool damage during mold opening or part removal. The tool can be modified via conventional machining operations or by adding resin to local areas. The soft epoxy tools are more commonly used with low pressure processes such as RIM or low pressure structural foam, but can be cautiously used for prototype injection molds in some applications. However, the epoxy tool life is very limited. Strategically placed metal inserts (such as sprue bushings, runner bars, etc.) that improve the tool life are required in most applications. The prototype tools should be run at the lowest possible clamping pressure settings, molding pressures and temperatures. In addition, low temperature polymers should be run in place of higher temperature engineering polymers for facsimile prototypes whenever possible.

5.1.6.2 Metal Shell Tooling

Metal shell tooling backed with either a metal or ceramic filled/reinforced epoxy resin, or alternatively a low melting point metal alloy, are considered intermediate quality prototype tools or in some cases, very limited production tools. Tools of this type are more durable than straight epoxy molds, provide better surface detail, better tolerances, and larger quantities of parts, perhaps more than 1,000 injection molded parts if zinc or aluminum alloys are cast as the shell back up material [47, 48]. The importance of low pressure mold protection, proper tool set-up, and careful maintenance cannot be overemphasized when these soft tools are used.

The metal shells necessitate the use of a pattern, which may have to withstand elevated temperatures for relatively short periods of time depending on the process that is used to make the shell. When high temperatures are a problem, the pattern can also be cored out for cooling (e.g., for water cooling) to prevent heat buildup. With some processes, the pattern must be heated.

An example of a mold core manufactured using Stereolithography is shown in Fig. 5.32. The SLA shell has been backed with metal powder filled cast epoxy to improve mechanical and thermal properties of the core. The injection molded PC/ABS prototype part appears on the image as well.

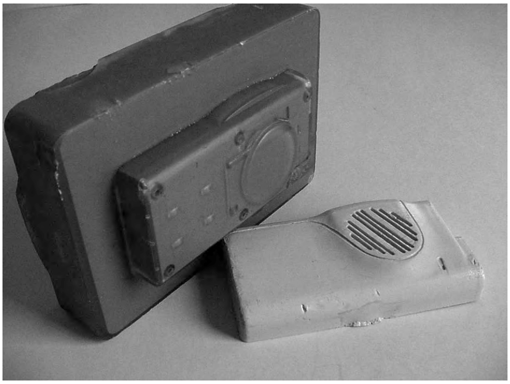


Figure 5.32 Stereolithography epoxy core shell backed with metal powder filled cast

Metal shell materials range from low melting point bismuth alloys, to hard, durable nickel. The shells are generated using dipping, spraying, electroforming, or vapor deposition processes

[4, 43, 47–49]. The simplest method that can be used to produce a cavity is to dip the master into a bath of molten alloy, kept just above its melting point. The cold pattern causes a thin shell to form around the pattern. Unfortunately, low melting point alloys are not very durable. A more durable metal shell can be produced using the Nickel Vapor Deposition Process [48, 49]. In this process, nickel carbonyl, in gaseous form, mixed with a carrier gas, are brought into a sealed chamber containing the mandrel/pattern of the cavity or core to be formed. The mandrel (typically machined aluminum) is heated to a uniform temperature of approximately 350 °F. When the nickel carbonyl gas comes in contact with the heated surface of the mandrel, the gas decomposes and a pure nickel deposit forms on the pattern (99.9 % pure nickel). The deposition rates are in the 0.010–0.050 in/h (0.254–1.27 mm/h) range, and can be applied in thicknesses from less than 0.001 in (0.0254 mm) to a maximum of 1.000 in (25.4 mm). The process can be used to form small to very large cavity/core shells. After the nickel shell has been formed, copper tube, pattern wax or polystyrene foam channel shapes can be applied directly to or close to the rear surface of the shell. The shell is then placed within a metal chase or frame (suitable to withstand clamp and injection forces) and backed with a highly filled epoxy system . The wax/foam channels can then be cleared by heating (melting the wax) or dissolving (the polystyrene foam).

Lower melting point metals of various types can also be arc or gas flame sprayed to produce cavity and core shells. In the spray metal shell process, an aluminum or zinc alloy wire is fed through a gun, where it is vaporized using either a gas jet or an electric arc, and is then sprayed over a pattern. The spray metal shell process can be used to produce virtually any size cavity [8, 28,32]. Typical steps involved in the manufacture of an arc sprayed metal shell tool, such as that shown in Fig. 5.33, are described below [47].

1) The process starts with the creation of a suitable model (pattern) that is built from well sealed wood, plaster, metal, machined plastic, clay, wax. The model can also be created using one of the many rapid prototyping technologies since the arc spray process is a relatively low temperature process, and a variety of different pattern materials can be used. The parting line is then clearly defined, and the model is mounted at the parting line on a mounting board. The pattern should be well drafted, and all negative drafts or

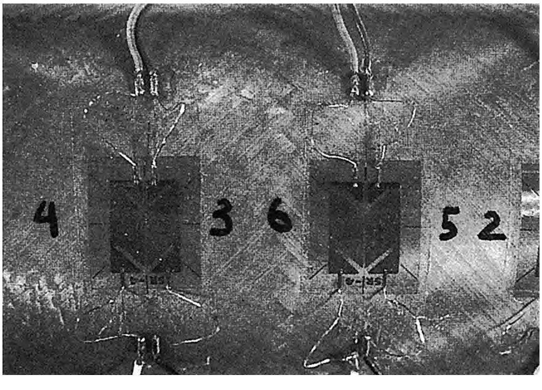


Figure 5.33 Basic components and construction of a spray metal shell prototype injection mold

undercuts should be filled and sanded smooth. Runners and gates are added to the model as are other features such as ejector pin bushings.

2) The pattern is cleaned, and several coats of release agents, typically PVA, are added to provide an appropriate foundation for the metal spray, and to assist in pattern release.
3) The metal spray is then applied to one side of the model and mounting board. The coatings are gradually built up to a thickness approximately 0.063 in (1.6 mm).
4) The external framework, including clamp slots, lifting bolts, alignment bushings, and cooling fittings is placed over the metal shell. The framework, typically aluminum or steel plate, must be strong enough to resist deflection due to both clamping and internal mold pressures.
5) An epoxy gel coat is then painted over the metal shell. Once this operation is complete, the cooling channels (typically copper tube) are put in place. The cooling channels should follow the contours of the shell and connect to the frame using compression fittings.
6) Once the cooling circuit is in place, a high temperature epoxy resin is mixed with aluminum chips, needles or powder. The mixture is poured over the shell (into the mold frame area) to back up the tool. It is good practice to vibrate the tool to assist in air removal, and to circulate cool water through the mold cooling channels during the exothermic epoxy cure reaction to limit the peak cure temperature and reduce the shrinkage of the epoxy.
7) Once the resin has fully cured, the tool is turned over, and the model mounting board removed.
8) The process (steps 1–7) is repeated using the reverse side of the model to produce the mating mold half.
9) The cured tool halves are separated, the model is removed, and the tool surface cleaned using warm water to remove mold release agent residue. The finished tool can be polished or plated to achieve the desired surface finish.

An alternative method of shell formation is electroforming. Electroforming can be used to produce hard nickel tool shells, with very fine definition. The tool shells will stand up to higher temperatures and pressures than conventional spray metal shells. To create the shell, a conductive (or conductive coated non-metallic) pattern is placed in an electrolytic bath where nickel is deposited until an appropriate thickness 0.050–0.125 in (1.27–3.18 mm) is built up. The process is time consuming, however, it is well suited for complex cavities [38]. The shells can be backed with either the metal powder or chip filled epoxies, or casting metals such as aluminum, or a lower melting point zinc/aluminum/copper alloy.

5.1.6.3 Machined Prototype Molds

Prototype injection molds are most commonly produced by conventional machining, grinding or electrical discharge machining (EDM) techniques. These machining methods are commonly used to produce prototype molds for small parts (typically one or two cavity molds) or for larger parts that have been simplified to some degree (typically a one cavity

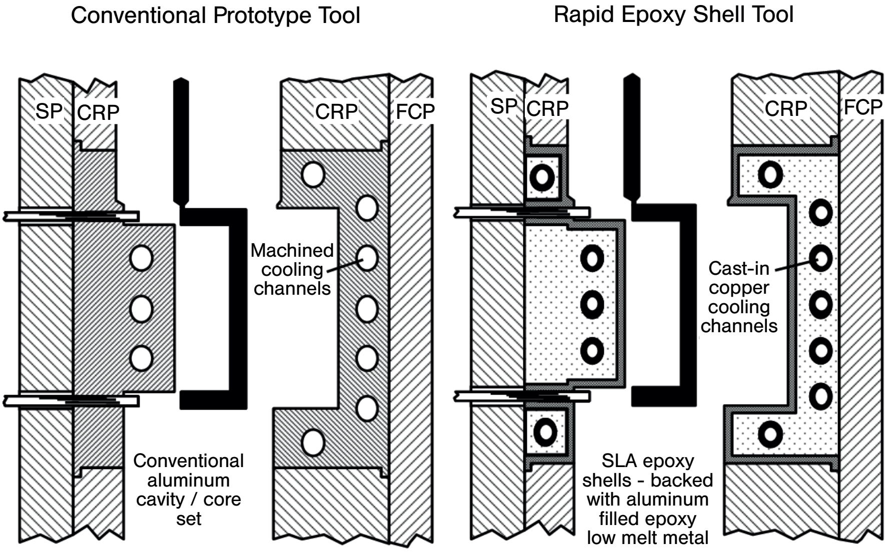


Figure 5.34 Conventional prototype tool vs. rapid epoxy shell tool

mold) where non-critical design features and details have been eliminated. The tools are machined directly from aluminum, brass, and soft or prehardened steel plate. P-20 steel is often used for very high tolerance, higher production prototype or limited production tools. Aluminum offers the greatest advantages in terms of machinability (and therefore cost and delivery) and improved heat transfer capabilities, however, the aluminum alloys are relatively soft, with lower yield strength and abrasion resistance than steel alloys. The advantages of aluminum are most significant for medium to large tools where a great deal of machining is required. Several aluminum alloys are commonly used for prototype tools. The traditional material for aluminum molds is the 7075-T6 aircraft quality alloy. Recently, Alcoa has introduced an aluminum alloy designated QC-7, that is significantly stronger and harder than the 7075 alloy. The alloy is widely used for prototype injection molds, and is currently available in plate thicknesses up to 6 in (152.4 mm). The cavities, cores, and tool actions can be plated or surface treated to improve lubricity, abrasion resistance and chemical resistance. When aluminum is used as the material for prototype tool construction, steel inserts are commonly used in areas where high abrasion, bending stresses, or compressive stresses are anticipated. The number of parts that can be produced in machined prototype tools can range from thousands to tens of thousands. The potential tool life for a soft metal tool (in terms of number of cycles) is highly dependent upon a number of factors including; the materials of construction, surface treatments, the part design, the tool design, the plastic material being molded, process conditions, and tool maintenance.

Machined prototype molds have the longest lead time and highest capital cost, however, they may be produced using conventional or CNC-machining equipment (with various levels of hand finishing) and are capable of producing the maximum number of prototype parts to the highest tolerances [50]. These tools provide a realistic indication of both product and mold

Table 5.6 Property comparison for aluminum and steel [52]

Property	Aluminum		Steel	
	QC-7	7075-T6	P-20	H-13
Typical hardness, Rockwell C	16	14	28 to 32	52 to 54
Typical yield strength, ksi	79 to 74	73 to 48	125 to 135	225
Thermal conductivitiy, Btu/h/ft^2/°F/ft	91	75	20	16
Average coefficient of thermal expansion, in/°F × 10^6	12.8	13.1	7.10	6.10
Density, lbs/in^3	0.101	0.101	0.284	0.280

performance, provided the tool is cooled, vented, and gated in a manner equivalent to that of the production tool as shown in Figures 5.29 and 5.30. Soft metal prototype molds are easily modified and can be designed with significant versatility, such as alternate gate locations as shown in Figure 5.31. Prototype tools are often initially built without features such as ribs, if there is some questions as to their inclusion (i. e., steel safe design) [5]. Interchangeable insert mold constructions have also been shown to be useful for both prototype and production tools for smaller parts. The interchangeable insert tools utilize common mold frames, and as a result, can reduce the machining requirements for the tool, resulting in shorter lead times [51].

5.1.6.4 Prototyping in Die Cast Tooling

In a limited number of applications, engineering plastic materials are used as direct replacements for metals with little or no change in part geometry. While it is better practice to design the part from "the ground up", many die cast metal parts are converted almost directly with few changes. It may be possible to convert the existing die cast tool to a prototype plastics tool, and in some cases, to a limited production tool while conventional, production plastics tooling is being built [53, 54].

The die cast tool could be run in a conventional thermoplastic injection molding machine, however, these tools are generally larger than standard thermoplastic molds and may require more platen area. A number of tool modifications are also required. Die cast parts are generally produced with thicker walls and sharper corners or fillet radii compared to thermoplastics. Rounding of sharp core corners or internal comer welds are modifications that would be required to reduce stress concentrations at wall intersections. The cavity and core surface finish may also need to be improved. Die cast tools are generally designed with a significant amount of venting to assist the high speed filling operation. The number or depth of the vents may need to be reduced to avoid excessive flash at the parting line.

The dimension of plastic parts produced in a die cast tool are likely to be different than the metal parts they replace. The molding shrinkages for zinc and aluminum are significantly lower than the mold shrinkage for a semi-crystalline thermoplastic such as nylon 6,6 which can be as high as 2.5 %. If assembly tolerances are tight, some machining may be necessary in order to obtain a proper fit. However, in metal to plastic replacement applications, the use of existing die-cast tooling for prototyping purposes is likely to save a significant amount of development time, since a large number of prototype plastic parts can be produced very early in the development cycle at a reasonable cost.

5.1.7 Low Pressure Structural Foam Prototypes

The need for prototype structural foam parts in product development is perhaps even more important than the prototyping needs for conventional thermoplastic parts. The property and design data available for these anisotropic, nonhomogeneous materials is often very limited. Unfortunately, molded structural foam parts are commonly used in applications where the parts are large, and production volumes are limited. The cost of large prototype molds can be very high, while low volume part prototyping budgets are often very small. As a result, the concept of steel safe (or aluminum safe) design is sometimes practiced with structural foam parts. In such a case, the prototypes parts are actually the first shots off of the production tool. The soft production tool dimensions are then modified based on the prototype test results. Like conventional solid moldings, structural foam prototype parts can also be described as facsimile prototype models or production (molded) prototypes. The molded prototypes are required for product testing or for an evaluation of the proposed tool design [2].

5.1.7.1 Facsimile Structural Foam Prototypes

Facsimile prototypes provide a working, life size or scale model which can improve communication, assist product promotion, provide geometric verification, or evaluate compatibility with assembly requirements. The models may also function as patterns for mold casting operations. Structural foam facsimile prototypes are most commonly fabricated from structural foam sheet stock, if it is available. The geometry of parts produced via this technique is limited, although crowned surfaces can be obtained by heating the sheet. The fabricated models should be made using materials that reflect, as closely as possible, the properties of the material to be used in the final application [2]. Hand fabricated prototypes can be generated soon after the part geometry has been conceived, however, they are of limited use in engineering testing, and are expensive on a per piece basis, limiting the technique to the production of one or a few models. Some limited engineering work, such as in locating areas of high stress or deflection, may give a rough indication where ribs or thicker wall sections are necessary. Solid facsimile models of structural foam parts having more complicated geometries can be produced using conventional prototype fabrication or casting methods.

5.1.7.2 Production Structural Foam Prototypes

Production prototypes allow a molder to produce a limited number of molded parts using virtually any polymer/foaming system. Parts generated using true to life molding techniques are more useful for engineering analysis, while the processing characteristics of the tool are simultaneously evaluated, leading to optimization of the production tool design. Various types of prototype tools are available ranging from very soft single shot tools to durable machined metal plate tools. Softer tools are less expensive and have shorter delivery times compared to hard tooling, however, they have shorter and more unpredictable service lives. Prototype tools can be built to various degrees of complexity with respect to cooling and ejection systems. However, it is important that structural foam tools are well vented. Extra care should always be observed when setting up prototype tools, as even the low clamp pressures of structural foam machines can damage soft tooling.

Structural Foam in Plaster Molds: A metal framed cast plaster tool (cast from a pattern) is perhaps the lowest cost and fastest method of producing a prototype tool for the low pressure structural foam process. However, these tools could be limited to a single shot or part. Given only one chance to make the part, the tool can be allowed to flash to relieve internal pressure and serve as an indication that filling is complete.

Structural Foam in Die Cast Tools: In instances where structural foam part is to replace a die cast metal part, the die cast tool can be modified and used for prototyping purposes as described in Section 5.1.6.4. For parts with relatively flat geometries, the parting line can be shimmed to produce a thicker flat section, while sidewalls and ribs remain thin and most likely solid. Fast fill speeds would be required to fill out thinner sections.

Structural Foam in Cast Epoxy Molds: Cast epoxy tools can be used to produce anywhere from a few to as many as 25 to 100 parts. The number of parts that the tool can produce is determined by both the complexity of the part and the molding conditions. Filled or reinforced epoxy formulations exhibit reduced casting shrinkages, increase stiffness, higher thermal conductivities and lower coefficients of thermal expansion. Cooling channels can be cast into the tool if more than a few parts are required. If no cooling and/or ejection provisions are added, the injection unit may need to be purged periodically until the part is cool and rigid enough to prevent distortion or post blowing. High internal pressures, high temperatures, and parting line wear are concerns with soft epoxy tooling. Wear plates can be added and lower processing temperature polymers should be used whenever possible. Cast silicone tools can be used in place of epoxy for very simple, shallow draw applications, when only a few parts are required.

Structural Foam in Metal Shell Molds: A more durable epoxy tool can be produced using metal shell technologies such as spray metallization, vapor deposition, or electroforming as described in Section 5.1.6.2. These thin metal shells, which are formed over a pattern, are backed with an aluminum powder, chip, or needle filled epoxy resin. The aluminum filler

Table 5.7 Relative prototype tooling costs [2]

Mold material	Relative cost*
Machined steel	100
Machined aluminum	50–70
Cast aluminum	40–50
Cast epoxy/metal shell	30–40
Cast epoxy	20–30*

* Based on a production tool cost index of 100

increases the stiffness and thermal conductivity, and brings the coefficient of thermal expansion closer to that of the shell. Cooling systems can be cast into the epoxy using copper tubing or machined along with ejection provisions. The tool is typically encased in an aluminum plate frame for support and clamping. Metal shell tools are relatively durable and can be produced at a fraction of the price of conventional machined molds.

Structural Foam in Cast Metal or Metal Plate Molds: Low melting temperature metals or alloys can be cast over a pattern to produce a durable tool directly. Aluminum, zinc alloy or even beryllium-copper (for smaller parts) molds capable of producing more than 1 000 parts with good surface reproduction capabilities can be used for structural foam parts. The metal casting techniques require higher temperature patterns and some machining after casting. Cast tools are an alternative to preproduction tooling that would generally be made using metal plates, usually aluminum, for a low pressure structural foam tool.

Prototype tooling programs often run concurrent with production tool building due to the lead times involved, especially for the harder tools. The decision to go with machined metal or soft tooling is not straightforward since it is likely that the designer may learn more with the harder tooling; however, by that time, the production tool may be past the point where significant changes can be made easily.

5.1.8 Coordinate Measuring Machines

Accurate measurements on production parts, prototype parts or tooling can be made using coordinate measuring machines (CMMs) in a fraction of the time possible with conventional techniques. Although this type of equipment has been available since the 1970s, integration of computer technologies and increased tolerance requirements for plastic parts have led to an increase in their use [55].

5.1.8.1 Contact Measurement Systems

CMMs consist primarily of a touch sensitive probe arm attached vertically to an overhead gantry or horizontally to a vertical guidebar. The three axes of motion are achieved by having the probe move in an x-y plane, while z axes motion is provided by the gantry or guidebar.

In certain cases, the probe can rotate for additional flexibility. Parts are placed on dimensionally stable granite surface block tables and the servo-controlled probe is brought to the parts surface (automatically or manually). When the probe touches the workpiece, the point of contact is defined in terms of the *x*-*y*-*z* axes of the coordinate system. The probe then moves to the next point of measurement and so on. The data are interpolated to determine the distances between the points and translated into part dimensions. The CMMs are extremely useful for evaluating the differences between actual and target dimensions on molded prototype parts, especially for parts with contours and irregular surfaces.

5.1.8.2 Non Contact Measurement Systems

Coordinate measuring machines are routinely measuring to 0.0001 in (0.0025 mm) and are therefore susceptible to humidity, vibration and temperature drift. Granite tables, ceramic machine components and environmental control have been used to address the problem, however, the use of contact measurement probes can still be a particular problem with flexible or soft plastic parts. Non contact coordinate measuring equipment, using lasers and video cameras, are promising new technologies. One system uses laser triangulation to lock onto a point, and analog LVDTs to determine the position of the probe axis [55]. Another system consists of a fixed platform with a rotating camera. As the camera rotates, a laser-based digitizer takes more than 250 000 three axis measurements in a matter of minutes. These measurements can be viewed on a computer screen and downloaded to NC machine equipment [8]. While the non contact technology offers a number of advantages, it can be sensitive to the surface finish and lighting conditions one might encounter when measuring inside dimensions. Future technologies such as magnetic resonance imaging may be able to both measure part dimensions and detect material flaws at the same time.

5.2 Experimental Stress Analysis

5.2.1 Introduction

Prototype plastic parts are commonly used to verify the performance of a proposed part design. The verification requirements range from geometric to structural, depending on the end-use requirements of the part. Parts intended for engineering applications are likely to require several prototyping steps, where environmental and structural characteristics of both the molding material and part geometry are evaluated. Ideally, the design engineer would like to evaluate molded prototype parts made using the production material formulation, however, the costs and time associated with a full product evaluation can be extensive. Design engineers may work with facsimile prototypes (such as machined or cast polyurethane parts) rather than production prototypes initially. The costs and turn around time for these facsimile prototypes allow the designer to evaluate the basic design, and potential problems related to part geometry. Based on the results of the initial studies, the part design would be altered, and a series of production prototypes, those produced using preproduction or prototype tooling, would then be evaluated in terms of product performance. Processing related factors, such as weld line strengths or morphological/orientation effects, can be evaluated using these molded prototypes.

A common objective of an experimental engineering study is to evaluate the performance of a true to life part subject to typical or worst case environment and loading conditions. Unfortunately, the product engineer may not be able to quantitatively define the typical or worst case service load or environment during the end-use application. It may be necessary to monitor service loads and environments as part of an overall prototype product evaluation program, although ideally, their limits should have been quantified very early in the design process. It is also important to develop a database of product testing results for future application for similar product development projects.

This section will discuss some of the basic techniques that can be used to evaluate the stress level in prototype or production parts. It is important to indicate that experimental stress analysis techniques do not measure stress, rather they measure strain or deformation (usually surface strain). The measured strains are then converted into stress using linear or non linear stress-strain relationships, i. e.,the appropriate modulus for the material being tested. Plastic parts are produced in a wide range of sizes and shapes, and are subjected to various types of loads and environmental conditions. As a result, a number of experimental stress analysis techniques are commonly used. These techniques include simple extensometer measurements, brittle coatings, electrical strain gaging, solvent testing, photoelasticity and direct optical measurement. The selection of the most appropriate technique(s) is determined by such factors as whether the test is a field or laboratory test, the type of strain to be measured (uniaxial, biaxial, tension, shear), the expected range of strain, the resolution of strain field required, and the operating environment. In many cases, a combination of experimental techniques is most appropriate [56, 57].

5.2.2 Brittle Coatings

Brittle coatings in the form of sprayed lacquers can be used to evaluate the surface strains in plastic parts. These coatings are especially useful when the direction and distribution of the strain are unknown. The brittle coatings are strain sensitive lacquers that are sprayed over the entire surface of the part to be evaluated (or as stripes), are allowed to dry, and are observed during or after external loading. The brittle coatings, available in a series of strain sensitivities, will show cracks that run perpendicular to the direction of the largest principal stress and are parallel to each other. The crack pattern will give an indication of the overall strain distribution, including the magnitude and directions of the strains [6, 56, 57, 59, 61].

This technique is an excellent method for obtaining a quick indication of high stress areas on a part (indicating the need for a design change) or for pinpointing the high stress location for more extensive strain gage testing. The coatings are formulated to crack at specific threshold values of strain, allowing a designer to approximate the maximum principal stress level. The stress value in the region of the crack is determined using the appropriate modulus value for the polymer, and the brittle coating's threshold strain:

$$\sigma_{\mathrm{p}} \geqslant E_{\mathrm{p}}\varepsilon_{\mathrm{t}} \tag{5.1}$$

The test is by nature incremental, providing crude strain sensitivity in comparison with a strain gages [56, 57]. However, the brittle coating technique has the advantage of displaying the entire strain field and strain gradient. The technique is described as semi-quantitative and calibration samples of regular geometry, for which stress or strain can be calculated, should be used in combination with the experimental analysis.

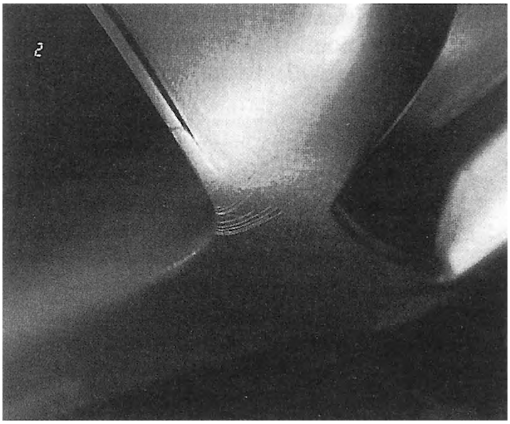


Figure 5.35 Cracks appear in a coated prototype housing after being loaded (Courtesy Miles Corporation, Pittsburgh, PA)

Brittle coatings provide an excellent indication of potential problem areas on a part, however, the technique does have limitations. The coating is a paint containing chemicals or solvents that could interact with the surface of the plastic part to be coated. In addition, the coating should be as thin as possible to avoid magnification effects. The method also assumes perfect adhesion between the strain sensitive coating and the part to which it is applied. The use of sealers or primers may improve stress transfer and act as barriers, but should be used only in cases where they are absolutely necessary due to coating thickness build up and related magnification effects. Residual stresses are not easily determined using this technique, and as a result, the coatings are primarily used in the evaluation of external assembly or end-use loading related stresses. In addition, a relatively large number of prototype parts may be required for a thorough experimental analysis. The principle stress value determined using this technique is only an estimate since the test results are affected by factors such as the composition of the coating, the coating temperature, the thickness, the environmental conditions and the biaxiality of the stress field. More quantitative techniques, such as strain gage studies, are a good follow up to the brittle coating strain measurement technique [59].

5.2.3 Strain Gages

The most widely used tool for experimental stress analysis is the bonded electrical resistance strain gage. Strain gages are useful for quantitative analysis of surface strains associated with either external loads or internal stress release [56, 58–60]. The resistance, *R*, for an electrical conductor or length, L, and uniform cross sectional area, A, is given by (5.2)

$$R = \varrho \frac{L}{A} \tag{5.2}$$

where ϱ is the resistivity of the conductor. If the conductor is stretched or compressed, its resistance will change due to changes in the conductors length and cross-sectional area, and the conductor's piezo resistance, an indication of the dependence of resistivity on mechanical strain. Conductors bonded to the surface of plastic parts will transform surface strains caused by a stress, into electrical resistance changes in a linear manner [49, 62].

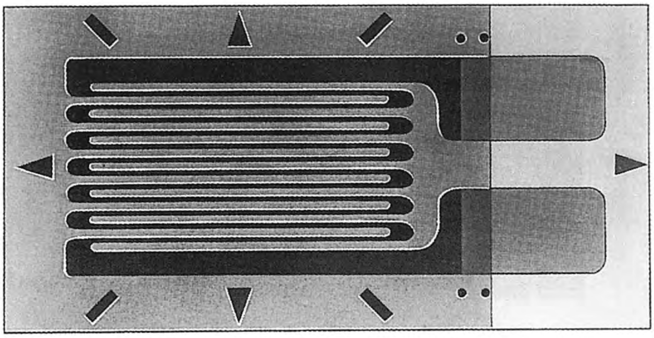


Figure 5.36 Typical uniaxial foil strain gage (Courtesy Vishay Precision Micro-Measurements Group)

While many types of strain gages are available for use as transducer elements, bonded metal-foil strain gages are used almost exclusively for general purpose stress analysis work. The gage is an extremely thin, small, strain sensitive electrical resistor bonded to a flexible backing material to assist handling. When the gage is bonded to the part under test, it transforms surface strains caused by stresses into electrical resistance charges. The conductive sensing elements are formed from sheets less than 0.0002 in (0.005 mm) thick using a photoetching process. The foil geometry is such that it maximizes the length of the conductor along a particular axis. The linear grid shown in Figure 5.36 is designed with fat end turns to reduce transverse sensitivity, a spurious input since this particular gage is intended to measure strain component along the length of the grid element (uniaxial). Foil gages also contain integral soldering tabs or presoldered leads [62].

The gage alloys used on most gages are copper/nickel, (constantan) or nickel/chromium alloys for very low or higher temperature work [56, 60]. Semiconductor or piezo electric gages are technologies which provide high precision strain measurements for very low strain or dynamic applications [56, 58, 62]. The foil gages come mounted on a flexible carrier film having a thickness of approximately 0.0010 in (0.025 mm), bringing the overall thickness of the gage to 0.0012 in (0.037 mm), plus the thickness of the adhesive layer, between the film and the surface of the part. The magnification error is expected to be significant only for thin wall sections, and can be nearly eliminated analytically. The adhesives used for strain gage testing (i. e., to bond the foil gage to the plastic part) are typically reactive monomeric adhesives. These adhesives offer good strength characteristics and low viscosity, generating a thin bond line. The quality of the adhesive joint is critical to the proper operation of the strain gage, since it is the link between the specimen and the carrier film. Problems may arise in the bonding area when working with very low surface energy plastic parts, or working in extreme temperatures and humidities. Parts should be cleaned and handled in accordance with standard adhesive bonding preparation practices for the plastic material being evaluated.

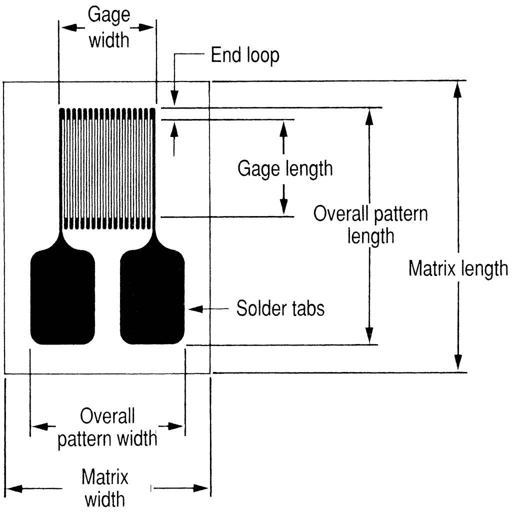


Figure 5.37 Nomenclature and features of typical foil strain gage (Courtesy Micro-Measurements Division of Measurements Group, Inc., Raleigh, NC)

Strain gages vary in the active grid size from approximately 0.010 in to as much as 4.0 in (0.25 to 102 mm). It is not possible to obtain a measure of strain at a geometric point since the grid covers a finite area, thus the gage reads an average strain over the area. If the strain gradient in the part beneath the grid is linear, the average value can be associated with the midpoint of the gage length. If the gradient is not linear, the point at which the gage's reading applies is somewhat uncertain. This uncertainty diminishes as gage size decreases, indicating that smaller gages are more appropriate for steep strain gradients, such as those occurring at wall intersections [62].

The gage sensitivity to strain, known as the gage factor, is the ratio of unit resistance change ($\Delta R/R$) to unit strain ($\Delta L/L$) and is given by:

$$G_{\mathrm{f}} = \text{Gage factor} = \frac{dR/R}{dL/L} = 1 + 2\nu + \frac{d\varrho/\varrho}{dL/L} \tag{5.3}$$

where ν is Poisson's ratio for the gage material. The gage factor is determined by the sum of the resistance change due to the length change, the resistance change due to the area change, and to the resistance change due to the piezo resistance effect. The strain in the gage (and

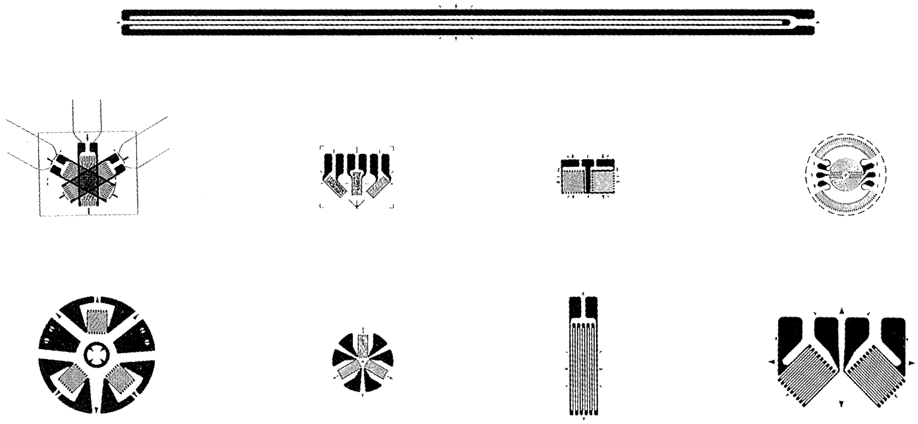


Figure 5.38 Common bonded foil strain gage configurations including uniaxial gages, planar rosettes, and stacked rosettes (Courtesy Micro-Measurements Division of Measurements Group, Inc., Raleigh, NC)

part) can then be determined by measuring the change in resistance due to loading:

$$\varepsilon = \left(\frac{\Delta R}{R}\right)\left(\frac{1}{G_{\mathrm{f}}}\right) \tag{5.4}$$

The resistance of an individual unstrained strain gage is relatively easy to measure, however, measurement of the gage factor requires cementing the gage to a specimen for which strain can be accurately calculated theoretically (i. e., regular geometry, homogeneous, elastic material) which would render the gage unusable. The gage-factor numbers supplied with purchased gages have not been determined individually, but are an average value obtained using samples from the same production run [62].

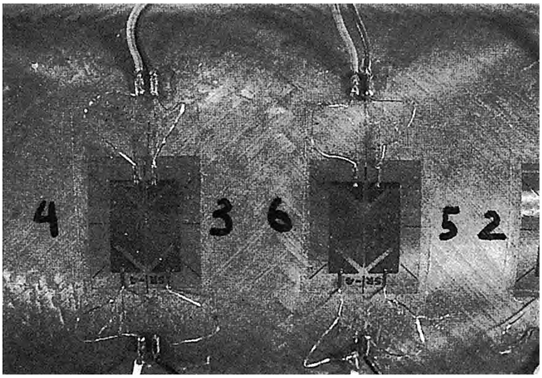


Figure 5.39 Example of a bonded foil strain gages used to evaluate surface strains for a plastic part

A series of multi-element strain gages having various configurations are also available. Strain gage rosettes, as they are called, reduce set up time and improve accuracy by eliminating the need for precise alignment of multiple, individual, single axis gages. For example, a three gage rosette, such as the planar rosette shown in Figure 5.40, will allow the determination of the magnitude and direction of an unknown surface stress [56, 57, 59-62]. Ideally, the three gages would be mounted at different angles, but at the same point. However, a stacked rosette suffers from disadvantages associated with heat build up and strain magnification errors, which may outweigh the advantages of the stacked point design [62]. In cases where the principle axes of a biaxial stress field are known, only two independent strain measurements are required to determine the principle stresses. This could be done using a two gage 90° rosette where the gage axes are in line with the principle axes [56]. Brittle lacquers can be useful for determining the location and the direction of the principle stresses before strain gages are mounted on replicate parts to evaluate the magnitude of the surface strains [58].

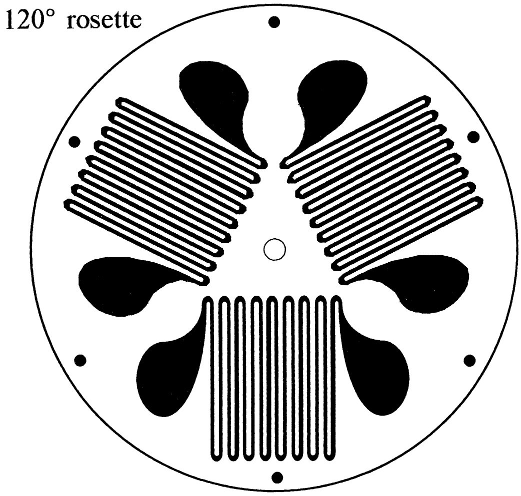


Figure 5.40 Typical planar rosette geometry

The measuring instruments used for the detection and presentation of the output from an electrical resistance strain gage are most often based on a wheatstone bridge circuit, in which the experimental strain gage forms one of the bridge legs. Temperature and humidity effects are important considerations in strain gage experimentation, since strain induced resistance changes can be quite small. Changes in temperature influence both the resistivity of the gage foil and the dimensions of all system components, while variations in relative humidity can change dimensions of hydroscopic adhesives, carriers and plastic parts. The thermal or moisture induced expansion mismatch between the gage and the underlying materials can result in significant error. Temperature compensated gages can be used, or the effects can be compensated for, or balanced out, by mounting a second strain gage (identical to the active gage) to an unstressed, dummy part. The dummy and active gages are placed on adjacent

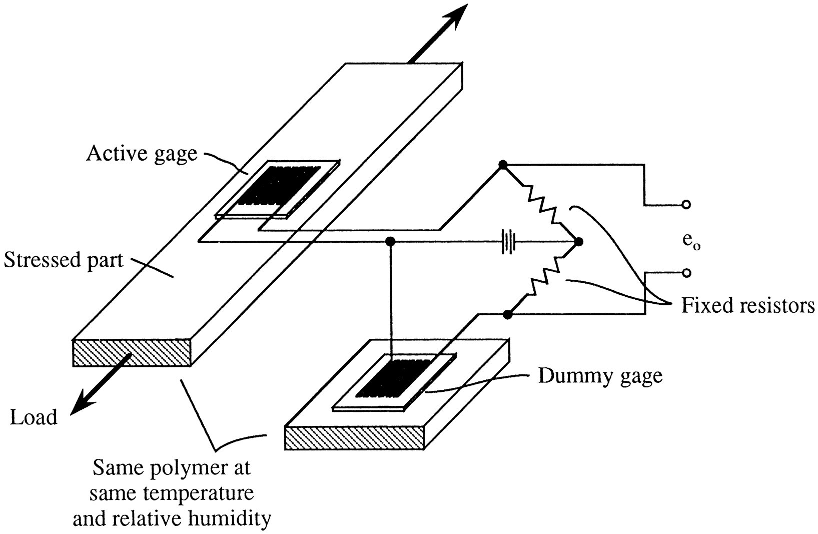


Figure 5.41 Wheatstone bridge circuit used with an active strain gage, and a dummy gage to compensate for temperature variation

legs of the Wheatstone bridge circuit, thus resistance changes associated with changes in the environmental conditions have no net effect on the bridge output [62].

Residual stresses, such as those introduced during the injection molding process, can be evaluated using strain gage techniques. Residual stress are important because they can lead to environmental stress cracking, warpage at elevated temperature, or may contribute towards product failure when service loads are superimposed on them. The residual (molding) stresses can be estimated using a strain gage "demolding test" [63] or a blind hole drilling technique [59]. The demolding tests are essentially unfixtured, elevated temperature stress relieving procedures, where the part is instrumented with strain gages. In the blind hole drilling technique, a rosette (typically a 3-element 120° planar foil gage) is mounted at the location of the strain measurement on the surface of the internally strained part. Drilling a small blind hole at the center of the rosette relieves the residual stress at that point, resulting in a measurable strain in the strain gage elements around the hole.

Bonded foil strain gages are perhaps the single most important tool for quantitative stress analysis. This technique has the potential to be sensitive to strains as low as 1 µm/m, can be used over a wide range of environmental conditions, and can be useful in the evaluation of residual stress. The primary limitation of the bonded foil strain gaging technique is that it provides only an average indication of the surface strain over a local area, rather than a stain gradient [56].

5.2.4 Solvent/Chemical Testing

The presence of internal or external stresses in a plastic part will reduce the solvent resistance of the part. This phenomenon can be a problem in service, where parts may craze, crack or fail at relatively low stress levels when exposed to a hostile chemical environment. However, the environmental stress cracking behavior of a particular polymeric material, when exposed to a particular solvent system, can be characterized and quantified, resulting in a potentially useful tool for experimental stress analysis.

One solvent based stress analysis approach uses two solvents of different strength, mixed together in a series of volume ratios. The strong solvent would be aggressive for the polymer in question, while the second solvent would be a miscible non-solvent. The term strength is most easily quantified as solubility parameter. As a general approximation, in the absence of strong interactions such as hydrogen bonding, solubility of a polymer in a solvent can be expected if the difference between the solubility parameter of the solvent and the polymer is less than about 1.7 to 2.0.

Polymethyl methacrylate, having a solubility parameter of 9.10, would be expected to dissolve in benzene with a solubility parameter of 9.15, but not in methanol, with a solubility parameter of 14.5 [64]. Solvent/nonsolvent mixtures can be made up in various ratios, to produce solvents of various strength. For example, in the case of polycarbonate, mixtures of toluene and n-propyl alcohol or ethyl acetate and methylalcohol have been used experimentally with good success [59].

The stressed plastic parts are dipped into containers, or coated with the solvent mixtures at a specific temperature for a specific period of time. The parts are then cleaned and dried of excess liquid. The appearance of cracks or crazes on the surface of the part indicates that the stress levels at that location of the part are equal to or higher than the critical stress level of that particular solvent mixture. This critical or threshold stress level for each solvent mixture/material would be determined in a set of calibration experiments with externally loaded samples of regular geometry, molded in the same polymer, for which theoretical stress calculations can be correlated with the onset of crack formation. The relative effects of residual and load related stresses must be separated using proper sample preparation and stress relieving techniques. Cracks develop perpendicular to the direction of the stress. The onset of crack formation can be correlated through the calibration samples to stress in the molded part using an appropriate ranking system. The accuracy of the test is determined by the number of solvent mixtures used (i. e., stress increment between critical stress values) and the judgment of the investigator, as the visual inspection can be to a large degree subjective.

A second approach to solvent stress analysis is to use one solvent of appropriate strength or solubility parameter, and evaluate the time duration from solvent application to crack initiation [57, 65]. For this method, parts must be continuously exposed to the solvent or solvent vapor. The method is especially appropriate for a semi-crystalline material such as high density polyethylene, which exhibits resistance to most solvents. The stressed parts can be placed in a transparent container along with the solvent or solvent vapor and inspected using time lapse photography or periodic visual inspection. The test can be accelerated by increasing the test temperature, although any significant internal stress relief at the higher

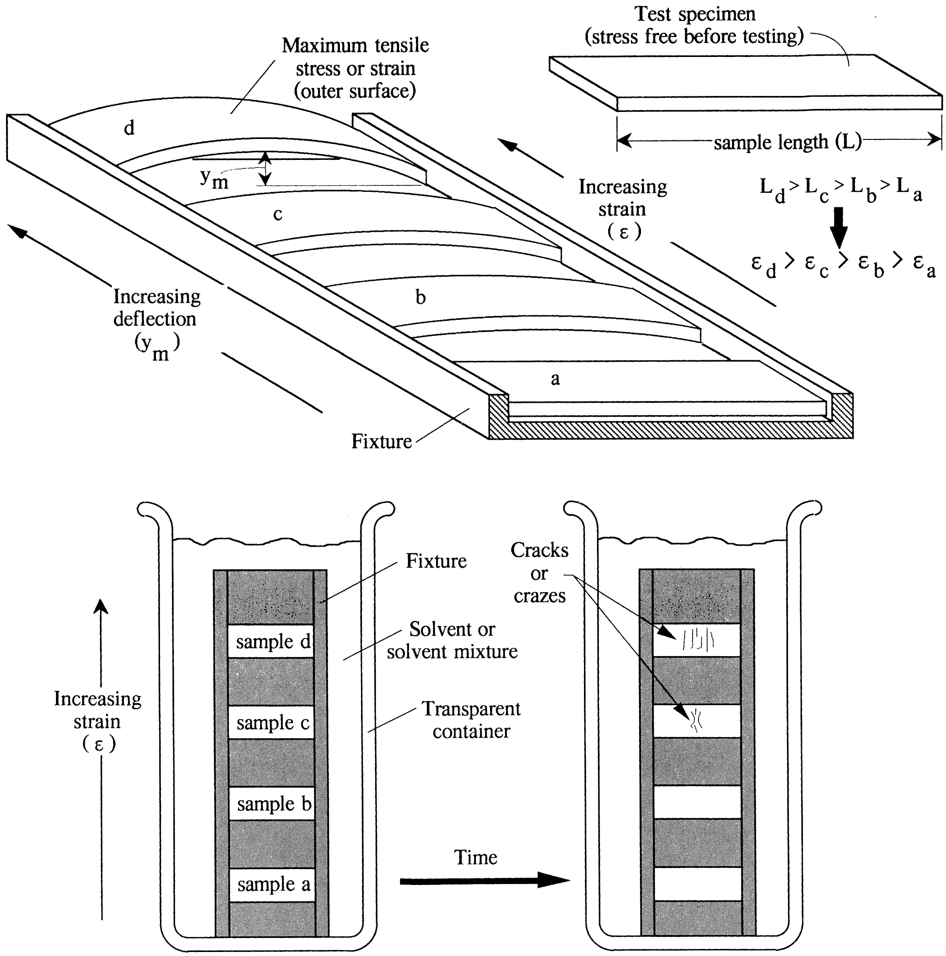


Figure 5.42 Solvents can be used to evaluate the stress level for many polymers, however, the stress crack resistance of the polymer must be quantified. Calibration samples produced from the same base polymer as the part being studied can be used to establish the relationship between tensile stress level and the appearance of cracks (in the presence of particular solvent)

temperature could invalidate the result. Cracks appear first at the areas of highest stress. A quantitative correlation can be obtained by placing stressed control samples of regular geometry (with stress levels that can be calculated theoretically) in the same enclosure as the part [63].

Solvent stress analysis techniques are quick, semi-quantitative tests that are especially useful for determining residual stress levels in molded plastic parts, however they can also be useful for evaluating load induced stress. It is important to note that proper safety precautions and proper ventilation should be utilized when working with potentially hazardous organic solvents.

5.2.5 Photoelastic Testing

Photoelasticity is a full-field, visual technique for measuring stress. Some isotropic plastic materials exhibit a temporary, double refractive index when stressed. The index of refraction will change with the level of stress (or strain), making this optical property the basis of the photoelastic testing technique. When a model or part made from a photoelastic material is loaded and viewed under polarized light, colorful fringe patterns are observed as shown in Figures 5.43 and 5.44. The fringe pattern or contours can be viewed analytically to provide an accurate indication of the magnitude and direction of the stress at a given location. The technique is useful for evaluating both processing related and externally induced stresses.

When the photoelastic material is stressed, the material becomes birefringent. Polarized light passing through the stressed material splits into two beams, each vibrating along a principle stress direction and travelling at a different speed. The phase shift between the two beams produces the colorful fringe pattern observed using the polariscope. Using the polariscopes measuring system, the plane of vibration is established to permit measurement of the principle stress directions. The phase shift is measured by optical compensation to determine the stress magnitude [56, 67].

Photoelastic testing is done using either two dimensional photoelastic models, three dimensional photoelastic models, or parts coated with a photoelastic material. Photoelastic model analysis is most useful at the early stages of product design where facsimile prototype parts can be made using a transparent photoelastic material such as polycarbonate, polymethylmethacrylate or cast polyester. Two dimensional models are generally cut from a flat, stress free cast sheet, typically 0.250 in (5.35 mm) thick, following machining practices which minimize machining stresses. The sheet is placed in a transmission polariscope along with wave plates of specific relative retardations. Part size is limited by the size of the polariscope, and scale models, such as the automotive panels shown in Figure 5.43, are sometimes evaluated. This experimental stress analysis technique is especially useful for evaluating stress concentrations due to holes, notches or other surface discontinuities [6, 59, 63, 66, 67].

More complex three dimensional photoelastic models can also be evaluated. In one technique, the three dimensional models are loaded or strained while at an elevated temperature in an oven, and cooled slowly back to room temperature to freeze in the photoelastic pattern [57, 67, 68]. The models or model sections can be cut into two dimensional thin slices using slicing techniques, and analyzed using a light transmission polariscope or microscope equipped with a polarizer/analyzer and a variable intensity light source. Sections of the part can be backed or embedded in a cast epoxy before slicing to maintain the dimensional stability of the part during the cutting operation. Small section slices of the part can be mounted on a microscope slide and viewed under polarized light.

Another widely used photoelastic technique involves coating a plastic part with a thin, uniform layer of a photoelastic material and using a reflection polariscope to analyze the effects of external loading. The technique is extremely attractive since it can be used with

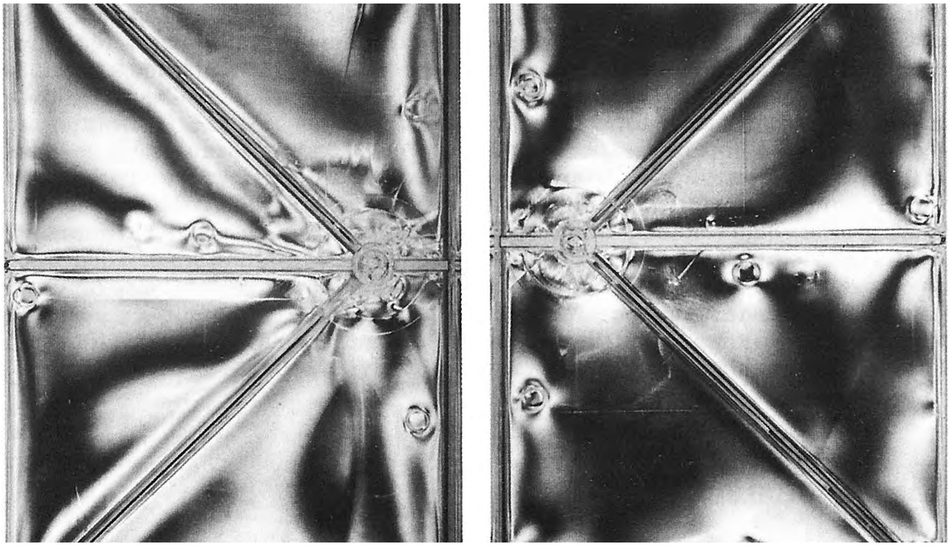


Figure 5.43 The residual molding stress levels for a part produced from Lexan® polycarbonate resin are evaluated using photoelastic analysis. The part on the left was molded via conventional injection molding, while the part of the right was molded using a lower stress injection-compression molding process. (Courtesy GE Plastics, Pittsfield, MA. Lexan® is a registered trademark of the GE Plastics)

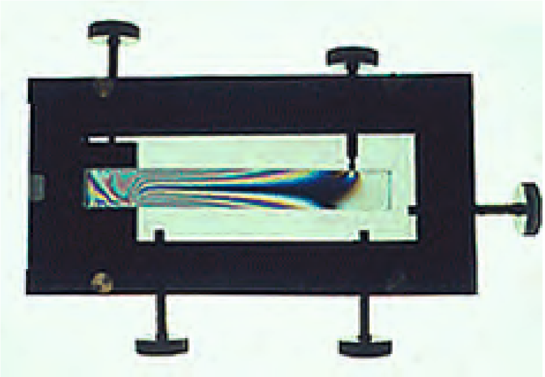


Figure 5.44 The residual molding stress levels for a part produced are evaluated using photoelastic analysis.

parts of virtually any size, shape or material, even those that are opaque. Prototype parts molded using the production material can be coated and evaluated. The surface strain distribution is displayed over the entire area, even for very steep strain gradients.

5.2.6 Optical Strain Measurement Techniques

A number of direct optical measurement techniques are also used in the area of experimental stress analysis. These techniques are commonly based on the principles of optical interference and include Moiré, laser or holographic interferometry.

Moiré Techniques: Moiré is the name given to the optical effect one observes when two closely spaced grids of parallel opaque lines, with equal width transparent bands, are superimposed. If the line spacing or orientation of one grid changes, periodic mechanical interference of transmitted or reflected light occurs, and a pattern is produced. The concept is used in stress analysis by bonding one of the identical grids to the part before it is loaded, using the other grid as a viewing reference. The grids are aligned precisely before the test part is strained. When the part is loaded, surface strains on the part and bonded grid deform the grid shape, causing fringes to appear when viewed through the reference grid [6, 56]. The interference is due only to geometric blocking of the light (ordinary white light) as it passes through or is reflected from the grids. The Moiré technique can also use photographic imaging techniques to produce and project grid images. The technique may be useful for high temperature work or where large plastic or elastic strains are involved, however, it is limited in many applications due to practical difficulties associated with making accurate strain measurements for small strains or steep strain gradients [43].

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