Such contourings – apart from the characteristics of the really contouring element, for example, the nozzle diameter – all have the droplet diameter and the blade diameter in common which primarily determine the precision of the employed x-y-(z) handling system and the quality of the model. The mechanical setup, the incremental actors, and the quality of the control are important influencing variables.

2.3 Generation of the Physical Layer Model

All rapid prototyping processes work in two steps when generating the physical layer model:

- Generation of a cross section (x-y plane)

- Joining this layer with the preceding one (before, during, or after the layer generation, z-direction)

Joining the layers in the z-direction with one another is achieved in the same way as joining them in the x-y direction, with the exception of layer lamination processes: The energy or the amount of binder necessary for the joining is proportioned in such a way that not only the layer itself but also part of the preceding layer is affected and thus joined to the new layer. In layer lamination processes the layers are cut out of foils with predetermined thicknesses (z-increment) and glued on top of each other.

For the implementation of the rapid prototyping principle several fundamentally different physical processes are suitable:

- Solidification of liquid materials (polymerization process) (Section 2.3.1)

- Generation from the solid phase (Section 2.3.2)
    - Cutting from foils or ribbons, milling from slabs or other materials (layer process)
    - Incipiently or completely melted solid materials, powders, or powder mixtures (extrusion and sinter processes)
    - Conglutination of granules or powders by additional binders

- Generation from a pasty phase

- Precipitation from the gaseous phase (Section 2.3.3)

2.3.1 Solidification of Liquid Materials Photopolymerization – Stereolithography (SL)

All processes in which the underlying mechanism is solidification of liquids (including pasts) are based on the concept of photopolymerization. They use a viscous monomer with few or no crosslinks that is interspersed with suitable photoinhibitors. Exposure to ultra-

violet radiation sets off a spontaneous polymerization, in the course of which the liquid monomer becomes a solid polymer. This process, which in principle also works under sunlight is adjusted to the special requirements of rapid prototyping regarding exposure strategy. Either a fine laser beam describes the contour of the particular cross section onto the surface of a resin bath (and that is the most common method), thereby generating the necessary critical energy density and consequently the necessary solidification locally, or the entire cross section is imaged onto a transparent mask by a process similar to photo-copying and is projected by means of strong UV lamps through this mask onto the surface of the resin bath. There are also processes that trigger the polymerization thermally. Today, however, they are still of no commercial significance.

Basic Principles of Polymerization

Polymerization is a chain reaction in which unsaturated molecules are linked to macromole-cules (polymers) [GRU93]. The liquid mixture of single molecules (monomers) is converted into crosslinked, cured plastics.

The monomers consist mainly of hydrocarbon compounds and possess double linkages that can be broken by heat or catalysts. A chain reaction follows in the course of which the monomers are linked to polymer chains. Depending on the type of reactive particles bringing the polymerization about, so-called radical, cation, and anion polymerizations are distinguishable. For the use in rapid prototyping processes (see Section 3.3.1) the radical and the cationic polymerizations are relevant. There are three different phases in polymeri-zation:

● Initial reaction

● Propagation reaction

● Termination reaction

The solidification of acrylates is based on *radical polymerization.*

During the initial reaction, an external energy input causes the initiators contained in the resin to disintegrate into their radicals, which are then left with a single unpaired electron on their outer shell [GRU93]. As the particle seeks to find a partner for its electron, radicals are extremely reactive.

During the propagation or growth reaction, the radicals react with the double-linked hydro-carbon in the monomer. Since the double linkage is broken, the monomer is also acquiring on one side a single electron on its outer shell. The new group reacts further with other monomers forming long polymer chains. The chain reaction is brought to an end by the termination reaction. The termination is caused by:

● Interlocking of two polymer chains into one

● Reaction of the polymer chain with the radical of an initiator

● Transfer of a hydrogen atom to a macroradical

● Elimination of a bondable hydrogen atom

The linkage of monomers to polymers is explained in the example of the polymerization of ethylene to polyethylene (Figure 2-15).
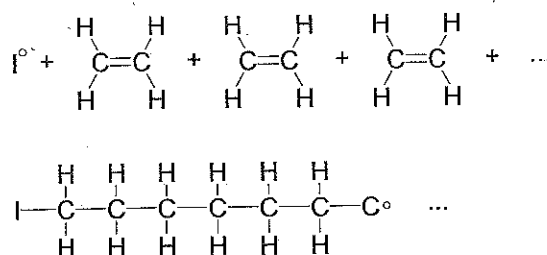

Figure 2-15 Polymerization of ethylene to polyethylene

The solidification of epoxy resins and vinyl ether resins is based on *cationic polymerization*.

In cationic polymerization, positive-charged ions (cations) always are found at the end of a chain. During the initial reaction, cations are generated from a catalyst. In most cases the catalysts are acids.

During the propagation reaction, ionic linkages are formed between the cation and the monomer. Further monomers can then be added to the end of the chain, which is now cationic.

The termination of the chain is brought about by an addition of anion from the catalyst. The termination of a chain by linkage of two polymer chains is impossible, as all reactive chain ends are positively charged.

An example of a cationic polymerization is the polymerization of isobutylene to polyisobutylene (Figure 2-16).
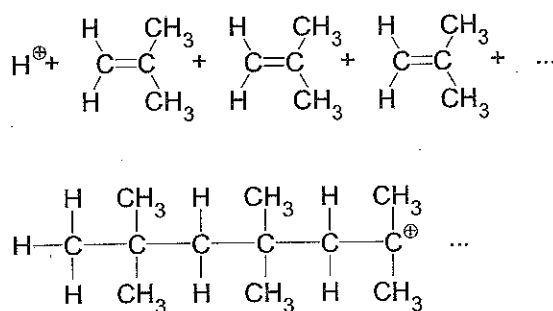

Figure 2-16 Polymerization of isobutylene to polyisobutylene

In stereolithography it is necessary to limit polymerization to allow specific single areas to be cured. In contrast to the polymerization processes in large-scale industry in which the disintegration of catalysts, for example, is started by heat input, the method employed is different here. The monomer is mixed with an initiator that disintegrates into two radicals or ions via the action of a photon of a certain wavelength. Because the polymerization can be started only with the aid of radicals or ions it is limited to areas affected by photon radiation.

The degree of polymerization is influenced by several factors. Among these is the presence of a degradative reaction, opposed to the growth reaction, that causes the monomers to separate from the polymer chains. The speed of this degradative reaction increases as the temperature increases so that at a certain ceiling temperature growth and decomposition are in equilibrium. Because polymerization reactions are highly exothermic (50 to 100 kJ mol^{-1}), large polymerization installations have to be cooled continuously to keep them under the ceiling temperature. It is not necessary to cool the resin in rapid prototyping installations as the polymerized amounts are too small. To achieve a temperature of approx. 25 °C to 30 °C which is beneficial for the flowability of the resin, even the resin container needs to be heated depending on the temperature of the environment.

The circumstances can change in the future with improved laser performance.

In addition to the degree of polymerization it is necessary to take into account the so-called polymerization rate, which defines the ratio of monomers not participating in the polymerization to the total mass. In contrast to the polymerization degree the polymerization rate grows with increased viscosity.

When monomers are linked to polymer chains the material is densified and the resin shrinks. This shrinkage causes tensions in the consolidated resin which can lead to warping and cracking. The extent of volume shrinkage for epoxy resins is 2% to 3%; for acrylic resins it is 5% to 7% (see also Appendix A2-15 to A2-19).

Laser-Induced Polymerization

A locally limited polymerization can be started by one of two processes:

- Reproduction of the entire layer by a smaller scale mask with the aid of a powerful ultraviolet light source (mask process, Figure 2-14c).

- Exposure to an ultraviolet laser beam, which "writes" the desired contours into the resin surface by means of certain scanning strategies (vector or raster processes, Figure 2-14a, b).

Although there are also processes that work with masks, laser stereolithography is the most important with respect to industrial implementation (see also Chapter 3). The basic principles of the laser and the characteristics of laser radiation are explained in [MIG96].

In the following passage some specialities are discussed which result from the use of laser-radiation sources for photo-polymerization.

Depth of the Cure Track

The local degree of polymerization and the rate of polymerization depend on the number of photons that pass through a certain activation cross section of the resin, thereby potentially reacting with the initiators.

From a critical surface energy (critical energy) onward so many photons react with the resin that it is transformed from a liquid to a solid state. This transformation point is called the gel point. At first the resin does not have any mechanical stability; only after the surface energy is increased the resin sufficiently polymerized to carry mechanical strain. The boundary surface inside the resin between the solid and the liquid state is formed by that surface in which the surface energy exactly corresponds with the critical energy.

For the surface energy irradiated on average onto the resin surface (z = 0), which is also the maximum energy affecting the resin surface, the following applies:

$$E_{max} = \frac{P_L}{v_s \cdot h_s}$$

(2.1)

with E_{max} = surface energy on the surface at z = 0
       P_L = average laser-performance
       v_s = speed of the laser beam
       h_s = hatch width

The absorption within the resin follows the Beer-Lambert equation:

$$E(z) = E_{max} \cdot \exp\left(-\frac{z}{D_p}\right)$$

(2.2)

with $E(z)$ = surface energy in the depth z
       E_{max} = surface energy on the surface at z = 0
       D_p = optical penetration depth of the resin.

The optical penetration depth D_p of a material is defined as the path length after which the intensity of a transmitted beam has dropped to the 1/e-fold part, or its energy to the $1/e^2$-fold part.

With the aid of the Beer-Lambert equation and the definition of critical energy E_c the cure depth C_d, down to which the resin is cured, is given as.

$$C_d = z(E_c) = D_p \cdot \ln\left(\frac{E_{max}}{E_c}\right)$$

(2.3)

With the first relationship between the laser performance and energy on the surface it follows:

$$C_d = D_p \cdot \ln \left(\frac{P_L}{v_s \cdot h_s \cdot E_c} \right) \qquad\qquad (2.3\,a)$$

As C_d is proportional to the logarithm of E_{max}, a straight line results if logarithmic representation is employed. The gradient of the straight line is defined by the value of D_p. The critical energy density, at which the cure depth is zero, is defined by the intersection of the straight line with the abscisse. As the curve is dependent only on the resin constants E_c and D_p and the maximum energy density, it is characteristic for a certain kind of resin and is also called a working curve (Figure 2-17) [HEL95][1].
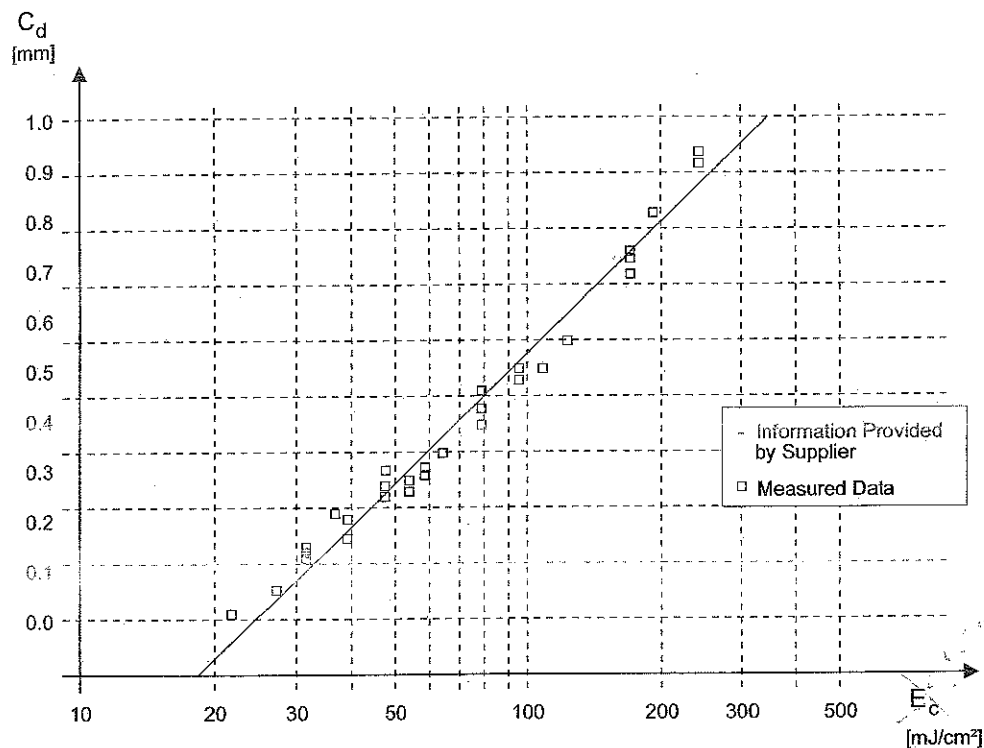

Figure 2-17   Cure depth as a function of the surface energy and the resin parameters, working curve
for the resin HS 660

Given the resin parameters E_c, D_p, and a constant laser performance P_L the cure depth of the resin can be established on the basis of the speed of the laser.

---

[1] Today the resin HS 660 is no longer of any technical importance. However, Figure 2-17 clarifies very well the principal relationships, which are also analogously valid for modern resins.

Contour of the cure track

In addition to the cure depth, the width and the shape of the cured track are significant. This calculation cannot be based on an average surface energy; the energy distribution of the Gaussian beam must be taken into account. For this purpose a system of coordinates is fixed with its x-axis in the direction of the laser speed vector and its z-axis in the direction of the beam. The surface fixed by the x- and the y-axis coincides with the resin surface. A cutting plane is laid through the zero point onto which the contour of the cure track is to be calculated. The distance between the midpoint of the laser beam and a point Q on the cutting plane is called r (Figure 2-18).
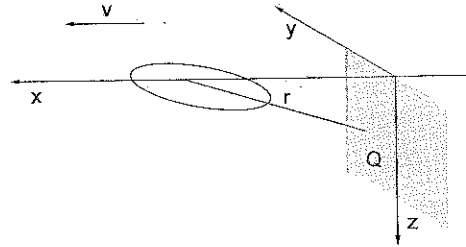

Figure 2-18 System of coordinates for the calculation of track geometry

For the intensity distribution in the Gaussian beam and with the relation between the intensity in the beam midpoint I_0 and the laser performance P_L at a Gaussian beam.

$$I_0 = \frac{2 \cdot P_L}{\pi \cdot \omega_0^2} \tag{2.4}$$

with $_0$ = beam radius on the resin surface.

It follows:

$$I(r,0) = \frac{2 \cdot P_L}{\pi \cdot \omega_0^2} \cdot \exp\left(\frac{-2 \cdot r^2}{\omega_0^2}\right) \tag{2.5}$$

The surface energy at a specific point on the section plane (y, z = 0), over which a laser beam runs with the intensity I(r,0), equals the temporal integration over intensity. By replacing I_0 according to Equ. (2.4) the surface energy on the resin surface results.

The periphery is to be found exactly where E(y, z) equals the critical energy E_c. By equating $E(y^*, z^*) = E_c$ and transforming, we arrive at the following equation:

$$\left(\frac{2}{\omega_0^2}\right) \cdot y^{*2} + \left(\frac{1}{D_p}\right) \cdot z^* = \ln\left[\sqrt{\frac{2}{\pi}} \cdot \left(\frac{P_L}{\omega_0 \cdot v_s \cdot E_c}\right)\right] \tag{2.6}$$

Equation (2.6) is the definition of a parabola. The cure track therefore has the geometry of a parabolic cylinder as shown in Figure 2-19.
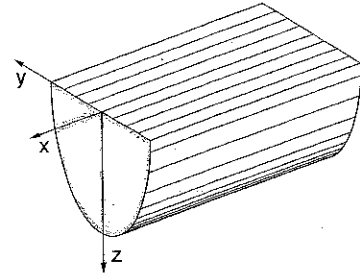
Figure 2-19 Parabolic shape of the cure track under the influence of a Gaussian-beam on a photopolymer

From Equ. (2.6) the relations for the track width L_W and the cure depth C_d can also be derived [JAC92], [FAS94].

Optimization of the Layer Thickness

Knowing the geometry of the cure track enables a layer thickness to be determined in which the time needed for curing a certain volume is minimal. For a reasonable coverage of the volume with parabolic cure tracks it is assumed that the cure track has a distance of 0.02 mm to both the lower layer and the adjoining layer.

With d as layer thickness for the curing time of a certain volume, the following proportionalty results:

$$T \sim \frac{1}{v_s \cdot d \cdot (L_w + 0.02mm)} \tag{2.7}$$

With the cure depth C_d = d - 0.02 mm and insertion of the relation for the track width L_w it follows:

$$T \sim \left\{ d \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{P_L}{\omega_0 \cdot E_c} \cdot \exp\left(-\frac{d - 0.02mm}{D_p}\right) \cdot \left[\frac{\omega_0}{\sqrt{2}} \cdot \sqrt{\frac{d - 0.02mm}{D_p}} + 0.02mm\right]\right\}^{-1} \tag{2.8}$$

Equation (2.8) is shown graphically in Figure 2-20. The minimum of the function is d = 0.3706 mm for an assumed optical penetration depth D_p = 0.25 mm. As only proportionalities were investigated there are no resulting absolute values for the ordinate.

The penetration depth D_p of 0.2 to 0.3 mm of different resins lies within the technically sensible dimension of 0.1 to 0.5 mm. If deeper layers are required, the surface energy needs to be increased, which simultaneously lowers the scan speed. Therefore, attempts are being made to produce resins that have a greater penetration depth. As shown in the following subsection, the alteration of the penetration depth also influences the stability of the components.
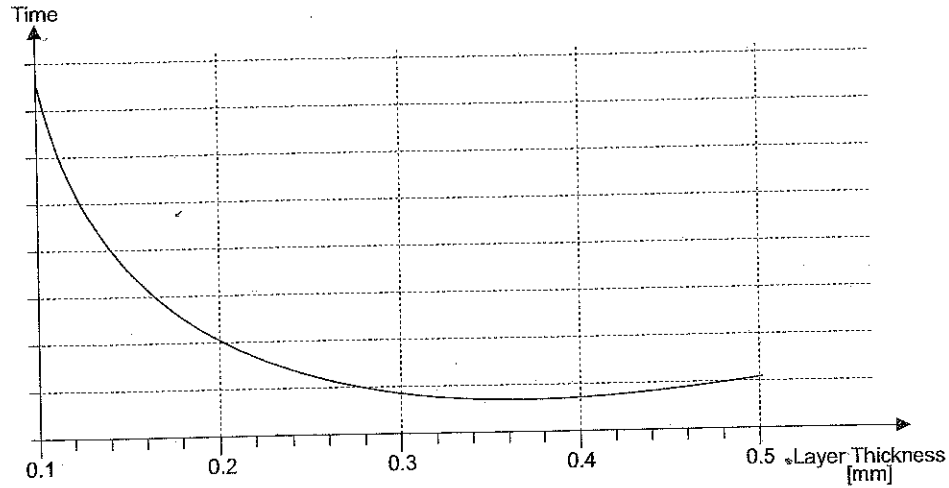
Figure 2-20 The time needed for curing in relation to the layer

If resins with a greater optical penetration depth are used it should be taken into account – especially in combination with higher powered lasers – that leakage radiation can result far more easily in undesired polymerization than previously and thereby have a negative influence on the accuracy of the components and above all on the aging of the resin.

Effect of the penetration depth on the stability of the component

By increasing the penetration depth D_p of the resin with a constant cure depth C_d the required surface energy on the surface of the resin is lowered. Accordingly, fewer photons are absorbed and the rate of polymerization decreases, which results in less stability of the component. The relevant value excess energy E_x is introduced here. This is a measure for the amount of energy available for the polymerization in addition to E_c. A useful definition for E_x is given in Equ. (2.9) [JAC92].

$$E_x = \left(\frac{1}{C_d}\right) \cdot \int_0^{C_d} \left(E(z) - E_c\right) \cdot dz \qquad (2.9)$$

After implementing Equ. (2.2) it follows that:

$$\frac{E_x}{E_c} = \left(\frac{D_p}{C_d}\right) \cdot \left[\exp\left(\frac{C_d}{D_p}\right) - 1\right] - 1 \qquad (2.10)$$

This function is illustrated graphically in Fig. 2-21.

The following fundamental relationships derive from Equ. (2.10) and Figure 2-21:

- The excess energy is directly proportional to the critical energy E_c. A reduction of E_c to achieve shorter build times will result in a direct decrease of stability during the green phase.

- By reducing the penetration depth or raising the layer thickness, the stability in the green state is increased. The effect is especially prominent with values of $C_d/D_p > 3$.
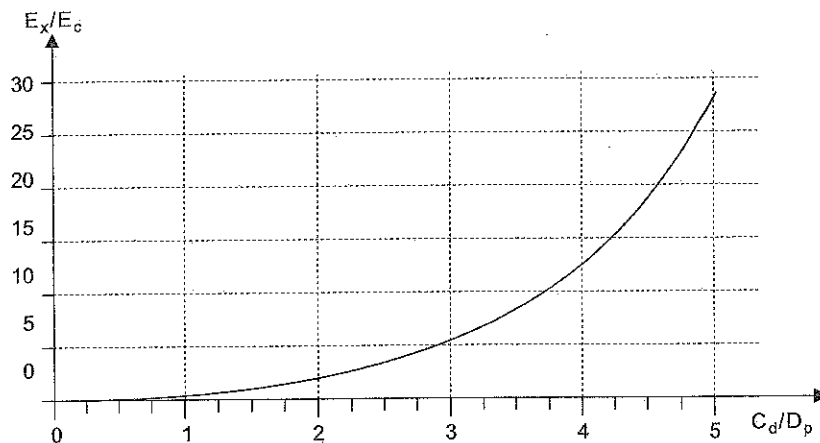

Figure 2-21 Excess energy relative to the cure depth and the optical penetration depth

The fundamental relationships discussed are valid for all photopolymerization processes, especially for laser-supported stereolithography processes. This explains the fundamental advantages and disadvantages of stereolithography processes which – with process specific restrictions – are in principle valid for all industrial processes discussed later.

Advantages of Stereolithography

Stereolithography, also known as stereography, is at present the most accurate of all rapid prototyping construction processes. Its accuracy is limited by the machine, but not by physical limits. For example, the minimal depictable land widths are in principle a function of the laser beam diameter. The tenuity of the z-stepping is not limited by the process. It is limited by the wettability of a solid layer by the (following) liquid monomer layer, expressed as the relationship of volume force (proportional to the layer thickness) and the surface tension. Thin layers consequently tend to "rip." These physical obstacles can be overcome if the layer thickness is limited by solids such as glass plates rather than a free surface.

It is in principle possible to contour the boundary of the x-y planes in the z-direction by appropriate control (five-axis) and exposure strategies (variation of pulse-pause relationship and laser performance) and thus to achieve a quasi continual z-modeling.

Stereolithography not only allows the production of internal hollow spaces, as do nearly all the other rapid prototyping processes, but also permits their complete evacuation as a result of the process technology. For this a drainage opening is necessary which should be clearly much smaller than the diameter of the hollow space. Together with the further advantage of the materials being transparent or opaque, this facilitates the visual judgment of internal hollow spaces as is, for example, necessary for medicinal use (e.g., mandible, mandibular nerve channel).

Complex models, or those of larger dimensions than the build chamber, can be assembled from single partial models into arbitrary complex complete models. If the same photosensitive resin is used as binder and UV radiation sources for local curing, the section points are unnoticeable in respect to their mechanical-technological properties and they are also invisible to the eye.

The models can be finished by sand blasting and polishing and, to a certain extent, by machining and coating.

Noncrosslinked monomers can be reused, and completely polymerized resin can be treated as household garbage.

Disadvantages of Stereolithography

Owing to its process technology, stereolithography is restricted to photosensitive material. When developing resins, therefore, this property is the most important. The usual primary properties such as resistance to extension, elasticity, temperature stability, and so forth are of secondary importance. Furthermore, material development is limited to stereolithographic usage and in view of the costs apportionable to the product it is correlated only with this market.

Stereolithography is in principle a two-stepped process in which the models are first solidified to a high percentage (> 95%) in the actual stereolithography machine; afterwards the finished model is placed into an oven to build up further crosslinkages until it is cured completely (this does not apply to printing processes or mask processes, SGC).

The green product must be cleaned with solvents (TMP, isopropanol). This requires the storage, handling, and disposal of solvents and is another time-consuming process. When making stereolithography models unsupported structures and certain critical angles of overlapping model parts cannot be realized without support, as during its generation in the resin bath the model is still a relatively soft green product. On the one hand these supportive structures need to be fitted when the model making is in preparation, and on the other hand they have to be removed manually from the green product or from the cured model.

To a small extent, photosensitive acrylates absorb oxygen, whereas epoxy resins are hygroscopic; this has to be taken into account when storing and processing the material. The models tend to creep even after being completely cured. After a few days or weeks unsupported walls show saggings that disappear if the model is turned over or supported. The newest epoxy resins show these characteristics less prominently.

benchmark for many others. The more important reason, however, is that the exact description of stereolithographic model making is suited to engendering a feeling for generative processes which, in many aspects, can be applied to other processes.

The reader is well advised to read this passage even if he is not interested in stereolithography.

3.3.1 Photopolymerization – Stereolithography (SL)

3.3.1.1 Machine Specific Basic Principles

The industrial application of the solidification of liquid monomers by photopolymerization is known as stereolithography. 3D Systems calls the process "StereoLithography;" EOS called it "Stereographie." Both terms are registered trade marks of the respective company.

Stereolithography is the origin of all industrially used rapid prototyping processes and, with more than 2500 installations (at the end of 2001) worldwide (more than 600 in Japan), it is one of the most widely used industrial application.

The oldest and most widely used system is based on the principle of point-by-point solidification by means of a laser scanner exposure. The lamp-mask process (solid ground curing) is described in Section 3.3.1.5. Nowerdays new processes based on photo polimerization are published: EnvisionTec uses a DLP-projector to cure the model upside down through a glass plate (Section 3.3.1.7.) and Objet takes printheads to apply the liquid monumer (PolyJet process) which is continuously hardened by a lamp (Section 3.3.1.8.). 3D-Systems (originally Optoform's (Nancy, F) paste polymerization process) applies a pasty monomeric resin using a docter-blade. Then each layer is shaped and polymerized by a laser. The process is not discribed in detail because it is not commercializd until now. It is obvious that the last two processes on one hand can be named "stereolithography" but on the other hand "3D-Printing-" or "Extrusion-Processes" as well.

In theory, liquid resin stereolithography machines consist of a container that is at the same time build chamber and storage space, filled with a liquid monomer. It is equipped with a build platform moveable in the z-direction and a laser·scanner unit, which "writes" or projects the current layer information on to the surface of the resin bath thereby curing one layer. The platform carries the model (on supports that hold projections and unconnected model parts in place and facilitates the defined lowering of the model on to the build platform and its removal from the platform) and lowers it by one layer thickness after a layer is solidified. A new layer is then prepared (recoating), again exposed and thereby solidified, and so forth. In this way the model "grows" layer by layer from bottom to top (Fig. 3-4).

All laser-supported stereolithography processes aim to solidify one layer resulting from single solidifications, so-called voxels. Voxels, which ideally have the shape of a paraboloid of revolution, result from the energy distribution in the laser beam and the penetration characteristics of the resin. To achieve the necessary compound stability, the voxels of one layer and those of two neighboring layers penetrate one another (overcure). The actual penetra-

tion depth (called cure depth) of the laser is thereby deeper than the layer thickness (see Fig. 3-5) and the generation of one layer and its interlocking with the lower preceding layer takes place simultaneously.
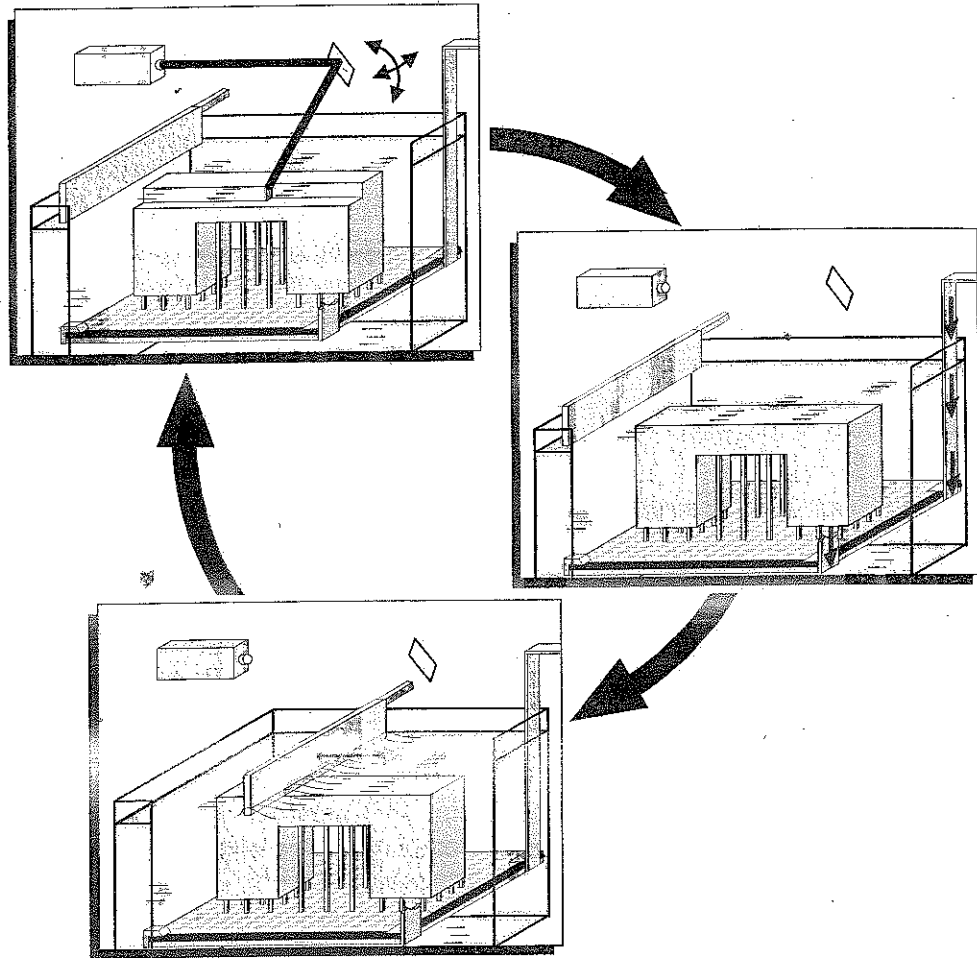

Figure 3-4 Principle of the stereolithography process (laser scanner)

In practice, the interaction of laser performance, beam parameter, scanning speed, and material characteristics (type of resin) decides whether a voxel structure really grows in the layer, or whether quasicontinuous paths are written.

For a rapid and exact polymerization different producers use different exposure strategies. Basically the layers are first contoured by borders and then internally cured by suitable hatches. The beam diameter is compensated for an exact generation of borders. To achieve this the laser path is diverted by half its beam diameter off the correct contour into the component (beam width compensation or line width compensation).
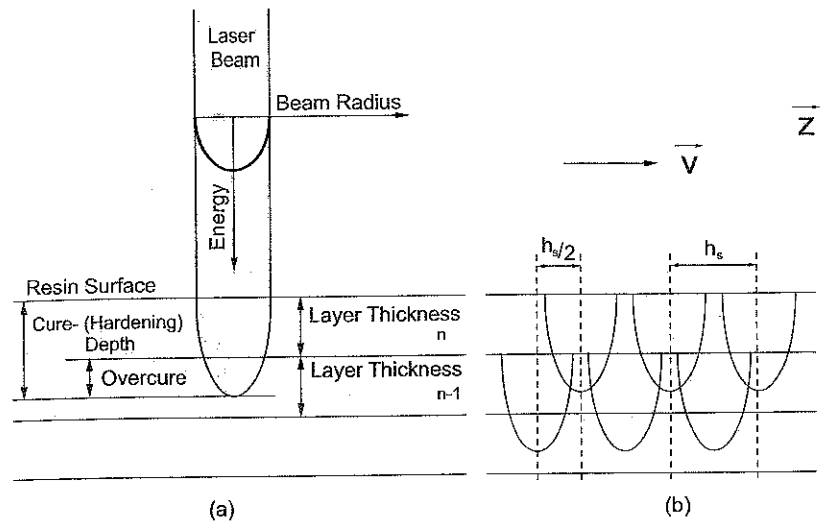
Figure 3-5 Interaction laser beam - resin surface. (a) Single beam voxel. (b) Voxel structure

The volume of the resin decreases due to polymerization and the model shrinks. The problem of shrinkage has been considerably reduced since the change from acrylates to epoxy resins (linear shrinkage: acrylate = 0.6% / epoxy = 0.06%). However, epoxy resins need up to three times higher exposure energy. There are several build strategies that are used in addition to the optimization of process parameters to counteract the effects of shrinkage. One possibility is not to join opposite walls continuously, but to generate gaps periodically (as shown in Fig. 3-6a) which prevent deformation due to their internal stress (retracted, 3D Systems).

Figure 3-6b shows the situation in a real component. The cure tracks do not touch one another (hatch distance, 0.26 mm) and leave sufficient distance to the border (retracted, 0.2 mm). The pattern was made with the aid of STAR-Weave technique (3D Systems).

The parts generated by laser scanner processes are of a relatively low stability during the build process (green strength), similar to that of gelatine. Overhangs, such as projecting elements or cantilever walls therefore need support by support constructions if they exceed a certain size or angle (Fig. 3-7).

The function of supports as substructure for the whole model is outlined in Fig. 3-7a. Support constructions such as these coordinate the plane of the build platform with that of the recoaters. They also enable the model to be removed from the build platform after the curing process is finished.

It is the main function of these structures to support projecting parts of the construction and also to pull other parts down which due to shrinkage tend to "curl" upwards. The supports shown in Fig. 3-7b are gussets, which are used especially for supporting rectangular geometric ramifications. Figure 3-7c shows a construction known as an "island." This aids the positioning and supporting of elements that start in later layers and join the model even

later. It would be impossible to build handles of cups, for example, without such supports because they would start "in the air."
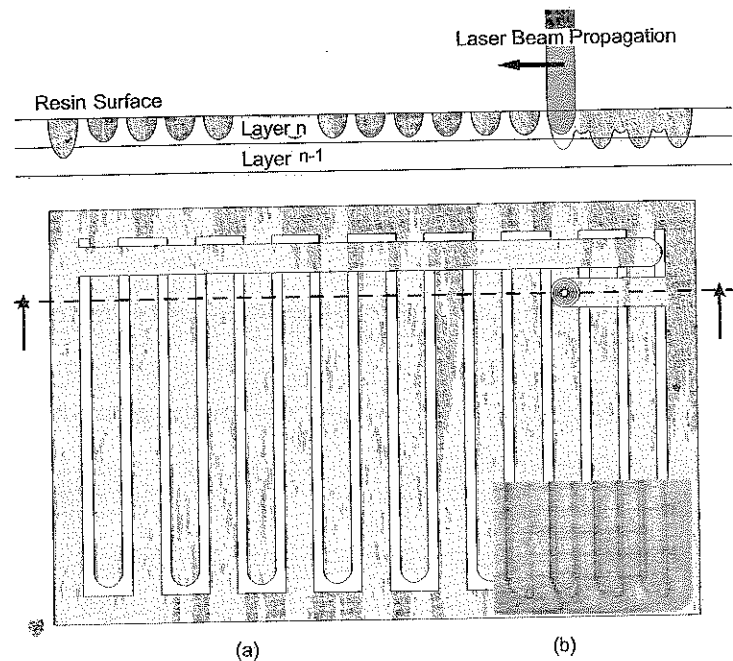

Figure 3-6 Build style to reduce internal stress (retracted). (a) Principle (b) Real structures of 3D System's STAR-Weave build style. (Source: CP)
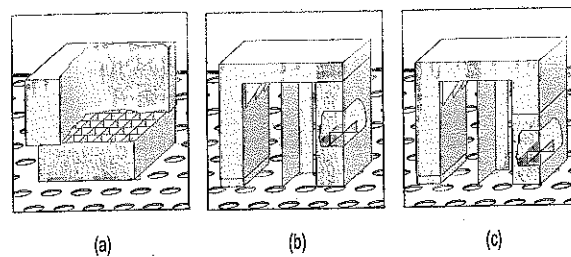

Figure 3-7 Support structures. (a) Substructure. (b) Support. (c) "Island"

These supports are (automatically) generated during data processing. That causes the amount of data to grow tremendously, especially with STL formulations. It has to be made clear that each support is materially a volume element and must be made not of just two but of twelve triangles as in a cuboid (Fig. 3-8a). Depending on the model, effort expended in generating and removing the supports (post-processing) can be enormous. In addition, the rather solid support structure can damage the model while it is removed using tools such as knifes.

Therefore a new support strategie called "fine point" was developed by 3D Systems and registered as the company's trademark. Figure 3-8b shows a model of a plasma welding device after the SL built process but still on the plattform and with fine point supports.

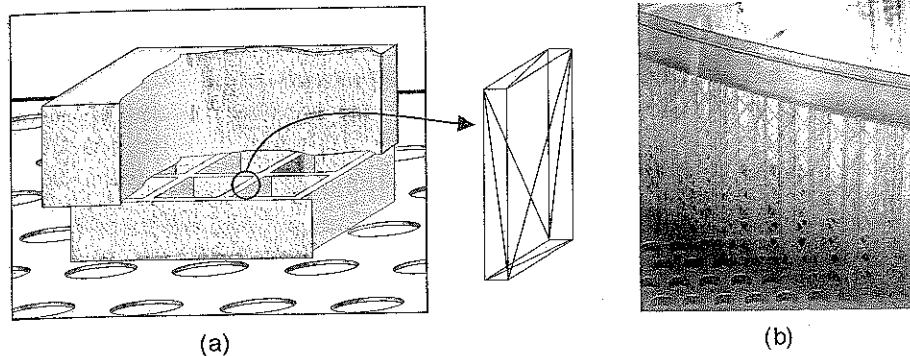(a)   (b)

Figure 3-8 Supports. (a) Classical support construction as volume element. (b) "Fine point" support
structure (Source: 3D Systems)

For the stereolithography processes of all manufacturers, build strategies have been developed with a higher proportion of hollow space volume to increase the build speed and to decrease the amount of material. These strategies are especially aimed at being able to employ models directly as lost models in a precision casting process (burning from ceramic precision casting molds). Walls that are in reality solid are designed as hollow walls connected by rod-type bridging elements. In addition, so-called skins need to be introduced that close the model at the top and the bottom (in the z-direction).

Hollow stereolithography models require openings through which the monomer that has not been cured can be drained. These openings must be closed again to ensure that no ceramic slurry can flow into the model and cause casting faults, if used as a precision casting master.

When the last (top) layer has solidified, the build process is finished. The model which is now completely dipped in the monomer is removed from the vat, enabling superfluous resin to run off and drip back into the resin container. If the machine is to be used economically it is better to place the model into a separate, preferably heated container to drain off. There are variants in which the resin is drained off by a process similar to the centrifuging of honeycombs. This is especially beneficial for hollow walls.

The procedure known as *post-processing*, in which the models are cleaned, the supports removed, and the models post-cured, is the same for all laser-supported stereolithography processes. The procedure is shown schematically in Fig. 3-9.

All models are first cleaned (acrylates with TPM); after cleaning, the solvents are removed as far as possible (TPM with isopropanol).

In laser-supported stereolithography processes the component is usually polymerized by up to about 96% (depending on the penetration depth). The models, therefore, are not post-

cured in the prototypers, but in special UV ovens (post-curing ovens). In the lamp-mask process as well as in the resin printing or paste polymerization process the models leave the prototyper completely cured.

The supports are removed before or after the curing, depending on the complexity of the model and the demands on accuracy and material. The supports are removed manually, a process that demands great care and that is therefore time consuming. It is thus advisable not to generate more supports (automatically) than is necessary, as this will slow down the build process of the model. To achieve higher accuracy with acrylate models it is sometimes advisable to cure them completely with the supports and remove the supports after the curing is completed. Thanks to the fine point support structure, even filigreed model parts can be cleaned whihout the risk of damage.

Another post-processing procedure is the implementation of a mechanical finishing by sand blasting, polishing, milling, and so forth as far as is necessary for achieving the qualities typical for this special process.

A differentiation is made between process-orientated post-processing and *finishing*, which means process-independent further treatment of the surface. This could, for example, be done with varnish, fillers, and stoppers of various kinds but also by electroplating or plasma coating and is not a rapid prototyping specific process step.
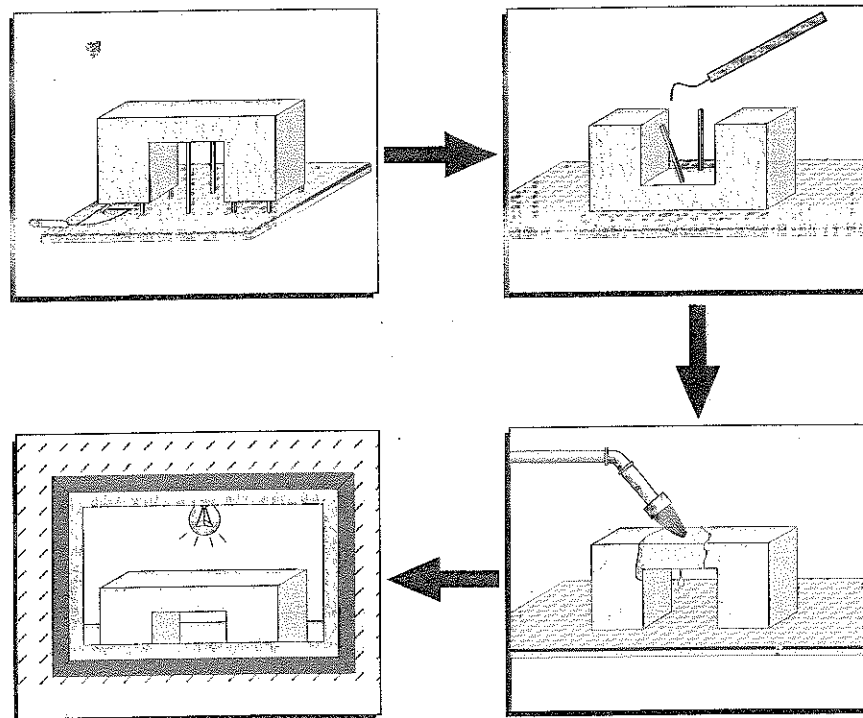

Figure 3-9 Post-processing in laser stereolithography (laser scanner method)

The producers of prototypers usually do not offer (but sometimes recommend) equipment and tools for finishing (polishing, sand-blasting, varnishing, etc.) and for subsequent casting processes. These aids must be chosen by the interested user himself.

Stereolithography models show the highest degree of details and the best surfaces. The modest mechanical-technological properties of resins are a disadvantage. Optimal polymerization comes first and foremost while all other properties such as resistance to tension, temperature stability, and so forth are of secondary importance.

A promising strategy is to separate the properties: The stereolithography process enables a reproduction in great detail. The required mechanical-technical properties are achieved afterwards by molding processes. For the production of plastic prototypes, therefore, the process chain – stereolithography – vacuum casting – is well established as a standard if the number of pieces required lies between 5 and 15 (sometimes more) and the simulation of the later injection molded material by castable or pourable (PU, polyurethane) plastic material is acceptable (see also Section 3.4).

Metal models are produced by making wax models by vacuum casting, which are then melted out by classical precision casting processes. As an alternative, hollow stereolithography models can be used directly.

Tools are produced by casting processes or counter-casting processes with metal-filled resin or by low-temperature coatings (see also Chapter 4).

3.3.1.2 StereoLithography Apparatus (SLA) – 3D Systems

Viper si2 (SLA250)/ SLA3500/ SLA5000/ SLA7000

3D Systems Inc., Valencia, California, USA

Short Description: The stereolithography machines produced by 3D Systems work with the laser scanner process. The model is generated on a platform. After contouring and haching the upper layer is completed and the platform is lowered into the resin bath by one layer thickness, enabling a new resin layer to be applied onto it's surface. The process is repeated until the model is finished.

The removal of the supports, the further post-curing in an UV oven, and the finishing of the surface are process steps that take place outside the prototyper and that are essential for producing high-quality models.

Range of Application: Geometric prototypes, functional prototypes (technical prototypes).

Tooling directly via ACES injection molding, indirectly via casting processes (Keltool).[1]

Development State: Commercialized.

---

[1] Investigation on and further development of the 3D-Keltool process was stopped in November 2001 by announcement of 3D-Systems. Existing customers will be supported futher on and new ones will be served based on the technical status quo. Details on the 3D-Keltool process see Section 4.2.2.2.