Stereolithography Epoxy Resins SL 5170 and SL 5180: Accuracy, Dimensional Stability, and Mechanical Properties

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Abstract

Stereolithography (SL) resins based on epoxy chemistry provide significantly improved overall part accuracy, dimensional stability, and mechanical properties relative to the earlier acrylate SL resins. In July, 1993, epoxy-based **SL 5170** resin was introduced for use on the SLA-250 system. In March, 1994, the epoxy-based resin for the SLA-500 system, **SL 5180**, was also released. These epoxy resins have minimal laser-cure and post-cure shrinkage, resulting in extremely low curl and distortion. Overall dimensional accuracy has also improved. Standard User-Parts built in **SL 5170** on the SLA-250, and now, **SL 5180** on the SLA-500, have recently achieved the highest level of dimensional accuracy from a statistically significant number of measurements taken in the x, y, and z directions. Diagnostic test results presented in this paper show that these epoxy-based resins are now capable of producing extremely flat parts when required. SL parts built in these resins also exhibit superb dimensional stability in the laser-cured state, as demonstrated by the "Green" Creep Distortion diagnostic test. Dimensional stability in the laser-cured state is critical, especially for SL parts having the characteristic quasi-hollow internal structure, generated using the QuickCast™ build style. Creep results are presented in this paper. Furthermore, the overall mechanical properties of these epoxy resins were measured according to the ASTM standards for plastics. Tensile, flexural, and impact properties for the epoxy-based and acrylate-based SL resins are presented in this paper. Mechanical properties of thermoplastics, acrylic plastic (PMMA) and medium impact polystyrene, are also presented for comparison. The data shows that the mechanical properties of epoxy-based **SL 5170** and **SL 5180** are comparable to, or exceed those of acrylic plastic and medium impact polystyrene.

For applications that require greater mechanical strengths than **SL 5170** and **SL 5180**, metal parts can be obtained using QuickCast. QuickCast, made possible with the development of these epoxy-based SL resins, is the key to successfully utilizing SL parts for shell investment casting applications, and the generation of precision metal components directly from SL parts. Furthermore, when a "negative" core and cavity pair of a part geometry is produced in metal using QuickCast, tooling is obtained. Prototype, and eventually, production functional parts may then be ultimately injection molded in the QuickCast tooling, using the desired engineering thermoplastic material.

Introduction

In July, 1993, 3D Systems Corporation introduced the first epoxy-based stereolithography (SL) resin, **SL 5170**, developed jointly with Ciba-Geigy, Limited. The epoxy-based SL resin photopolymerizes via cationic chemistry, as opposed to the common free-radical chemistry of acrylate-based resins. The epoxy resin has demonstrated many significant advantages over the conventional acrylate SL resin systems[1]. SL parts built in the **SL 5170** resin showed a high level of overall accuracy, improved flatness, and superior dimensional stability. These properties allow one to generate solid SL parts of exceptional accuracy. However, **SL 5170** resin is only suitable for building on an SLA-190 or 250 machine, which uses the Helium-Cadmium (HeCd) laser. In March, 1994, Ciba-Geigy and 3D Systems released an epoxy-based resin for the SLA-500. The **SL 5180** resin was developed specifically for use with argon ion laser systems. The dimensional accuracy for this resin also had to be determined, on the SLA-500.

As you will see in this paper, these epoxy resins have major advantages over the conventional acrylate resins. Significant improvements were realized in the overall accuracy, flatness, and dimesional stability of SL parts. Also, parts built in these resins exhibit substantial and reproducible improvements in their mechanical properties, relative to conventional SL acrylate resins systems. These properties, and a number of other properties characteristic of the epoxy resins, were also responsible for achieving QuickCast capability. Finally, the release of epoxy resins **SL 5170** and **SL 5180** culminated with the QuickCast capability, for both SLA-250 and SLA-500 systems.

QuickCast SL parts have continued to succeed in directly generating precision metal parts using **SL 5170** or the **SL 5180** epoxy resins, [2,3] including the generation of QuickCast™ Tooling in A-2 tool steel.[4] Direct functional testing of SL parts built in the solid build style called ACES ™ , is also attractive due to the remarkable optical clarity and improved surface finish, in addition to the improved mechanical properties presented in this paper.

This paper focuses on three major dimensional properties, to demonstrate the accuracy achieved by **SL 5170** and **SL 5180** epoxy. Among various diagnostic tests available to characterize SL resins and build processes, the following three methods were chosen. The overall dimensional part accuracy is demonstrated by the statistically significant SL User-Part analysis.[5] Part flatness is determined by the Slab 6X6 flatness test.[6] Finally, the dimensional stability of the laser-cured ("green") SL resins are demonstrated by the Green Creep Distortion test.[1] The latest results are reported in this paper.

In addition, this paper discusses the mechanical properties relevant to SL users including tensile, flexural, and impact properties of various commercially available SL resins, measured according to ASTM (American Standards for Testing and Materials) standards. Mechanical properties of thermoplastics such as acrylic plastic (PMMA) and medium impact polystyrene are also presented for comparison.

Dimensional Properties of SL Resins

Rapid Prototyping and Manufacturing (RP&M) technology will not survive without adequate and repeatable dimensional accuracy necessary for end use applications. To advance the RP&M technology, two simple, but fundamental requirements must be met. On the one hand, the user must have an understanding of the level of accuracy and tolerances required for his application. On the other hand, the RP&M machine supplier has a responsibility to present statistically significant data adequate to define the dimensional accuracy and repeatability that can be achieved by that RP&M machine.

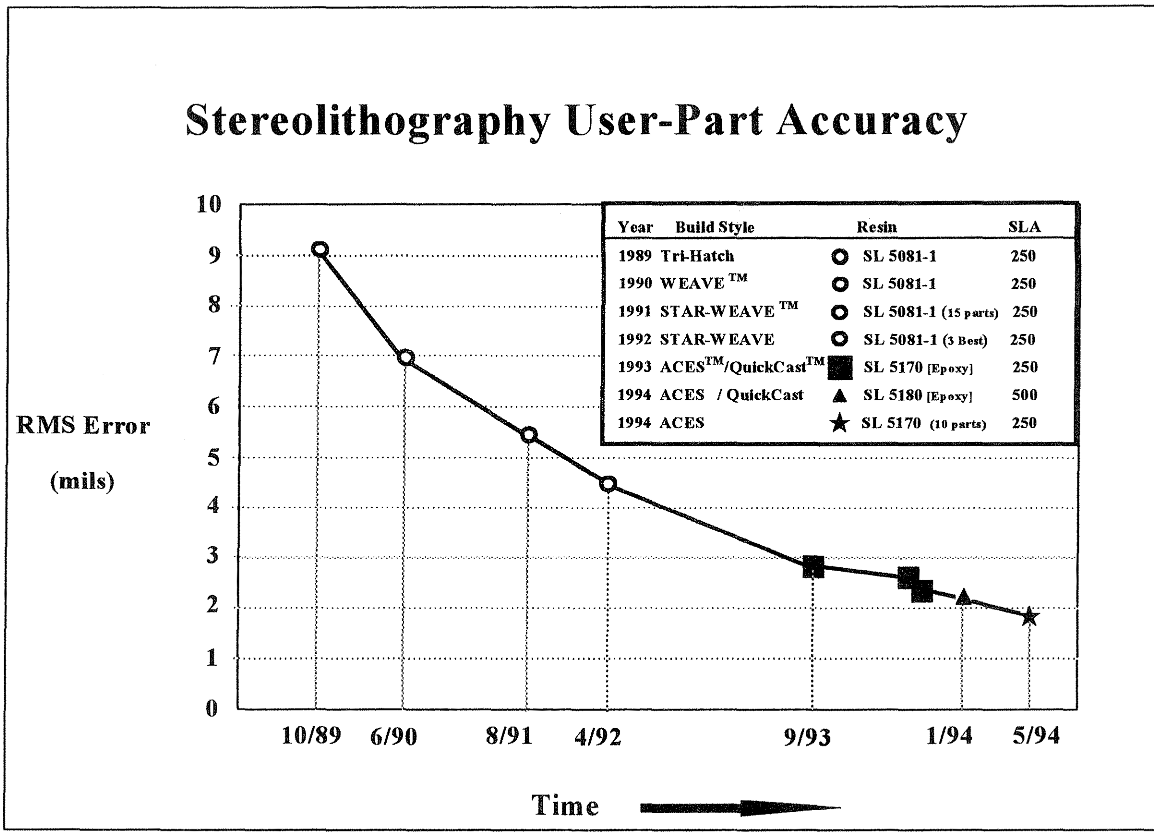

Figure 1

The User-Part Accuracy Test

The User-Part accuracy diagnostic, described in detail elsewhere[5,7] was designed by the North American Stereolithography User Group just for that purpose. The key aspect of this accuracy diagnostic test is the statistical significance of data obtained from accurately measuring 170 dimensions from each User-Part on a coordinate measuring machine (CMM). The statistical significance increases as the number of User-Parts tested increases, therefore multiple parts are built. Multiple User-Parts also determine the repeatability of the process.

The User-Part is 9.5 inches long, 9.5 inches wide, and 1.5 inch tall, and was designed such that it uses almost all of the SLA-250 build area. The measured dimensions of a User-Part include long, medium, and short dimensions spanning almost two orders of magnitude, from 0.100 inch to 9.500 inches, comprising bosses, thin walls, and internal round and square holes.

In the User-Part diagnostic test, a root-mean-square error, or RMS error is reported from the set of 170 dimensional measurements taken for each part. The RMS error is obtained by first generating the Error Distribution Function, and then a Cumulative Error Distribution.[5] If the error distribution is Gaussian, 68% of the dimensional measurements will fall within ± 1.0 RMS error of their CAD value.

The RMS error values measured for Stereolithography User-Parts built in the five-year period from October, 1989 to May, 1994, are presented in figure 1. The figure clearly shows a significant increase in the accuracy of SL User-Parts over the last five years. Note that SL part accuracy has improved from the RMS error of about ± 9 mils, to about ± 1.8 mils. This represents a *five-fold improvement in dimensional accuracy over a period of only five years.*

The improvement in overall part accuracy was a result of a number of factors. Improvements in hardware, software, process, and resin all contributed incrementally to better SL part accuracy. However, some factors contributed more than others. For example, all of the accuracy data between 1989 and 1992, shown in figure 1, corresponds to User-Parts built with **SL 5081-1** acrylate-based SL resin. Most of the improvements in this time period, resulting in a two-fold accuracy improvement from RMS error of ± 9 mils to ± 4.5 mils, were due to SL process development. SL process includes the appropriate selection of parameters that basically defines the SL part "build style." Some of these parameters include laser scanning speed, drawing sequence, border overcure, hatch spacing, layer thickness, part deep dip distance, etc., as well as, leveling and recoating. In particular, the two-fold improvement of the accuracy data in SL 5081-1 resin was mostly due to build style improvement from Tri-Hatch* , to WEAVE™, to STAR-WEAVE ™ build styles, in the initial period of three years.

However, process alone could not continue to improve part accuracy indefinitely. At that time, in retrospect, there was an inherent limitation due to the SL resin systems. In early 1993, the development program for **SL 5170** was finalizing. At this time, the first User-Part was built in **SL 5170**. The dimensional accuracy immediately jumped from an RMS error of ± 4.5 mils in **SL 5081-1**, to ± 2.8 mils in **SL 5170**, resulting in another nearly *two-fold improvement in accuracy.*

This advance in accuracy was necessary, especially for the QuickCast application, which was also commercially released together with **SL 5170**, in July, 1993. In the QuickCast application, SL pattern generated in the QuickCast build style is converted directly into metal using shell investment casting technique. With the advent of QuickCast, and the subsequent availability of metal prototypes from SL patterns, SL part accuracy requirements have been pushed substantially. The accuracy requirements for a functional prototype are much greater than for parts that are intended mainly for visualization and verification.

In March 1994, the epoxy-based SL resin for the SLA-500, **SL 5180**, was also introduced. With the added help of the hardware and software improvements that culminated with the development of the Orion™ Imaging Technology, as well as the new Diode Laser Leveling system, both developed by 3D Systems, the User-Part built in **SL 5180** was able to achieve an RMS error of ± 2.2 mils.

Furthermore, the latest results from **SL 5170**, built on the SLA-250, produced ***today's record of ± 1.8 mils RMS error***. It is important to note here that this RMS error value is based on, not one, but *ten* User-Parts (viz. 1700 measurements) built on the same

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* Tri-Hatch is one of the earlier SL build styles that resulted in pockets of liquid resin trapped between walls of cured SL resin. WEAVE and STAR-WEAVE are advanced build styles resulting in minimal internal stress, and maximum volume of laser-cured resin on an SLA. Chapter 8 of reference 5 explains the latter two build styles in great detail.

machine over a period of two months. This demonstrates that SLA has a very high repeatability, when built with the epoxy-based **SL 5170** resin.

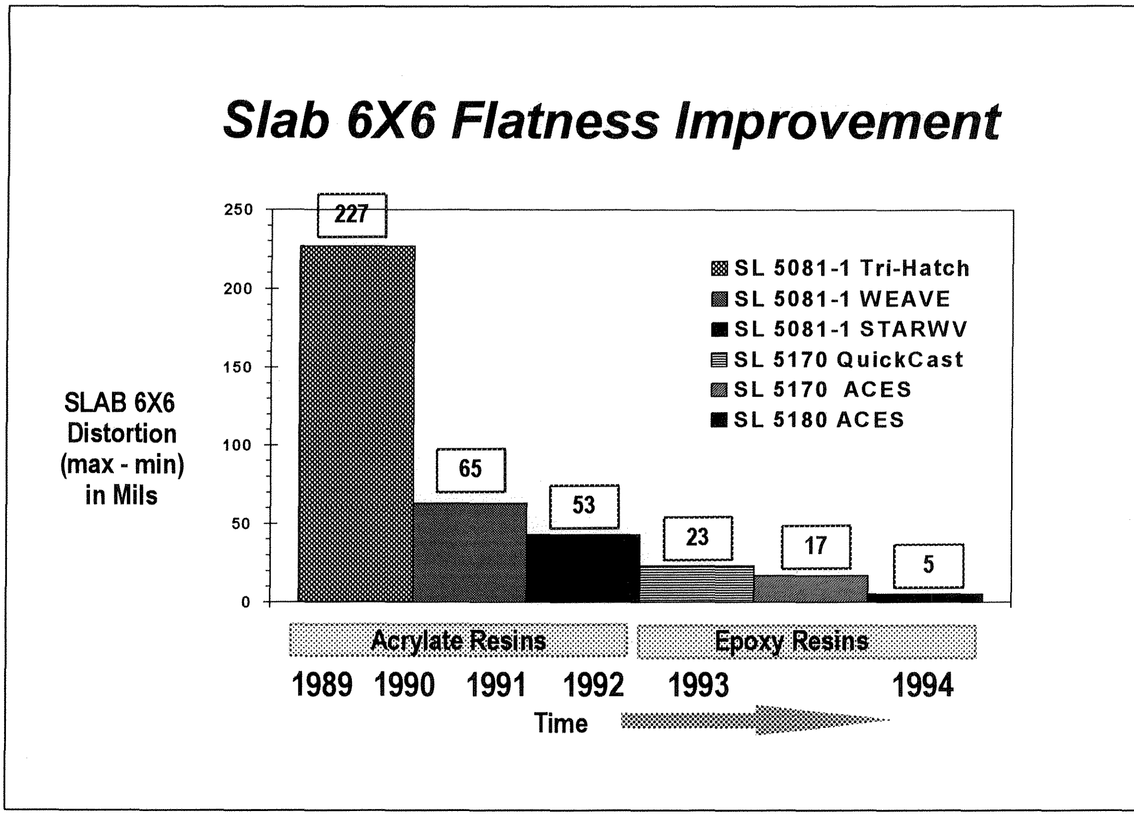


Figure 2

Slab 6X6 Flatness Test

The User-Part is an excellent diagnostic to determine system accuracy from a statistical set of data, especially in the x-y plane (coincident with liquid resin surface). Even though the analysis of each User-Part includes 14 measurements in the z (depth direction) direction, the bulk of the dimensional measurements (156 data points out of 170 measurements) are taken in the x-y plane. In addition, the geometry of the User-Part tends to depress the out-of-plane distortion in the z-direction. Hence, the User-Part analysis is particularly weak in detecting distortion in the z-direction, including the flatness of SL parts.

The Slab 6X6 flatness diagnostic test is suitable for filling that gap. Slab 6X6 is a simple 6 inches long, 6 inches wide, 1/4 inch thick, nominally flat horizontal slab, built flat on an SLA. While this part may seem simple, it is actually one of the most difficult parts to build accurately in SL, or any other layer-additive RP&M method that involves a phase change, or variation in the dimension of the solidifying layer during the building process. It should be stressed that parts that have vertical walls, or other stiffening features on top of a thin horizontal slab tend to depress distortion. This is due to the increased moment of inertia. The end result is that, in general, a flat slab section with added complex components tends to build flatter than a simple thin horizontal slab. Conversely, a thin slab is an excellent "worst case" diagnostic part to characterize flatness.

In the Slab 6X6 test, the slab is first built on an SLA. Next, the part is taken off the platform and supports are removed. Then, the part is post cured from one side only, to simulate the worst case scenario. Finally, the Slab 6X6 is allowed to sit for seven days, such that any creep distortion during this time would manifest itself in the final measurement. The Slab 6X6, built with acrylate-based resins, usually comes out warped upward (i.e. concave up) after the seven-day period, looking like a shallow bowl.

The distortion range (i.e. highest measurement minus lowest measurement) is established using a CMM on the upper surface. Generally, the highest values occur at the corners and the lowest in the middle of the slab. Additional measurements are actually taken between each process steps in the Slab 6X6 test procedure. However, for purposes of this paper, only the final maximum error value, measured seven days after the build, will be reported.

The Slab 6X6 flatness test results are summarized in figure 2. In 1989, the Tri-Hatch build style was found to build a highly distorted slab 6X6, having a distortion range of 227 mils, or almost 1/4 of an inch. As soon as the newer build styles WEAVE and STAR-WEAVE were introduced in 1991, and 1992, the *flatness improved immediately by more than three-fold*, to 65 mils, and 53 mils, respectively. The best (i.e. smallest) distortion range values in 1992 were achieved by **SL 5081-1** acrylate-based SL resin.

However, further process modifications on the acrylate resin did not yield better results. When the epoxy resin, **SL 5170**, was introduced in 1993, together with the QuickCast build style, *the flatness improved immediately, by more than a factor of two relative to the acrylate resin*. The Slab 6X6 distortion dropped from 53 mils to 23 mils. With further process optimization, and especially with the development of the new ACES ™ build style, the distortion was further reduced to 17 mils.

Now, the Slab 6X6s were finally starting to look like flat slabs. Remember, again, that the Slab 6X6 test involves the absolute worst-case of post curing from one side only. In real applications, such a flat structure would be post cured from both sides such that the part is evenly irradiated, to minimize post cure distortion.

The resin development continued beyond **SL 5170**, resulting in the release of **SL 5180** in 1994, an epoxy-based resin for the SLA-500. The Slab 6X6, built in **SL 5180** in the ACES build style, resulted in a superior flat slab, having a maximum distortion of only 5 mils. ***This Slab 6X6 distortion, obtained in 1994, corresponds to almost 50-fold improvement compared to that of 1989, and 10-fold improvement from the best Slab 6X6 results in 1992***.

Now, the SLA users can build very flat, nearly undistorted parts when required, using the epoxy-based SL resins **SL 5170** and **SL 5180**.

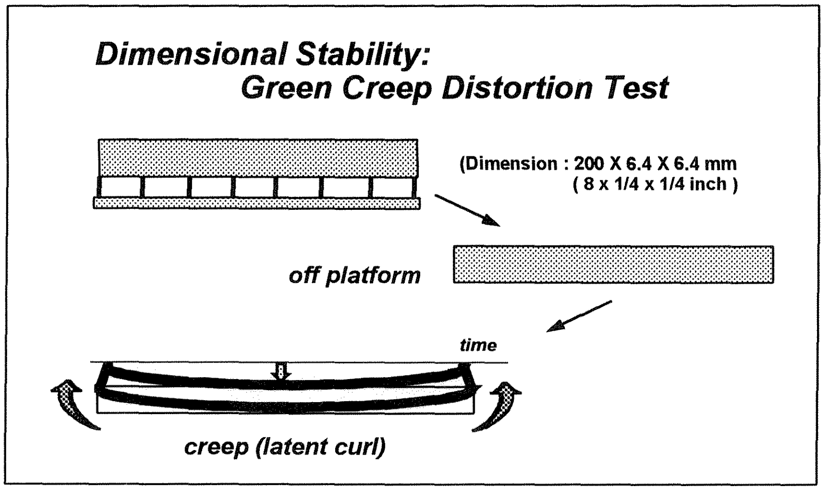


Figure 3

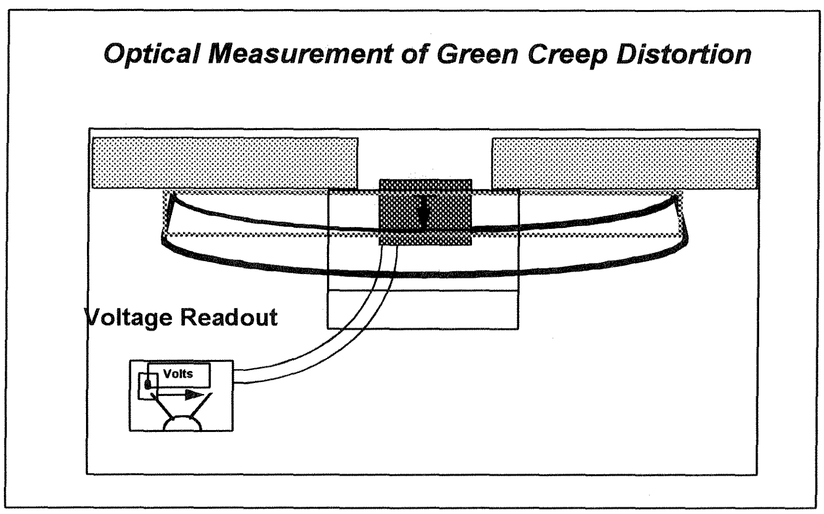


Figure 4

Green Creep Distortion

So far, the User-Part analysis showed the overall part accuracy, obtained from a statistically significant number of dimensional measurements, with emphasis in the x-y plane. The Slab 6X6 test demonstrated the part flatness, indicating accuracy in the z-direction. Both results exhibited great advances in the overall accuracy of the epoxy-based SL resins, **SL 5170** and **SL 5180**. However, both the User-Part and the Slab 6X6 tests involve post-cured parts.

The Slab 6X6 parts are post-cured within one hour after the parts are built. Then the post-cured Slab is allowed to distort over one week. This raises questions about the dimensional properties in the intermediate stage of cure, the so called "green state." Do SL parts creep in the laser-cured, "green" state? How would an SL part behave when left in the green state for an extended period of time?

Some SL parts are complex enough that cleaning and finishing may take many hours. Also, a part may be unintentionally left sitting in the green state before it is post-cured. This may be simply because the part finished building at midnight, or during the weekend, and no one was available to carry out the finishing work. These are both very realistic issues.

In addition, new dimensional requirements for SL resins in the green state became apparent, especially with the development of the QuickCast process. In the QuickCast process, SL parts are built in a quasi-hollow structure. When the QuickCast SL part rises out of the SLA vat, the part is initially filled with liquid resin, trapped in cells between the thin, outer boundary of cured resin. Next, a set of vent and drain holes are generated at appropriate locations either manually, or using the latest QuickCast 1.1 software during SL file preparation, and the uncured liquid resin is drained out of the QuickCast part. In a QuickCast part, the internal volume is "topologically simply connected," allowing liquid resin to flow freely from one internal section of the part to another. This allows complete drainage of the liquid resin before the QuickCast part is further processed for shell investment casting.

Due to the finite viscosity and surface tension of the liquid resin, the draining is certainly not instantaneous. The epoxy-based resins have viscosities of about 200 cps at 30°C, which are already an order of magnitude lower than the viscosity of the earlier conventional acrylate resins. This allows some simple parts to drain in a few minutes, and most parts, in a few hours. However, some complex parts resulting in long, narrow, internal passages, may take several hours to drain. This is a process that is carried out in addition to the normal support removal and finishing processes. During this draining time, what happens to the part dimensions? This is a concern especially because the SL QuickCast parts comprise thin walls, and are left in the laser-cured state, throughout this period.

The Green Creep Distortion (GCD) Test was developed to investigate the dimensional stability of SL parts in the green state. The test procedure, described in detail in reference 1, is schematically described in figure 3. The test involves a 200-mm long, and 6.4 X 6.4 mm (8 X 1/4 X 1/4 inch) square cross-section strip, called the CreepBar. The CreepBar is first built flat on an SLA, in the selected resin. Remember that a long, thin strip, with a high aspect ratio, is one of the most difficult parts to accurately build in layer-additive rapid prototyping methods. The strip is completely supported such that it stays flat on the SLA platform during the building cycle. The part is then removed from the SLA vat. The supports are removed, and the SL strip is placed on an optical measuring device, shown schematically in figure 4. The strip is then intentionally allowed to undergo creep distortion in the green state. To simulate the worst creep distortion, the *strip is not postcured in this test.* Post-cured strips are expected to creep much slower, and to a significantly lesser extent. The maximum deflection at the midpoint of the green CreepBar, or conversely the two ends of the CreepBar, is called the "Green Creep Distortion," (GCD). The GCD, measured optically, is automatically recorded on a computer over a period of 24 hours.

The Green Creep Distortion for the three acrylate-based resins, **SL 5143**, **SL 5149**, **SL 5081-1**, all built in STAR-WEAVE, and the epoxy-based resins, **SL 5170** and

SL 5180, built in the QuickCast build style, are presented in figure 5, as a function of time. The data for the epoxy-based resins built in the solid ACES build style are not plotted in this figure because the results were indistinguishable from the data for QuickCast build style.

Note, from figure 5, that the GCD rate for all resins is quite significant initially, and then the distortion rate slows down very quickly. For all acrylate-based resins shown in figure 5, more than 60% of the absolute GCD measured at an elapsed time of 20 hours occurs within the initial 2 hours. For example, the CreepBar built in **SL 5143** distorts to 48 mils after 20 hours. At 2 hours, the distortion is already about 35 mils, which is about 70% of the final distortion after 20 hours. Among acrylate resins, **SL 5081-1** has the lowest creep distortion. This data suggests that part-cleaning and finishing of acrylate-based SL parts should be performed as quickly as possible once the restraining support structures are removed from the part.

From this data, it is clear that both epoxy resins **SL 5170** and **SL 5180** have very low GCD, hence, they are dimensionally much more stable than the acrylate resins. Both epoxy resins have GCD of less than 4 mils within the 24 hour period.

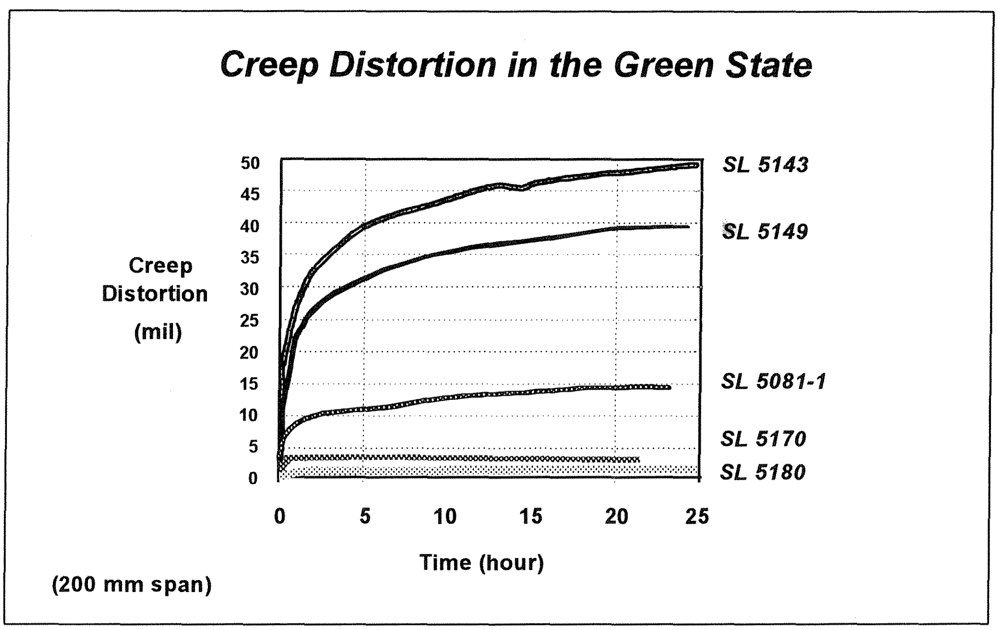


Figure 5

Furthermore, when the GCD data was plotted as a function of the logarithm of time, it was found to be log-linear, as in figure 6. This behavior is due to the viscoelastic nature of cured SL resins. Viscoelastic bodies have been found to behave in a log-linear fashion with time. Using this characteristic log-linear creep behavior, a convenient parameter, called Log Green Creep Rate (GCR), that characterizes the rate at which the SL test part undergoes creep distortion, was defined. It is indicated by the slope of the curve. *This way, a single parameter may be used to describe the creep behavior of SL resins*, and allows one to compare the dimensional stability of various resins, and / or build styles.

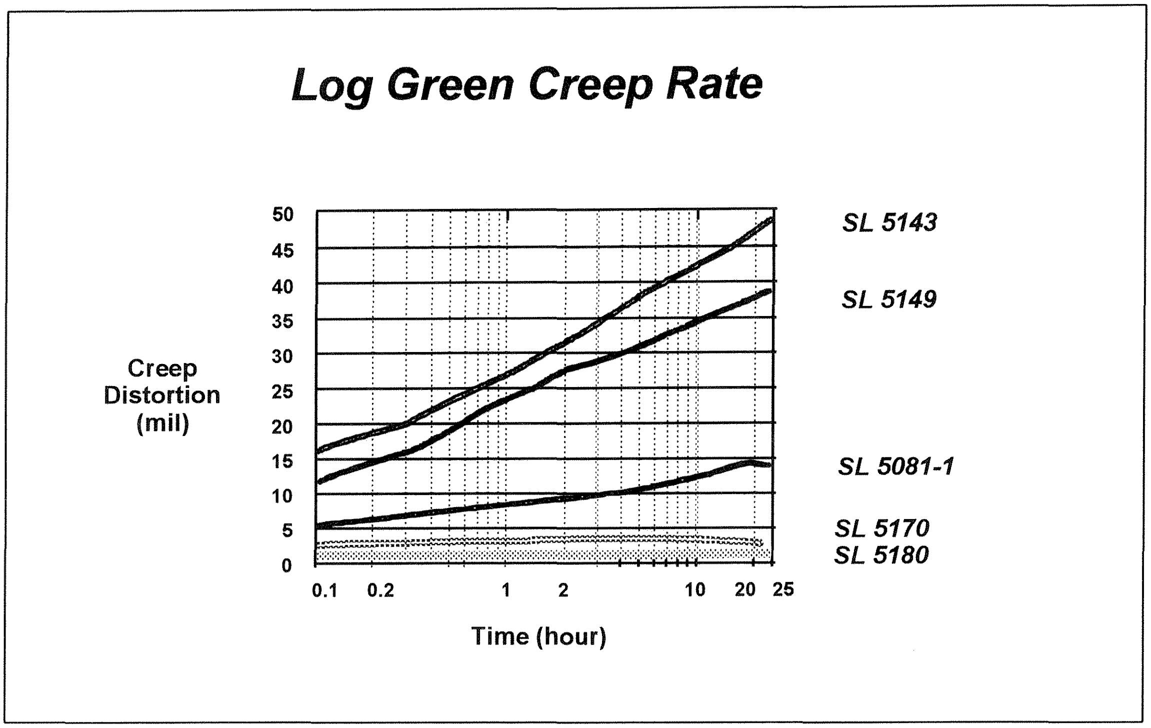


Figure 6

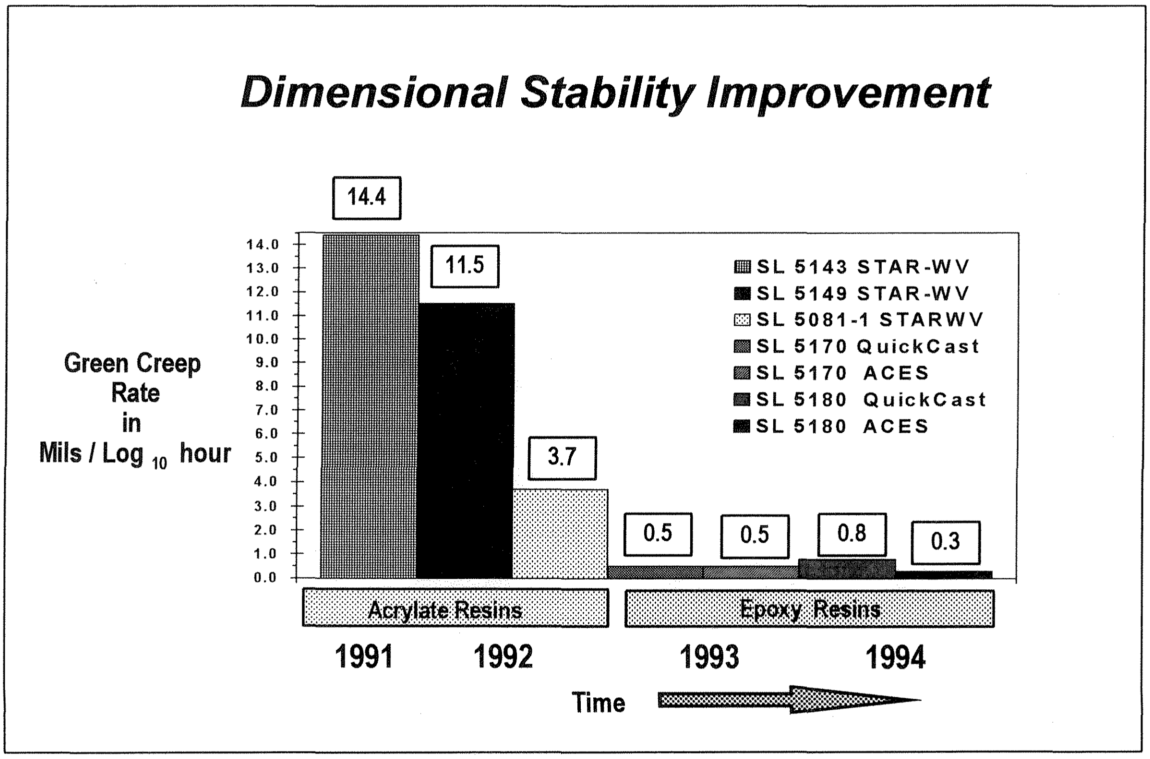


Figure 7

The GCR values for the SL resins tested are shown in figure 7. It is apparent that the epoxy resins have much lower GCR values than the acrylate resins, indicating that the epoxy resins are dimensionally highly stable. The latest result shown in the bar chart of figure 7, indicates that **SL 5180** built in ACES, with the log GCR of 0.3 mils/$\log_{10}$ hour, has the highest dimensional stability in the green state, among the SL resins tested. However, within the error-bar for the experiment, this is comparable to the log GCR of 0.5 mils/$\log_{10}$ hour of **SL 5170**, built in either QuickCast or ACES build styles.

Compared to one of the acrylate-based resins, the *dimensional stability of the epoxy resins improved almost thirty (30)-fold over the period of three years*, from 14.4 mils to about 0.5 mils per every multiple of 10 in time. In summary, the dimensional stability in the green state may be ranked according to the following order, in the descending order of dimensional stability:

SL 5170 & SL 5180 >> SL 5081-1 > SL 5149 > SL 5143.

ASTM Mechanical Properties

At this point, the dimensional accuracy and stability of the epoxy-based resins were demonstrated. Once accurate and stable parts are generated on the SLA, one would also like to know how strong they are. How do the mechanical properties of the epoxy-based resins compare to those of acrylate-based SL resins, and also compared to other thermoplastics?

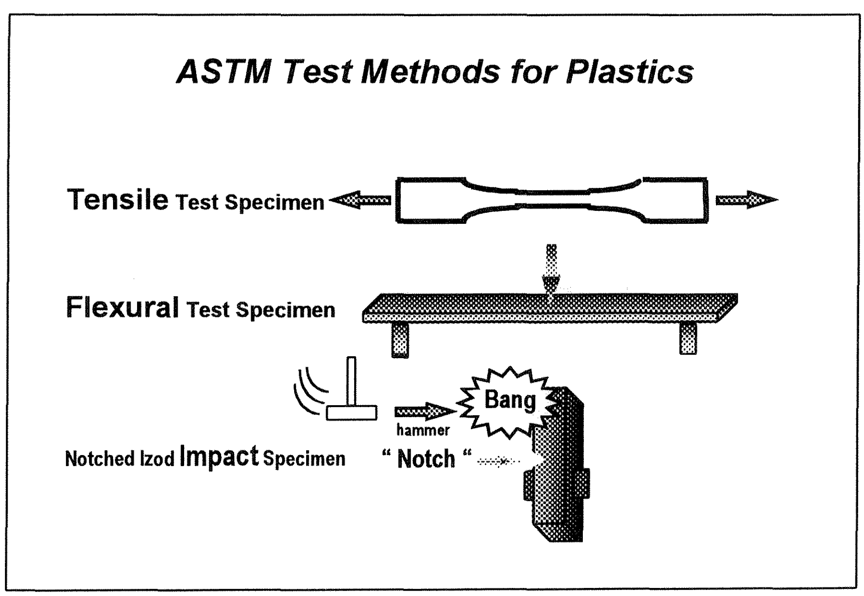
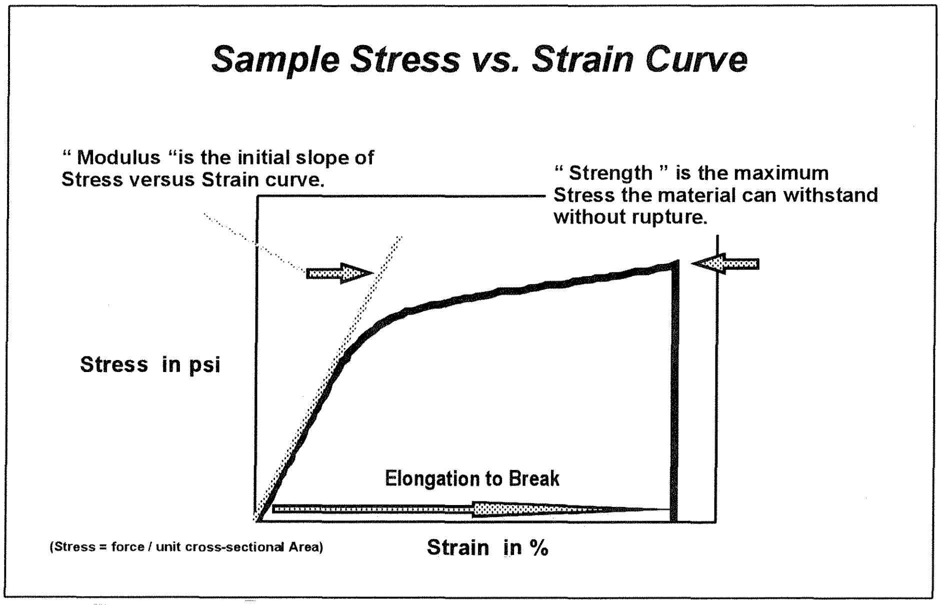


Figure 8

Six types of properties, tensile strength, tensile modulus, elongation to break, flexural strength, flexural modulus, and impact strength, were measured according to the American Standards for Testing and Materials (ASTM) for plastic materials. The results for the epoxy-based SL resins are compared to the literature values[8] for acrylic plastic (PMMA) and medium impact polystyrene. The mechanical properties for acrylate-based SL resins, in particular, urethane-acrylate-based **SL 5143**, **SL 5149**, **SL 5154**, and epoxy-acrylate-based **SL 5081-1** and **SL 5131**, are also presented for comparison.

As a side note, the description for **SL 5081-1** and **SL 5131**, "epoxy-acrylates," may be misleading. Epoxy-acrylates are a type of acrylates. It should be emphasized that these resins are *not epoxy-based monomers*, and *do not contain epoxies*. The *precursor* molecules for the monomers in the resin was an epoxy. Furthermore, the reaction mechanism for epoxy-acrylates is 100% free-radical polymerization, characteristic of acrylates.

For mechanical testing, the SL resins are all built on the appropriate SLA using the recommended solid build styles, and are post-cured normally. For the epoxy-based **SL 5170** and **SL 5180** resins, ACES build style was used. The other SL resins were built in STAR-WEAVE.



Figture 9

The ASTM mechanical tests are schematically described in figure 8, and a simple definition of modulus, strength, and elongation to break, as applied to tensile testing, is given in figure 9. These are some of the most typical mechanical properties considered in the materials selection process for various prototype and end-use applications in product manufacturing.

The mechanical properties for the SL resins are given in figures 10~16, together with those for acrylic plastic and medium impact polystyrene. The horizontal bars represent the values, and the darkened tips provide the range of values. For the **SL 5170** and **SL 5180** resins, the range is based on the error bar associated with ASTM tests of multiple samples. At least five samples were tested. For the non-epoxy SL resins, the range includes, in addition to the measured range, small, but non-negligible variation between the SLA-250 and SLA-500 versions of similar resins. For the acrylic and medium impact polystyrene data, the literature values presented include the range of values corresponding to multiple grades of materials available in the market that may be described as "acrylic plastic" and "medium impact polystyrene." Obviously, there are a number of manufacturers as well as a number of grades of these common thermoplastics. For some materials, the range of the mechanical property values may be very large.

Acrylic plastics are used for transparent aircraft enclosures, radio and TV parts, lighting equipment, and goggle lenses. Medium impact polystyrenes are most commonly used for radio and TV cabinets, toys, and containers and packaging applications.

Tensile and Flexural Strengths

Tensile testing for SL resins was performed according to the **ASTM D638** method. The tensile strength data, given in figure 10, demonstrates that the high strength, but relatively brittle resins, **SL 5081-1** and **SL 5131**, have the highest tensile strengths in this group. Their tensile strengths are 7,200~11,500 psi. The urethane-acrylates have the lowest strengths, for both tensile and flexural tests, with strengths of about 5,000 psi. The **SL 5170** and **SL 5180** resins have tensile strengths in the range of 6,000~9,000 psi. These tensile strengths are in the same range as those of acrylic plastic, with 6,000~9,000 psi. The tensile strength of **SL 5180** is comparable to medium impact polystyrene, however, **SL 5170**, with the tensile strength of about 8,800 psi, is almost 50% stronger than medium impact polystyrene.

The flexural strength is defined as the stress measured at fiber strain of 5% as designated by the **ASTM D790** criteria for flexural testing. For most applications, flexural strength is more relevant for SL parts because parts are more often bent than pulled along the long axis. The urethane-acrylates have the lowest strengths, for both tensile and flexural tests.

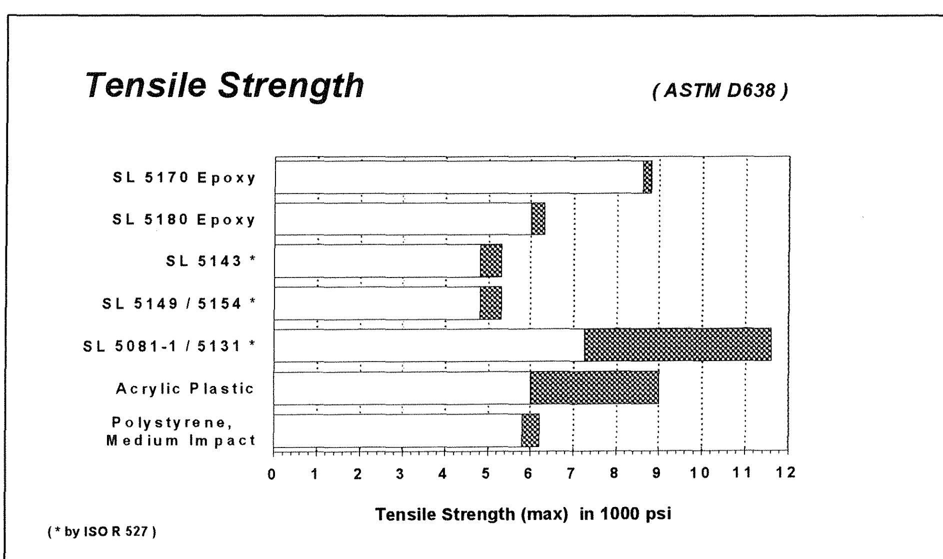


Figure 10

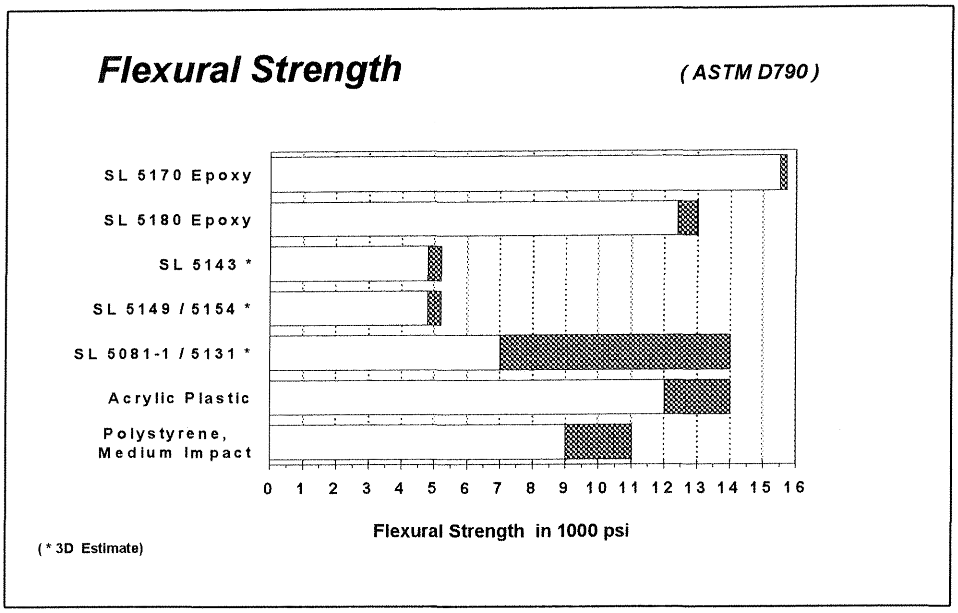


Figure 11

Generally, flexural strength scales with the tensile strength. However, an interesting trend is observed between the acrylate- and epoxy-based resins. In the case of acrylate-based resins, the flexural strengths are equal to, or only slightly greater than their tensile strengths. For example, the maximum tensile strength for **SL 5081-1** is 11,600 psi whereas the flexural value is 14,000 psi, an increase of about 30%. However, epoxy-based resins have significantly higher flexural strengths than the tensile strengths. For example, the flexural strength of **SL 5180** is 12,700 psi, which is more than 100% greater than its tensile strength of 6,100 psi. This tensile strength of **SL 5180** is comparable to that of medium impact polystyrene, however, it is 20% stronger in flexural strength. Similarly, for **SL 5170**, the increase from tensile to flexural strengths is from 8,800 psi to 15,600 psi, an increase of almost 80%. *Furthermore, SL 5170 has a higher flexural strength than the strongest acrylate SL resin, SL 5081-1, and is even stronger than acrylic plastic or medium impact polystyrene.*

Tensile and Flexural Modulus

Modulus is a measure of how much the material elongates, or deforms, when it is subjected to a given load or stress. This is one of the most important parameters that is often referred to as the "rigidity" of the material. The tensile modulus was measured in compliance with **ASTM D638**, and for flexural modulus, with **ASTM D790**.

The tensile modulus, given in figure 12, of **SL 5081-1** resin, is relatively high among the SL resins, with the maximum value approaching 600,000 psi. The urethane acrylates, **SL 5143** and **SL 5149**, have relatively low values, ranging from only 100,000~160,000 psi, compared to the tensile modulus for acrylic and medium impact polystyrene, which is about 390,000~470,000 psi. The epoxy-based resins, however, range from 400,000~600,000 psi. Hence, **SL 5180** is comparable to the thermoplastics.

However, **SL 5170**, on the other hand, has tensile modulus that is almost 30% greater than either acrylic or medium impact polystyrene.

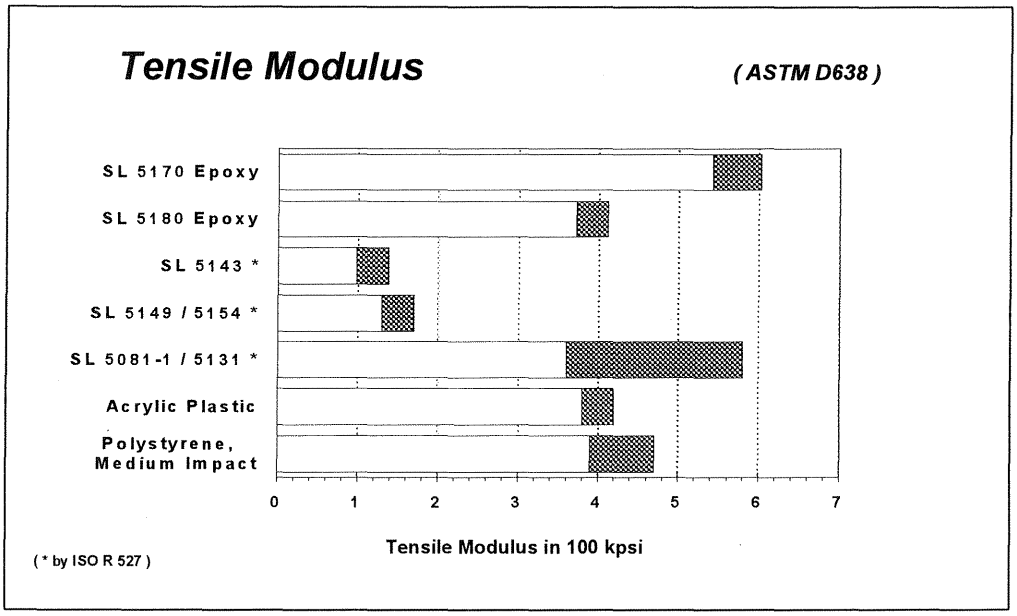


Figure 12

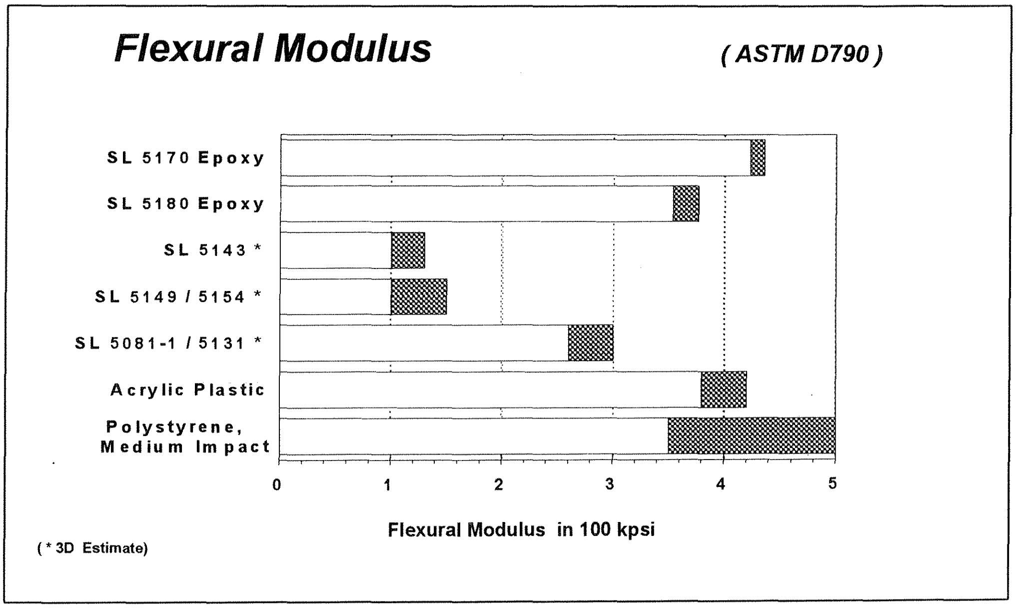


Figure 13

The flexural modulus, shown in figure 13, is a measure of bending, or flexural deformation, when the material is subjected to a stress perpendicular to the long axis of the test sample. The bending deformation results in shear forces inside the part, and is a common deformation mechanism in complex geometries. The flexural modulus test was carried out pursuant to **ASTM D790** procedure.

The trend for flexural modulus is similar to that for tensile modulus, discussed above. Notice, though, that the epoxy-based resins are more rigid than the acrylate-based resins. Even the high strength acrylate resins **SL 5081-1** and **SL 5131**, have only about 75% of the flexural modulus of **SL 5170** and **SL 5180**. The difference between the urethane acrylate systems **SL 5143** and **SL 5149** is much greater. *The **SL 5170** and **SL 5180** resins are almost three times as "rigid" as those SL resins.* High modulus is the key to improved dimensional stability.

<u>Elongation to Break</u>

The elongation to break data, obtained according to **ASTM D638**, is shown in figure 14. The elongation to break for the flexible urethane-acrylate SL resin, **SL 5143,** is the greatest among SL resins. The range of elongation to break values for medium impact polystyrene is extraordinarily large. The values for medium impact polystyrene may be as small as 3%, or as large as 40%, depending on the grade of material. In contrast, **SL 5081-1** has maximum elongation to break of only 3%, the lowest in the group. The epoxy resins **SL 5180** and **SL 5170**, have elongation to break values of as much as 16, and 19%, respectively. This is substantially greater than the corresponding values for acrylic plastic of 7%, or for the urethane acrylates, **SL 5149** and **SL 5154**, of 11%.

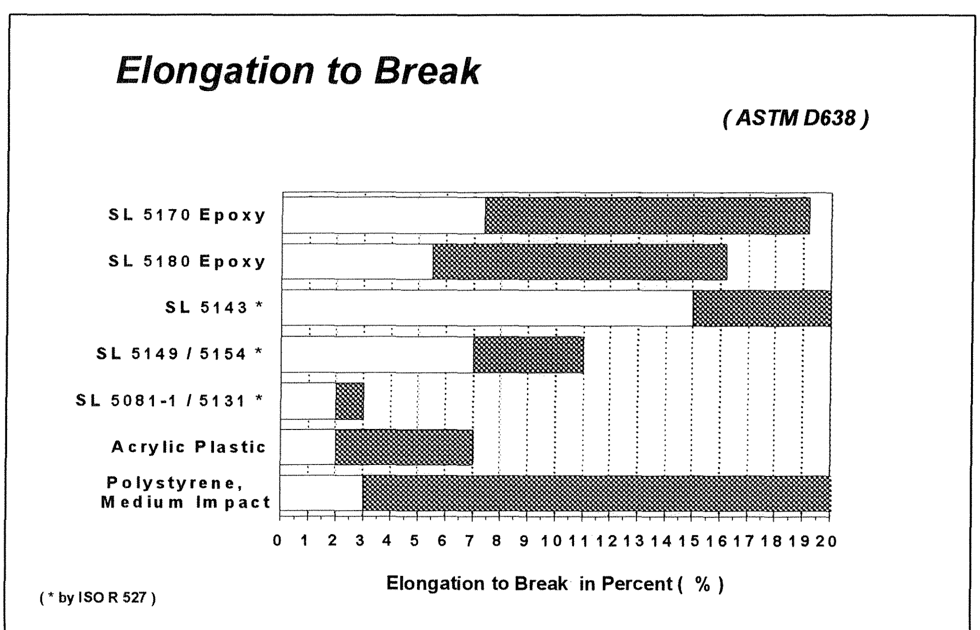


Figure 14

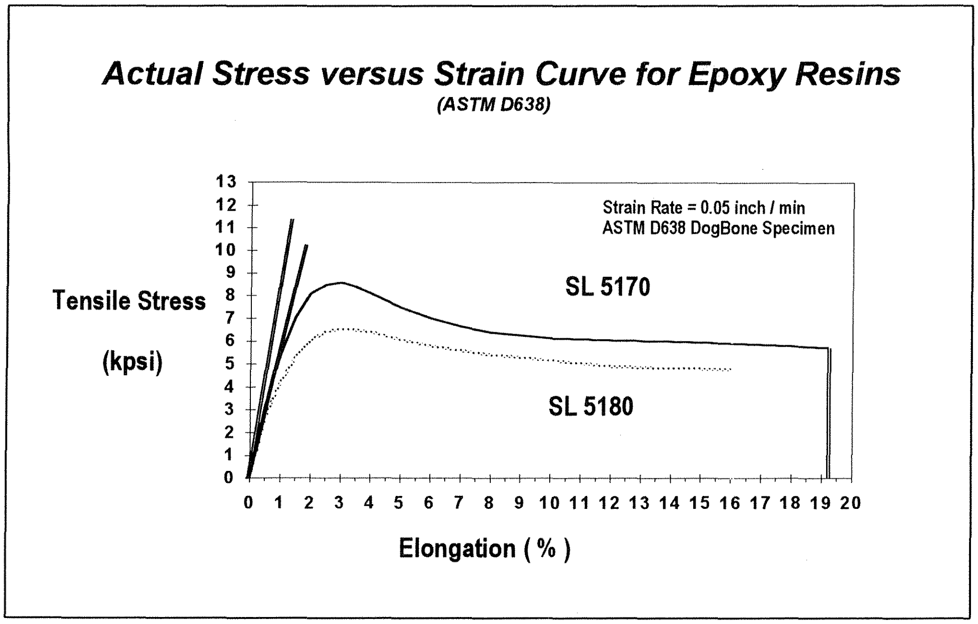


Figure 15

The experimental tensile stress data for **SL 5170** and **SL 5180** is plotted as a function of elongation, in figure 15. The tensile modulus values, defined as the slope of the intial linear portion of the stress vs. strain (elongation) curve, are slightly different between the two epoxy-based resins. **SL 5170** has a greater slope than **SL 5180**, corresponding to the difference in the tensile modulus value of 570,000 psi vs. ~ 400,000 psi. Notice that the measured stress increases as the tensile sample is elongated further, up until an elongation of 3%. Since the stress becomes maximum at this point, in this case, the stress values are assigned as the tensile strengths for the two resins. Then, the curves passe beyond the yield point, and go into *plastic deformation* before it finally breaks at about an elongation of 16~19%. *Plastic deformation is usually not a characteristic of crosslinked polymer systems.* However, these photo crosslinked epoxy-based resins **SL 5170** and **SL 5180** undergo substantial elongation, beyond the yield point. Most other SL resins do not substantially elongate beyond the yield point, except for flexible systems.

Material toughness is defined as the area under the stress vs. strain curve. In this view, the **SL 5170** and **SL 5180** are considered tough materials. Admittedly, there are high-molecular weight engineering thermoplastics that have considerably higher toughness than **SL 5170** and **SL 5180**. However, these epoxy-based SL resins have proven to be extremely rugged and tough for numerous applications, based on SLA user surveys carried out in late 1993. (SL 5180 was not released yet, however, it had been in Beta testing stage.) **SL 5170** and **SL 5180** parts have survived many functional tests that include spinning propellers at high speeds, exposing models to high velocity flow in wind-tunnels, snap-fits for such parts as telephone and computer housings, and fluid flow testing in liquids, to name a few. Some of these functional tests could not be performed with the earlier acrylate-based resins.

Impact Strength

Finally, the impact strengths of SL resins, shown in figure 16, were measured according to the specification of **ASTM D256**. The impact samples were notched in the CAD data, such that no machining was involved, and the SL parts were ready to be tested immediately. The width of the impact test sample was 1/4 inch, a thicker sample, instead of the thinnest allowed, of 1/8 of an inch, by ASTM. This was because thin samples are known to result in higher impact strength values due to the flexing and multi-nodal bending of the sample during the impact, dissipating the energy from the impact much more than for thicker samples. Therefore, such values from thin samples may not be representative of the actual impact strength of the resin. A thicker sample can concentrate the energy of the impact in one direction, and is representative of the material, and not the geometry.

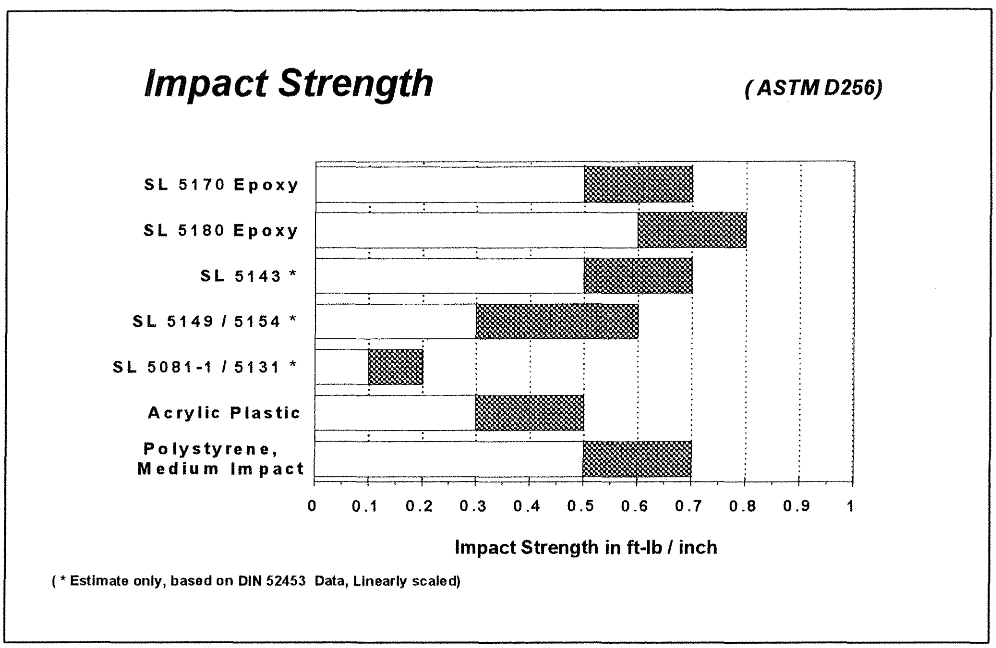


Figure 16

The impact strengths of the epoxy-based resins are comparable to medium impact polystyrene, and are slightly greater than acrylic plastic. In addition, these SL resins, **SL 5170** and **SL 5180**, having impact strengths of 0.5~0.8 ft-lb/inch, are *3~4 times more impact resistant than the earlier acrylate resins **SL 5081-1** and **SL 5131***, which have impact strengths of only 0.1~0.2 ft-lb/inch. **SL 5180**, have the greatest impact strength, with a maximum value of 0.8 ft-lb/inch. Within experimental error, **SL 5170** and **SL 5180** have impact strengths that are comparable to medium impact polystyrene and acrylic plastics.

Precision Metal Prototypes

For applications that require greater mechanical strengths than **SL 5170** and **SL 5180**, metal parts can be obtained by using QuickCast. With QuickCast, *precision* metal components can be directly produced from SL parts.

	Common Plastics	**Aluminum**	**Steel**
Tensile Strength (kpsi)	**~10**	**~100**	**~200**
Tensile Modulus (Mpsi)	**~0.5**	**~10.0**	**~30.0**

Table 1.

The mechanical properties of metals, in general, can be orders of magnitude greater than plastic. Some mechanical properties of metals are given in Table 1, for comparison with those of plastics for reference. For example, even aluminum, which is considered a "soft" metal, have tensile strength that is an order of magnitude greater than plastics. The difference is greater for tensile modulus. Metals such as steel is 60 times more rigid than plastics are. Impact resistance, is a measurement available for materials that break and fail. Most ductile and maleable metals do not break and hence impact strength can not be measured. However, if it is measurable, the impact strengths for metals is expected to be orders of magnitude greater than plastics.

Furthermore, when a "negative" core and cavity pair of a "positive" geometry is produced in metal using QuickCast, tooling is obtained. With the metal core and cavity pair, prototype, and eventually production functional parts may be *ultimately injection molded in the desired engineering thermoplastic material.* This allows the user to test his designed object quickly, in the material of his choice.

Conclusion

The dimensional properties of the stereolithography resins based on epoxy chemistry were measured. These resins, **SL 5170** and **SL 5180**, were found to generate parts with significantly improved overall part accuracy, dimensional stability, and mechanical properties relative to the earlier acrylate SL resins. Also, **SL 5170** resin, for the **SLA-250** system, and **SL 5180**, for the **SLA-500** system, have resulted in extremely low curl and distortion.

Overall dimensional accuracy, measured by building not one, but *ten sets of User-Parts* built in **SL 5170** on the **SLA-250** have established the accuracy record to date. The measured RMS error, based on 1700 data points, is ± 1.8 mils, or about ± 45 microns. **SL 5180**, built on the **SLA-500**, is the next most accurate, with RMS error value of about ± 2 mils. The result from ten User-Parts built in **SL 5170** demonstrated, not only high overall accuracy, but outstanding repeatability of the SL process. The accuracy result, based on the 1700 dimensional measurement made by a CMM machine taken in the x, y, and z directions, is statistically significant, and indicates the high level of repeatability achieved by the combination of building parts on an SLA and using the epoxy resin.

The flatness diagnostic Slab 6X6 test showed that these epoxy-based resins are now capable of producing extremely flat parts that were formerly a challenge with the conventional acrylate-based resins. The maximum Slab 6X6 distortion in the epoxy resin, compared to a flat surface, is only +5 mils, even when the Slabs were post cured from one side only, to simulate the worst-case scenario. Now, SLA users can build very flat parts with high confidence.

SL parts built in these resins also exhibit superb dimensional stability in the laser-cured state, as demonstrated by the Green Creep Distortion diagnostic. Green Creep results presented in this paper showed that the log Green Creep Rates (GCR) for **SL 5170** and **SL 5180** are extremely small, with a creep distortion rate of only about 0.5 mils for every decade in time. This is almost a 30-fold improvement over conventional SL acrylate resins. Dimensional stability in the laser-cured state is very important for most SL applications, however, it is critical, for parts generated using the QuickCast™ build style.

Furthermore, the overall mechanical properties of these epoxy resins, measured according to the ASTM standards, were found to be comparable to or exceed those of plastics such as acrylic plastic (PMMA) and medium impact polystyrene.

With respect to the conventional acrylate resins systems, the **SL 5170** and **SL 5180** resins exceed in almost every category of measured mechanical properties. It is worth noting that, in general, the magnitude of these improvements are not incremental, but substantial. For example, flexural strength of the epoxy resins is *two to three times greater*, and the tensile and flexural modulus is more than *four times greater* than the conventional urethane-acrylate-based SL resins. The elongation to break for the epoxy resins is more *than six times greater* than the epoxy-acrylate SL resins. Finally, the impact strength is comparable to the *flexible* urethane-acrylate. However, the impact strength for **SL 5170** and **SL 5180** is *four to seven times greater* than that of the epoxy-acrylate systems, **SL 5081-1** and **SL 5131**. The epoxy resins are considered to possess the best combination of mechanical properties for numerous end-use applications.

Significance of SL 5170 and SL 5180 for SL Users

The improved dimensional and material properties realized by the epoxy-based **SL 5170** and **SL 5180**, bring about numerous advantages. For example, the outstanding strengths, modulus, and dimensional stability makes **SL 5170** and **SL 5180** suitable for building thin walls. Without these tributes, thin walled parts will creep, bend, or, simply collapse if the load is excessive, or distort to the point where the parts become unacceptable. Many successful thin-walled parts such as housings, and custom containers, have been built in the ACES solid build style, by numerous SL users.

Of course, the greatest significance of the epoxy-based resins is associated with the QuickCast application, for which high inherent strength of the resin is essential to prevent premature deformation, especially because QuickCast patterns necessarily require a quasi-hollow internal structure to prevent breakage of the ceramic invesment casting shells during the burn out cycle. The toughness, rigidity, and impact strength of the QuickCast SL patterns made of **SL 5170** and **SL 5180** are much greater than those of waxes commonly used for investment casting. This allowed foundries to shell investment cast thin walls and delicate features that were once thought to be impossible for patterns made in waxes.

Accuracy, dimensional stability, and good overall mechanical properties are a key to expanding SL into new applications, such as generating prototype and, eventually, production tooling via QuickCast Tooling. Finally, functional parts may be produced by injection molding in the "negative" core and cavity or, QuickCast tooling, to generate parts in the desired engineering thermoplastic material.

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