Accuracy of Stereolithography Parts: Mechanism and Modes of Distortion for a "Letter-H" Diagnostic Part

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Abstract

Rapid Prototyping and Manufacturing (RP&M) users need to compare the accuracy of various commercially available RP&M materials and processes. A good diagnostic test for both material and the fabrication process involves a 4-inch long "letter-H" diagnostic part. This diagnostic part, known as "**H-4**", was developed to measure the inherent dimensional characteristics of various RP&M build materials. It is also less dependent on the calibration status of particular RP&M machines, and is excellent for the purpose of generating simple but meaningful accuracy information, which can be used to further understand the mechanism and the modes of distortion in RP&M materials. **H-4** parts were prepared and built in Stereolithography Apparatus (SLA) using Ciba-Geigy epoxy based resins SL 5170 and SL 5180, and results were compared to acrylate based SL 5149. Experimental data involving the magnitude, mechanism, and the modes of distortion for these three resins are analyzed in this paper.

Introduction

The term "accuracy" associated with some of the RP&M build materials is sometimes used without sufficient supporting evidence or data, and causes misunderstanding among users hunting for materials that are essential for their applications, especially those users who are relatively new to the industry.

Mechanical, electrical, and thermal properties of RP&M parts are quite easy to comprehend due to their commonality with other fields and applications. However, part accuracy associated with the RP&M build materials have always been quite difficult to grasp until one sees a few distorted parts. Depending on the part geometry or build direction, distortion may not manifest at all. As most RP&M users have learned from experience, the distortion nature of layer-additive fabrication is not always intuitive.

If a user would like to obtain a set of statistically significant dimensional accuracy data, the User-Part[1], designed by the SLA Users Group, is suitable. However, the User-Part accuracy measurment of 170 dimensions requires a CMM, and a relatively involving and sophisticated analysis of the measured dimensions. This takes a substantial amount of time, unless the procedure is automated with a computer.

In Stereolithography, one can build a Christmas-Tree diagnostic[2], which is an accuracy tuning tool for SLA, with the resin of interest, to obtain resin shrinkage and the line width compensation values. Nevertheless, some of the relevant distortions do not manifest in either the User-Part or the Christmas-Tree diagnostic parts.

A cantilever part[3] which gives the degree of curl distortion of an *unsupported* cantilever, is still relevant for SL resins in some limited applications for which support are not accessible for removal. However, since most of the users are supporting almost all of the downfacing features especially with the recent availability of various automatic support software products, some of the significance of the cantilever diagnostic is quickly being lost.

One can build a straight rod and measure the dimensional error compared with the CAD dimension. This diagnostic process is too simplistic. Besides, it is quite difficult to separate the inaccuracies due to the degree of shrinkage compensation applied, and the level of calibration used for the particular SLA. A good diagnostic test for resin comparison must measure the inherent dimensional performance characteristic of the SL resins, and less dependent on the particular SLA machines they are tested on.

In addition, to allow for a simple comparison, the diagnostic test should be relatively small, and simple to prepare, to build, to post process, and to analyze the data, as well as to interprete the results.

A smaller 2-inch version of letter "H" diagnostic was first introduced by Joe Allison in 1994[4] and was found to be an excellent candidate for the purpose of simple but meaningful accuracy diagnostic. Now, a 4-inch version, **H-4**, was developed. The diagnostic parts were prepared and built in Ciba-Geigy SL resins SL 5170, SL 5180 , and SL 5149. The diagnostic design and results for the three resins are discussed below.

H-4 Dimensions and Distortions

The 4-inch-long **H-4**, with 0.25 inch-cross sections were prepared. The diagnostic part represents a "letter H". The dimensions are described below in figure 1.

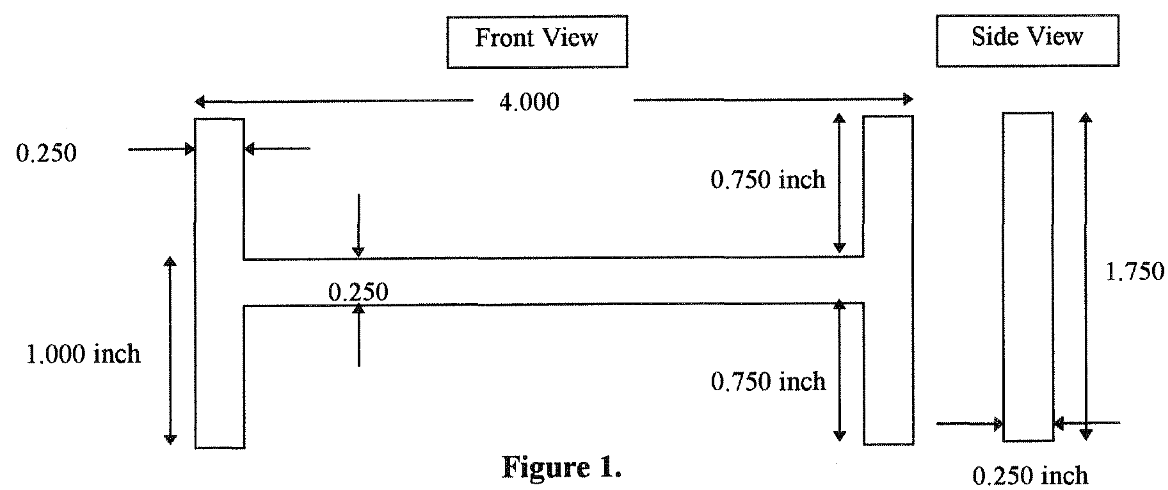

Figure 1.

The final distorted **H-4** parts were analyzed, and five critical dimensions, H-top, B-top, Waist, Ankle/Foot, and Lateral, were identified. These are listed next to the object in figure 2.

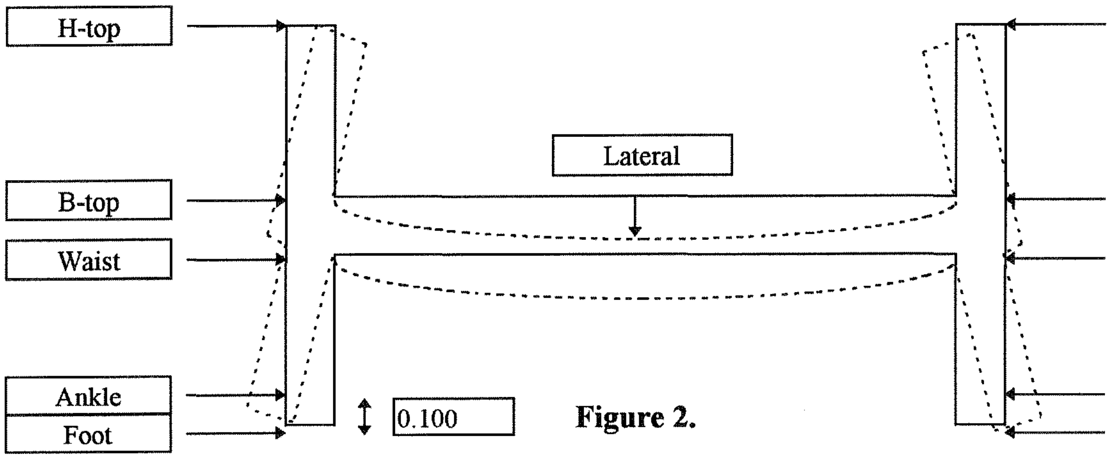

Figure 2.

In this figure, solid lines represent the CAD dimensions, or an undistorted **H-4** part as it is built on the RP&M machine, and the dotted lines represent those of the distorted part, with the distortion grossly exaggerated for purposes of illustration.

<u>Modes of Distortion in **H-4**</u>

Three modes of distortion were found to take place in this part:

<u>1) During SLA building (In-vat Distortion)</u>

The Waist distortion happens during SLA building. As the legs are built layer-wise from the bottom, and the first down-facing layer of the "seat" (bottom of the lateral part) or the "bench" is drawn, the shrinkage of the curing layer pulls the legs horizontally toward each other. This shrinkage action gives rise to the formation of the "Waist" in the final, distorted part. As the subsequent layers are cured on top of the first downfacing layer, the shrinkage forces decrease relative to the strengths of the previous layers. If the distortion is large, the waist becomes a dent. When the distortion is small and gradual, the ends of the bench becomes curved or angled with as opposed to being perpendicular. Eventually, as the final layer of the 0.250 inch "bench" top is cured, the length of the bench top (B-top) becomes very close to the nominal value.

However, the actual B-top dimension depends on various factors including the cure shrinkage during laser drawing, SLA calibration, shrinkage and line width compensation factors used for SLA building. As previously mentioned, a diagnostic test for comparison of materials should focus on the distortion of the resin, in the case of SL, and not on the calibration status of the particular machine. The former is what we're interested in, the latter is a hardware issue. Therefore, the nominal CAD dimension is not to be used as a comparison point, but the B-top dimension will be used as an internal reference dimension. Nevertheless, the dimension of the part should not be grossly different from the 4-inch length, for comparison purposes.

In this test, the distortion at each of the positions designated in figure 2 will be defined by the difference in dimension *compared to the dimension at B-top*. By using the dimension at B-top as the reference dimension for this **H-4** diagnostic testing, the distortion values are truly internal, and depend minimally on the SLA on which it was built. The argument applies similarly to other RP&M machines.

The Waist distortion is an extremely relevant distortion mechanism for SLA, *as well as for other layer-additive RP&M methods that incorporate dimensional changes due to physical or chemical change as the materials are laid and solidified*, because this type of distortion CANNOT be easily corrected by simple shrinkage or linewidth compensation operations on the build machines.

The nature of the supports also strongly affects the Waist distortion. If the supports extend continuously from one leg to another (sideways) along the long axis, filling the gap between them, the shrinkage forces of the first down-facing layer of the lateral section may not be strong enough to move the legs towards each other. Thus, it is essential to use supports that *least restrict the legs from moving toward each other* for this test.

In this test, "edge profile supports" have been suppressed, and only the supports that are perpendicular to the expected distorting direction were used, allowing the legs to move toward each other in the vat with least resistance. For this experiment, the support separation was 5-mm. Also, the bottom of the legs were supported with an "+ " -shaped web support.

Note: The distortion at the H-top is essentially suppressed during the SLA building because the legs are tied to the platform, and the lateral bench section is also held by supports. The H-top distorts only when the lateral section bends, as discussed in the next section. However, a small, non-negligible distortion occurs at the Ankle/Foot positions as the legs splay inward relative to the platform in the green state.

2) After Removal from the Platform (Post-support Removal Distortion)

Once the "green" unpostcured **H-4** part is removed from the platform, the legs are free to splay out. There are no longer any restricting forces exerted by the supports and the platform. This frees the "seat" portion of the **H-4** part, and it undergoes curl distortion in the lateral direction, as shown in figure 2. This latent lateral curl distortion, which is essentially a creep distortion[5], is a dimensional manifestation of the residual internal stress of the part. As the lateral distortion takes place, the stress correspondingly splays the H-top portion (the "arms") inward, and the Ankle/Foot outward. The H-top distortion, therefore, is a post-building distortion.

At this point, the distortion of the Ankle/Foot portion now has two distortion components. One is a small but non-negligible in-vat distortion due to the shrinkage of the first few down-facing layers of the "seat", explained in 1), and the other is the one due to the lateral distortion, leading to the splaying of the legs outwards. The lateral distortion generally increases over time, especially when the **H-4** part is left in the green state, and the H-top and Ankle/Foot distortions correspondingly increase.

For purposes of standardizing this **H-4** diagnostic test, all of the dimensional measurements for the green part were taken one hour after the part was removed from the platform. Because there is some rounding of the downfacing edges that increases measurement error at the Foot position, dimensions at the Ankle position, which is offset from the Foot position upward by 100 mils, was used for calculating the degree of splaying out. Hence, the dimensional measurements taken at the Foot position were not utilized for analysis.

3) After UV Postcure (Postcure distortion)

The green **H-4** part is then UV postcured in an appropriate UV oven for an appropriate duration from one side only, laying down. In this test, **H-4** parts were UV post cured for one hour. After UV postcure, all dimensions are expected to shrink equally. There are, of course, additional internal stresses introduced by the postcuring process, which may further distort the part. However, the expected postcure distortion is mostly in the plane of the **H-4** part when postcured in this manner. The distortions in the plane of the **H-4** part is not considered for this diagnostic. The inhomogeneous part of the postcure distortion relative to the dimension at B-top, is expected to be small enough for this geometry such that it can be neglected for this test, as hown in the data presented. The overall postcure shrinkage, however, is included for this test. The postcure shrinkage value is also measured at the B-top position.

Experimental **H-4** Distortion of SL 5170, SL 5180, and SL 5149

The **H-4** diagnostic part was built in epoxy based Cibatool resins SL 5170, SL 5180, and acrylate based SL 5149. The HeCd and Argon ion laser powers were 20 mW, and all parts were built in 6-mil layers (1.75 inch height = 292 layers). The resin specific build parameters recommended by 3D Systems were used, including shrinkage compensation and line width compensation factors. SL 5170 and SL 5180 were built in the ACES ™ style whereas SL 5149 was built in the recommended STAR-WEAVE ™ style.

All parts were built without sweeping for this experiment. Z-wait was increased to 45 seconds for the epoxy based resins, and 60 seconds for the acrylate to ensure appropriate layer recoating. Sweeping action is not expected to affect the results. However, too fast of a sweep may sway the parts back and forth in the vat if the part is built horizontally against the sweeper blade, and may result in layer-to-layer dislocation. Besides, sweeping introduces error associated with the blade gap adjustment inaccuracy, if it is present.

Without sweeping, building three **H-4** parts takes approximately 8 hours at the laser power of 20 mW. If a sweeper is used, it should take about 6 hours to build one **H-4** part. Of course, the building speed can be further accelerated by increasing the laser power.

The experimental results obtained from three simultaneously built **H-4** parts for each resin, are tabulated below in **tables A to I**.

Dimensions* (mils)

Resin	Green State (GR) 5170	5180	5149
H-top	3997.9	3998.9	3980.7
B-top	4000.3	4000.6	4009.6
Lateral	- -	- -	- -
Waist	3988.7	3992.2	3963.1
Ankle	4003.1	3999.5	4062.4
Foot	3999.3	3997.1	4071.0

Resin	Postcured State (PC) 5170	5180	5149
H-top	3997.1	3997.3	3971.3
B-top	4000.0	4000.0	4000.0
Lateral	- -	- -	- -
Waist	3988.4	3992.3	3951.6
Ankle	4002.4	3999.8	4052.0
Foot	3998.5	3997.4	4061.9

*Measured using Micro-Vu (X-Y positioning device with microscope. Measurement resolution ca 0.5mils.)

Table A **Table B**

Distortion (mils) vs. B-top as Reference

Resin	Green State (GR) 5170	5180	5149
dH-top	-2.4	-1.7	-28.9
dB-top	*0.0*	*0.0*	*0.0*
d-Lateral	1.8	1.8	17.6
dWaist	-11.6	-8.4	-46.5
dAnkle	2.8	-1.1	52.8
dFoot	- -	- -	- -

Table C

Resin	Postcured State (PC) 5170	5180	5149
dH-top	-2.9	-2.7	-28.7
dB-top	*0.0*	*0.0*	*0.0*
d-Lateral	1.4	2.1	24.7
dWaist	-11.6	-7.7	-48.4
dAnkle	2.4	-0.2	52.0
dFoot	- -	- -	- -

Table D

Linear Green Shrinkage (B-top,$_{GR}$ - Waist,$_{GR}$)

Resin	5170	5180	5149
mils/4inch	11.6	8.4	46.5
%	0.29	0.21	1.16

Table E

Linear Postcure Shrinkage (B-top,$_{GR}$ - B-top,$_{PC}$)

Resin	5170	5180	5149
mils/4inch	0.3	0.6	9.6
%	0.01	0.01	0.24

Table F

Effective Ankle Splay out, mils (dAnkle,$_{eff}$)

Resin	5170	5180	5149
dWaist	-11.6	-8.4	-46.5
dAnkle	2.8	-1.1	52.8
dAnkle,$_{eff}$	14.4	7.3	99.4

Table G

Lateral Distortion values, mils (d-Lat)

Resin	Green SL 5170	SL 5180	SL 5149
Calculated*	1.5	1.1	17.7
measured	1.8	1.8	17.6

Table H

Resin	Postcured SL 5170	SL 5180	SL 5149
Calculated*	1.8	1.8	17.6
measured	1.4	2.1	24.7

Table i

The dimensions were measured using Micro-Vu, an X-Y positioning device equipped with a microscope. The measurement error associated with this part, including human error, is about ±0.5~1.0 mils. The values are listed in Table A for a green **H-4** part, and in Table B, for a postcured one. The distortion at each positions, H-top, Lateral, Waist, Ankle, and Foot, were calculated relative to the reference dimension at B-top. They are given in Table C for the green part, and in Table D, for the postcured part. Negative numbers indicate that the dimensions are less than the corresponding B-top dimension.

H-4 Distortion Data Analysis

First, notice that the relative differences between the distortion values of the green and postcured parts given in Tables C and D are very small, indicating that the postcuring process leads to a relatively uniform shrinkage. The lateral distortion, however, should be considered separately because the lateral distortion changes with time, and there are inadvertently some time lapse before the **H-4** parts were postcured. In this experiment, the parts were left in the green state after removal from the platform for one hour. Then they were UV postcured for one hour.

Linear Green Build Shrinkage

The difference between the Waist dimension and the B-top dimension represents the shrinkage that occurs in the green state during the building process as discussed in section 1). The Waist distortion results mainly due to the shrinkage of the first downfacing skin layer of the bench section, as well as some contribution from the shrinkage resulting from a few subsequent layers. This may be referred to the "linear green build shrinkage" for a 4-inch long part. The values are shown in Table E.

As accurate as the epoxy resins may be, their linear green build shrinkage is still in the range of 8-12 mils/4inch. This is still a few factors away from the User-Part RMS error of about ±2 mils[6]. Furthermore, the User-Parts do not explicitly demonstrate dimensional inaccuracies of this type. The build shrinkages must be decreased even more, to futher increase SL part accuracy. The epoxy resins, nonetheless, have about five times less build shrinkage than the acrylate based 5149 resin.

Linear Postcure Shrinkage

The postcure shrinkage can be calculated from comparing the B-top dimension before and after postcuring. This is straight forward. The values are given in Table F.

Postcuring can introduce additional internal stresses. For thin sections, a nearly homogeneous UV postcure can be achieved. However, postcuring thick sections inevitably results in an inhomogeneously cured regions, due to the light absorbance characteristics of the photopolymer material. The surface will be cured more than the interior. If the material does not shrink by postcuring, no additional internal stresses will arise. Indeed, a perfect SL resin will have no postcure shrinkage.

SL 5170 and 5180 have a measurable postcure shrinkage of 0.01%. The acrylate based SL 5149 has almost 25 times more UV postcure shrinkage, of about 0.24%, or about 10 mils/4inches.

Ankle Distortion (dAnkle)

As explained previously, the legs of the **H-4** part splay outward due to two distortion mechanisms. One is the in-vat shrinkage distortion that snaps the two legs toward each other, and the other is the lateral curl of the bench section that happens after removing the part from the platform. The dimensional change at the Ankle is difficult to interprete because it is a combination of two different types of distortion mechanisms, distorting in the opposite directions.

The linear shrinkage, especially for the first downfacing layer of the bench section, pulls the top of the legs inward, leading to a small but non-negligible negative (narrowing) distortion between the two Ankles. When the supports are removed, the lateral distortion generates the outward splaying of the legs, which results in a positive (widening) distortion at the Ankle position.

The effective splaying out of the ankle, $\mathrm{dAnkle}_{\mathrm{eff}}$, may be compensated by the difference between the inward distortion of the Waist, by offsetting the inward distortion distance. In other words, $\mathrm{dAnkle}_{\mathrm{eff}} = \mathrm{dAnkle} - \mathrm{dWaist}$. The effective ankle splay values are tabulated in Table G.

The legs of the **H-4** part built in the epoxy based SL 5170 and 5180 splay out about an order of magnitude less than the acrylate based SL 5149, about ~10 mils versus 100 mils.

H-Top "arms" Distortion and the Lateral Distortion

The H-top distortions (dH-top) for the epoxy versus the acrylate based SL 5149, shown in Table D, are dramatically different. The dH-top of the epoxy based resins are at least an order of magnitude less than that of the acrylate based SL 5149. The dH-top of the epoxy resins SL 5170 and 5180 are about -3 mils, compared to about -30 mils for 5149.

As discussed previously, the dH-top does not take place in the vat during SLA building. It occurs only after the parts are removed from the platform, because of the lateral distortion that happens at the bench seat section. In other words, the dH-top is also a measure of the lateral distortion (bending of the middle section). As an evidence, the dH-top values and d-Lat values scale similarly for all three resins tested. The lateral distortion phenomena in the green state is the same distortion that occurs in the green creep distortion observed elsewhere[7]. The low dH-top values for the epoxy resins indicate that the lateral bench section is dimensionally stable throughout green to postcured states.

The lateral distortion, (d-Lat), may also be calculated from the measured dH-top values by the following equation, derived trigonometrically:

$$\boxed{\text{d-Lat} \sim \frac{(\text{dB-top X h})}{(\text{dB-top - dH-top})}\left(1-\cos\left[\frac{(1/2)\,(\text{dB-top - dH-top})}{\text{h}}\right]\right)} \qquad \text{Equation 1.}$$

where h (=0.750 inch) is the height of the "arms" above the lateral bench seat section. In this experiment, the lateral distortion was experimentally measured by the Micro-Vu. This equation assumes that the angular distortion of the arms are small (arcsin (a/b) ~ (a/b) for (a/b) << 1 where a = (1/2)(dB-top-dH-top) and b=0.750 inch).

For example, in the case of SL 5170, a = -0.0012 inch, which gives (a/b) = 0.00160, and $\arcsin(0.00160)_{\text{in radians}}=0.00160$. The comparison between the calculated and measured d-Lat values are tabulated in Table i. The agreement is very good, except for the value of the postcured SL 5149. This equation allows even those with only precision calipers to calculate the lateral distortion based on the measured dH-top dimensions. Lateral distortions cannot normally be measured using calipers.

Waist Distortion

The distortion that gives rise to the formation of the "waist" on the **H-4** diagnostic part, (dWaist), is perhaps the most significant of all. First, the mechanism by which the waist forms is unique to layer-additive fabrication. Second, the dWaist is the most relevant distortion for SL technology because *this distortion cannot be fixed by varying the two major accuracy maximizing tools in SLA: the shrinkage compensation and line width compensation factors.* This distortion can not easily be fixed by controlling postprocessing either, because dWaist is an IN-VAT distortion that happens in the SLA during the building process. When two legs splay inward, resulting in the wrong positioning compared to the CAD dimensions, there is not much one can do to fix it.

Of course, for this particular geometry, adding more supports can restrict the dWaist. However, there are many geometries that will not tolerate such over-supporting. Most of all, one can almost be certain that resins that show high dWaist values are generate parts that are dimensionally relatively inaccurate. The **H-4** analysis can be summarized in the table below:

H-4 Distortion Analysis				
No.	**Distortion Type**	**SL 5170**	**SL 5180**	**SL 5149**
1	**Linear Green Shrinkage**	0.29 %	0.21%	1.16%
2	**Linear Postcured Shrinkage**	0.01 %	0.01%	0.24 %
3	**Effective Ankle Splay**	14.4 mils	7.3 mils	99.4 mils
4	**Lateral Curl Distortion, Green**	1.8 mils	1.8 mils	17.6 mils
5	**Lateral Curl Distortion, Postcured**	1.4 mils	2.1 mils	24.7 mils

Summary

A simple diagnostic part, a 4-inch long letter-H shaped "**H-4**", is proposed as a tool to allow the RP&M users to compare various materials commercially available. This diagnostic part, despite the simplicity, exposes many relevant accuracy issues of the build material and the process to the users, both visually, and quantitatively. There are numerous advantages for this diagnostic part.

The **H-4**, because it uses its own internal dimension as a reference, does not depend on the calibration of the hardware, or the shrink factor, or line width compensation factors used for the building of the diagnostic. The distortion values can be compared with each other even if the **H-4** parts are built on different machines.

The in-vat waist "tucking" distortion, latent lateral curl distortion that occurs following the support removal, and the splaying out of the arms and the legs are easily measured using standard calipers. A CMM or high precision specialty equipment are not necessary for this diagnostic, unless a more precise work is required.

Linear green build shrinkage and postcure shrinkage can be easily calculated from the diagnostic part. Lateral curl on the horizontal section, which was not previously accessible for measurement with a caliper, can now be accurately calculated from the distance between the **H-4** arms measured using calipers.

The **H-4** diagnostic contains elements of the Christmas-Tree (linear shrinkage) and the CreepBar (latent curl distortion), and an additional in-vat diagnostic capability (waist distortion), plus visualization of distortion. The **H-4** diagnostic has an advantage that the in-vat build distortion appears separately as the waist distortion, and the out-vat distortion appears in the distortion of the vertical arms. The two distortions can be clearly separated in this diagostic.

Best of all, most of the distortion can be visually inspected. If the distortion is extremely small, one can feel the edges of the part to determine if the waist distortion is present. The splaying of the the arms and legs is visually detectable in most cases, because even the small lateral distortion is amplified in this 4-inch long part. If the **H-4** part does not appear distorted, one can be quite sure that the particular build material will build relatively accurately.

In this report, the **H-4** diagnostic test was applied to the Ciba-Geigy SL 5170, SL 5180, built in ACES™ style, and SL 5149 resins, in STAR-WEAVE™. The diagnostic clearly demonstrated the accuracy advantages of the epoxy based over acrylate based resins. The epoxy based SL 5170 and SL 5180 were found to have linear green, and postcure shrinkages that are *only 1/5, and 1/24* compared to that of acrylate based SL 5149, respectively. Effective ankle splay distortion values, and lateral curl distortion both in the green and postcured states, are also about *an order of magnitude* less for the epoxy based resins. These results correlate very well with numerous other diagnostic parts built at 3D Systems, as well as with the general experience of the resin users, fed back from the SLA users.

An accuracy study of other RP&M materials and techniques using this diagnostic will be extremely interesting, and highly desired, to increase the understanding of the distortion mechanisms both during and after part fabrication.

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