ADVANCES IN STEREOLITHOGRAPHY ACCURACY

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INTRODUCTION

It has been almost four years since the SLA - 1 ushered in the new technology of StereoLithography, and about 2½ years since 3D Systems introduced the SLA-250. Since then, nearly 300 systems have been installed worldwide and are currently providing benefits in a range of applications which might well be summarized by the term "Rapid Prototyping and Manufacturing" or "RPM".

During the past year the accuracy of parts built with StereoLithography has benefitted significantly from nine important technological advances. The research and development efforts which formed the foundation for this progress originated within the Process, Chemistry and Software departments of 3D Systems.

The following is a listing, and brief description, of the key features of each of these advances.

1. WEAVE™

This proprietary building method was developed at 3D Systems during 1990. WEAVE™ is a trademark of 3D Systems, and a patent application for this technique has been filed. The WEAVE™ building method substantially reduces part swelling, improves shrinkage uniformity, decreases post-cure distortion and dimensional instability (creep), enhances "green strength" and significantly improves overall part accuracy. WEAVE™ is currently operational on the SLA-190, SLA-250, and SLA-500.

2. SOFTWARE RELEASE 3.81 with IMPROVED RESIN LEVELING

Formerly, the leveling operation was performed shortly after the z stage / platform had moved downward during the recoating sequence. The motion of the platform resulted in resin free-surface oscillations which were not completely damped when level sensor sampling occurred. The result was long leveling intervals, involving multiple plunger corrections which themselves caused additional surface perturbations resulting in errors as great as ± 2 mils. With release 3.81 for the SLA-190 and SLA-250, the resin level is now sensed after laser drawing. Consequently, neither the platform nor the leveling system plunger have moved for the longest possible time, and thus the fluid surface has very nearly reached stable equilibrium. As a result, the leveling system is now operating with a standard deviation of about 0.2 mil and a maximum error of ± 0.5 mil.

3. NEW POST-CURING APPARATUS (PCA)

The earlier PCA utilized compact, high intensity mercury lamps. Test data showed excessive heating, the development of thermal stresses and considerable post-cure distortion. The new PCA utilizes actinic fluorescent lamps, provides a nearly optimal spectral irradiance distribution resulting in more uniform post-cure, significantly lower part temperatures, greatly reduced thermal stresses, and improved part accuracy. The PCA-250 applies to all resins used in either the SLA-190 or the SLA-250. The PCA-500 is optimized for the resins used in the SLA-500, and also accommodates correspondingly larger parts.

4. TWIN-SCREW ADJUSTABLE RECOATER BLADE

The primary function of the recoater blade is the accurate and reproducible generation of uniform fresh resin layer thickness. Errors in blade clearance can lead to delamination, excessive curl, and reduced overall part accuracy. Previously, recoater blade adjustment was a tedious, time consuming process with a mean error of about ± 2 mils. With the implementation of the new apparatus, the time required to set the blade gap has been significantly reduced and the mean error in blade gap is now down to ± 0.5 mil. The result is more accurate recoating, more consistent layer thickness and reduced incidence of layer delamination. The new twin-screw blade has been retrofit on earlier SLA-250's and is currently installed on all new SLA-250's.

5. "WINDOWPANE" METHOD FOR DETERMINING RESIN PARAMETERS

Until recently, the key resin parameters Dp (penetration depth) and Ec (critical exposure) were determined from "working curves" (an experimentally determined plot of polymer cure depth vs. the logarithm of the laser exposure) which exhibited standard deviations in cure depth of 0.5 mil, and maximum variations of about ± 1.5 mils. Errors of this size could often negate all the potential advantages of WEAVE™. A new method, know by the visually descriptive title "WINDOWPANE", was designed, developed, tested, optimized, documented, and is now in use throughout 3D Systems. The new "WINDOWPANE" test results indicate standard deviations in cure depth of 0.2 mil, which is sufficiently accurate to exploit the advantages of WEAVE™, and is now the basis of quality control for all resins produced by Ciba-Geigy for StereoLithography applications.

6. AUTOMATIC COMPUTATION OF EXPOSURE AND LASER DRAWING SPEED

With accurate knowledge of Dp and Ec it is now possible to correctly determine the required exposure necessary to achieve a given cure depth. Also, coupled with an accurate measurement of the laser power at the resin surface, the current software now automatically computes the proper drawing speed to achieve the required exposure and, ultimately, the correct cure depth.

It is no longer necessary for the user to manually insert step periods or step sizes. Cure depths generated with the current software are more accurate and more consistent than those established by the prior method.

7. MORE ACCURATE MACHINE CALIBRATION TECHNIQUE

A new calibration technique was developed for the SLA-250. The new method is not only faster (approximately 3 hours vs. 13 hours), but is also more accurate than the previous calibration technique. Results were obtained using a coordinate measuring machine (CMM). Data was taken for short, medium and long dimensions on a standard diagnostic test part specifically used for machine calibration.

8. NEW PART CLEANING PROCEDURE

Formerly, most StereoLithography parts were cleaned with alcohol. Careful experimental measurements showed that even a relatively brief exposure of "green" parts to alcohol resulted in significant part distortion (e.g. 8 mils of swelling on a 2 inch dimension of a part built with WEAVE™ after exposure to alcohol for 0.5 hours). Using the new part cleaning process, with TPM (Tri Propylene Glycol Monomethyl Ether) as the solvent for uncured resin, the data shows dramatically reduced part distortion (e.g. less than 0.5 mil on the same 2 inch WEAVE™ part dimension for exposures up to 5 hours !). Therefore, 3D strongly recommends that users adopt the new cleaning method. Detailed information regarding the requirements for implementation of the new part cleaning procedure will shortly be available from 3D Systems.

9. STAR-WEAVE™

During 1991 an even more advanced building method was developed and tested. This proprietary technique, known as STAR-WEAVE™, is also a trademark of 3D Systems, and a patent application for this technique has also been filed. STAR-WEAVE™ extends the improvements already documented with WEAVE™ through the addition of three new features. Specifically, the acronym "STAR" is derived from the inclusion of STaggered WEAVE™, Alternate sequencing, and Retracted Hatch.

STaggered WEAVE™ involves offsetting the vectors of a given hatch pattern (e.g. the x vectors) on the (N+1)th layer, by exactly half a regular hatch spacing, relative to those on the Nth layer.

The result is a more closely packed density of cured hatch vectors. The vectors on the second pass (e.g. the y vectors) are also staggered on consecutive layers.

Experiments have shown that STaggered WEAVE™ results in a higher average level of cure for "green parts," increases average "green strength," reduces post-cure distortion, improves dimensional stability, reduces swelling, and virtually eliminates voids, drainage zones and micro-cracks. In general, STaggered WEAVE™ results in parts with improved homogeneity.

Alternate sequencing reduces non-uniform part distortions as well as hatch dislocations tangent to interior openings, which are a consequence of using identical drawing sequences on each layer. The non-uniform distortions are quite probably due to layer-to-layer accumulation of internal bending moments resulting from delayed shrinkage phenomena. By alternating both the sequence and direction of propagation of the x and y hatch vectors drawn on successive layers, a partial cancellation of opposing moments can be achieved, with a corresponding reduction in part distortion. Also, hatch dislocations are no longer superimposed from layer-to layer and hence do not cause structural weakness, cracks or extensive fissures. Software release 3.82 for the SLA-190 and SLA-250, and software release 1.4 for the SLA-500, both due in September 1991, will provide the capability to do STAR-WEAVE™ with eight-fold Alternate sequencing (viz. alternating all eight possible combinations of two vector types with four propagation directions).

Finally, Retracted hatch involves attaching each hatch vector at only one border while retracting the hatch vector by a short distance (e.g. 20 mils) from the opposite border. Furthermore, the retraction sequence is itself alternated. Thus, a given vector may be retracted from the left border while its adjacent neighboring vector would be retracted from the right border. In this way, equal strength is preserved at all borders. As a result, the polymer cured on the first pass of STAR-WEAVE™, on any layer, is free to shrink without generating substantial reaction forces. Thus, Retracted hatch reduces internal stresses and bending moments, diminishes part distortion and provides a corresponding improvement in part accuracy. Test results for STAR-WEAVE™ are included herein.

RESULTS

In order to provide quantitative results regarding the accuracy of StereoLithography parts, it is necessary to select a particular accuracy test standard. The ideal standard test part would have the following properties:

a. It would be large enough in x and y to insure that the system is capable of building accurately near the extremes of the platform as well as near the center.

b. It would have a large number of small, medium, and large dimensions.

c. It would have both "inside" and "outside" dimensions. This is important in order to check that linewidth compensation is working properly. Inside dimensions will tend to be too small, while outside dimensions will tend to be too large if linewidth compensation is either not operational or imprecise.

d. It should not take too long to build.

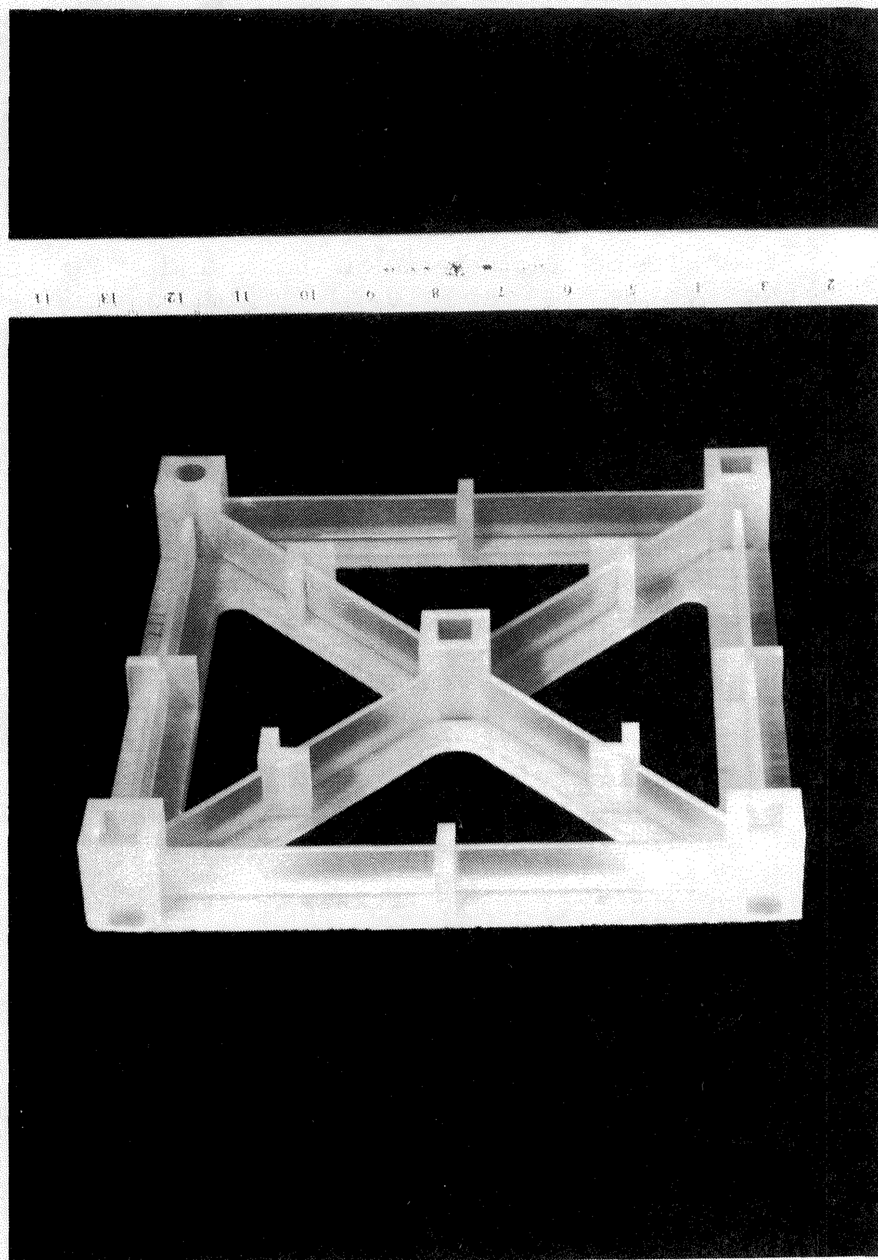
e. It should not consume a large quantity of resin.

f. It should be easily measured with a CMM.

g. It would have many of the features of "real" parts (e.g. thin walls, flat surfaces, holes, etc.).

h. Ideally, it would be a part not designed by 3D Systems, to insure complete impartiality.

Fortunately, such a part does exist. During the past year, the StereoLithography Users Group, consisting of about 150 industrial companies, service bureaus, U.S. Government laboratories, and Universities, developed exactly such an accuracy test standard. Known simply as the " User-Part", a photograph of this part is shown in **Figure 1,** A drawing of the User-Part is shown in **Figure 2,** which also shows some of the many dimensions to be measured on a CMM. In all, a total of 170 measurements are made on each User-Part. Of these, 78 are in x, 78 are in y and 14 are in z.



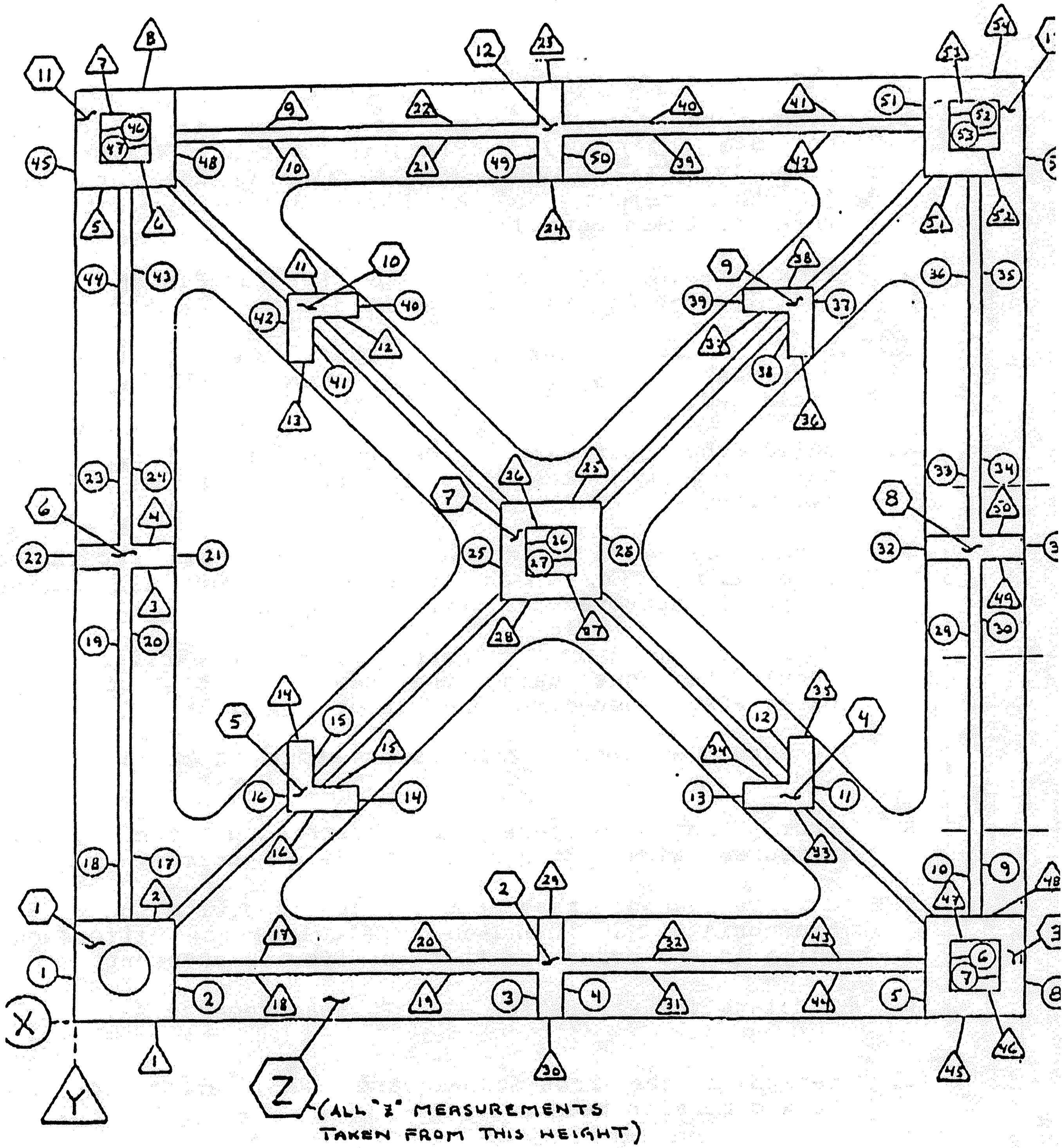


FIGURE 2

The procedure is as follows:

1. Pick a build style. One might choose to build with 50 mil 60°/120°/x triangler hatch, WEAVE™ or, recently, STAR-WEAVE™. In developing the data base for this report, 3D has built User-Parts with all three of these methods.

2. Pick a resin. 3D has built the User-Part in XB 5081-1, XB-5131, XB-5139 and XB-5143.

3. Pick a resin shrinkage factor and a linewidth compensation value. These values will later be optimized.

4. Build the User-Part. Depending upon laser power this normally takes 8 to 10 hours, and can be done overnight.

5. Clean the part. As noted earlier, this should be done using TPM, which is effective for all resins currently approved for StereoLithography.

6. Postcure the part. Again, as noted earlier, this should be done using the new actinic fluorescent based PCA. Post-cure takes about 1 hour.

7. Measure the part. This takes about 20 minutes on a CMM.

8. From these measurements, determine the <u>actual</u> measured values of each of the 170 dimensions.

9. Compare each of these <u>actual</u> dimensions with the appropriate CAD dimension. Calculate the difference, which is the error for that specific measurement.

10. Tabulate the errors for all 170 measurements.

11. Determine the root-mean-square (RMS) error for the 78 x dimension measurements.

12. Determine the RMS error for the 78 y dimension measurements.

13. Determine the RMS error for the 14 z dimension measurements.

14. Determine the RMS error for <u>all</u> 170 measurements.

15. Plot the error distribution function (i.e. the number of errors lying between 0 and +1 mil, the number of errors between +1 and +2 mils, etc.) over the whole range of errors from $-\infty$ to $+\infty$.

16. Plot the cumulative error function (i.e. the integral, or in this case the sum, of the error distribution function). This plot describes the total number of measurements within any desired tolerance level.

17. Plot the 99% confidence limit (i.e. 3 standard deviation) error level as a function of scale. This plot describes how the errors are distributed for small, medium or large dimensions.

18. Change the values of the shrinkage factor and linewidth compensation to reduce the errors.

19. Repeat the entire procedure, using the new shrinkage factor and linewidth compensation value.

20. Continue iterating until the optimum results are achieved.

It is important to note that once this process has been completed, for a particular resin and build style, all subsequent parts that are built with the same resin in that style, using the optimum shrink factor, should achieve the highest level of accuracy. Also, the reason for independently determining the RMS errors in x and y, as well as the RMS error for all measurements, is to check the machine calibration. If the RMS errors for the x and y dimensions are very nearly equal, then the SLA is properly calibrated. However, if they differ significantly, then the system will probably benefit from re-calibration.

Figure 3 shows the error distribution function for a single User-Part built with resin XB-5081-1 on an SLA-250 (S/N 90-076) in the Process Department at 3D Systems, using STAR-WEAVE™. A number of important features of this data are worth noting:

1. Within the limitations of a finite sample (viz. N=170 data points), the error distribution function is nearly Gaussian.

2. The function is also nearly symmetric (i.e. almost the same number of positive errors as negative errors). The fact that this function is not perfectly symmetric suggests room for further improvement.

USERPART

REPEATABILITY

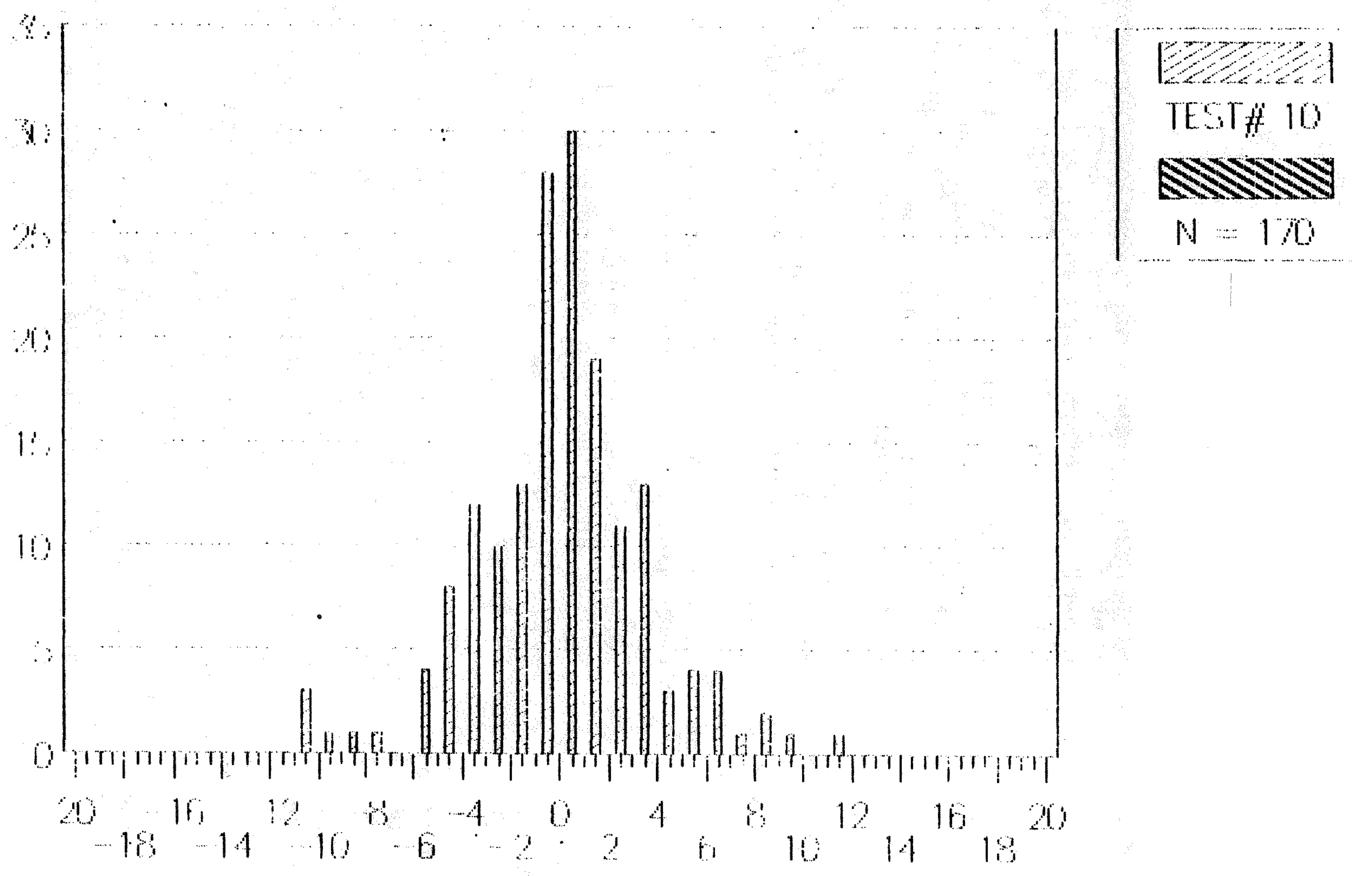


FIGURE 3

3. The most probable error is very near zero. (i.e. the peak of the plot occurs near zero error).

4. The majority of errors are within ± 3 mils.

5. The overall RMS error is about 4 mils.

6. Nonetheless, a few errors are as great as 11 mils.

Figure 4 is a plot of the cumulative error function for the same part. From figure 4 we may conclude for this part:

1. About **35%** of the dimensions of this part are within **± 1 mil** of their CAD value.

2. About **65%** of the dimensions are within **± 3 mils** of their CAD value.

3. About **85%** of the dimensions are within **± 5 Mils** of their CAD value.

4. However, about 2% of the dimensions have errors between 9 and 11 mils.

Figure 5 is a plot of the 99% confidence limit error as a function of the length of the dimension. This plot is generated by taking all the dimensions of the User-Part that lie within a certain range of lengths (e.g. from 0 to 1 inch, 1 inch to 2 inches, etc.), and then calculating the 99% confidence limit error for this sub-set. Inspection of Figure 5 shows the following:

1. The 99% confidence limit error increases with increased length.

2. However, the increase of error with length is nonlinear! Thus, characterizations of "RPM" accuracy based on "percentage" of length, or "mils per inch", both of which imply a linear function, are simply not in agreement with experimental results.

3. The actual results suggest that the 99% confidence limit error scales very nearly as the square-root of the length. Thus, for example, 9 inch dimensions will tend to have errors about 3 times as great as 1 inch dimensions, not 9 times as great!

From these results, it should be evident that characterizing the "Accuracy" of StereoLithography is not as simple as referring to a particular number, be that a percentage or a maximum error. At this time we stongly believe that the best measure of accuracy

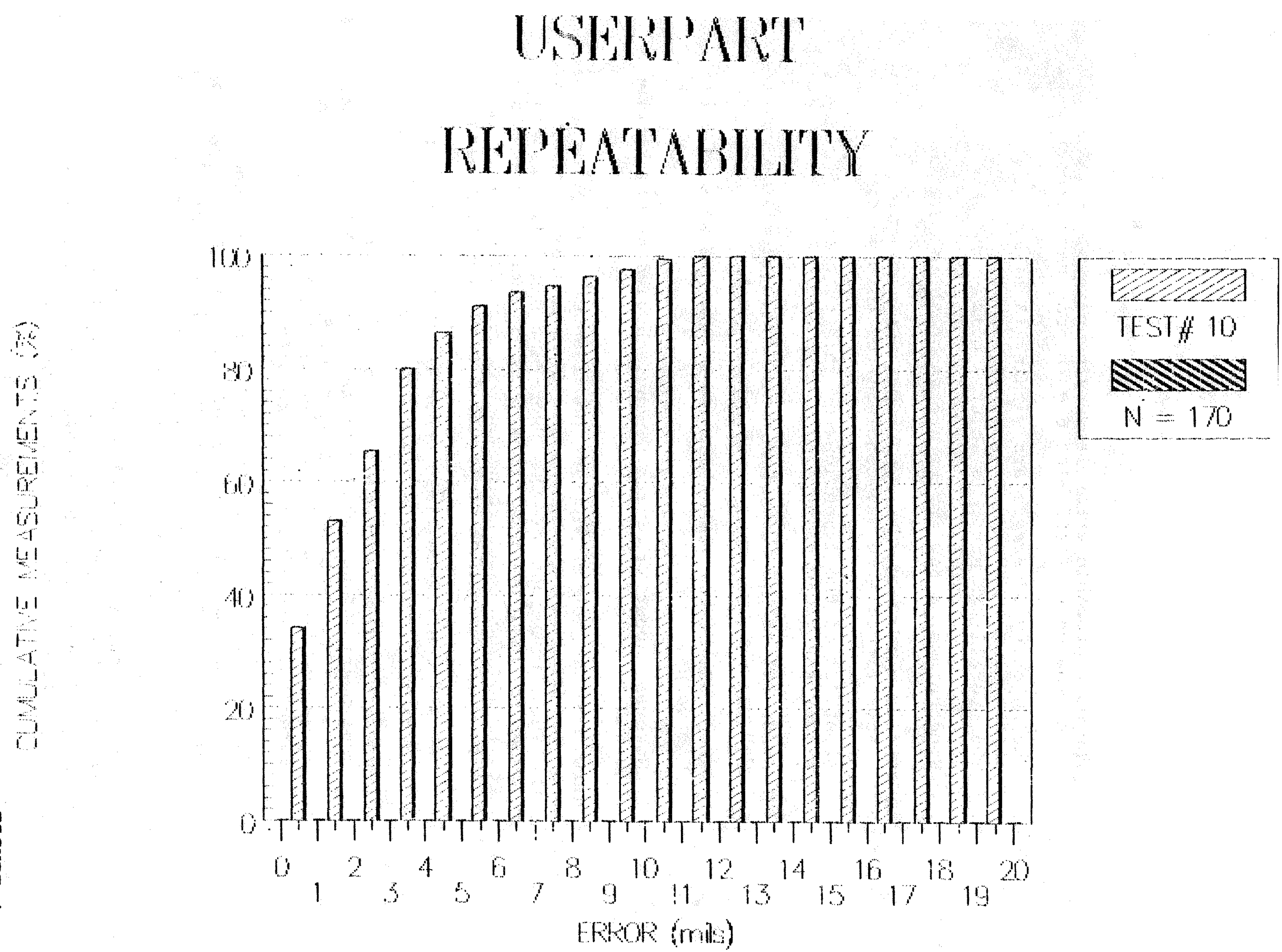
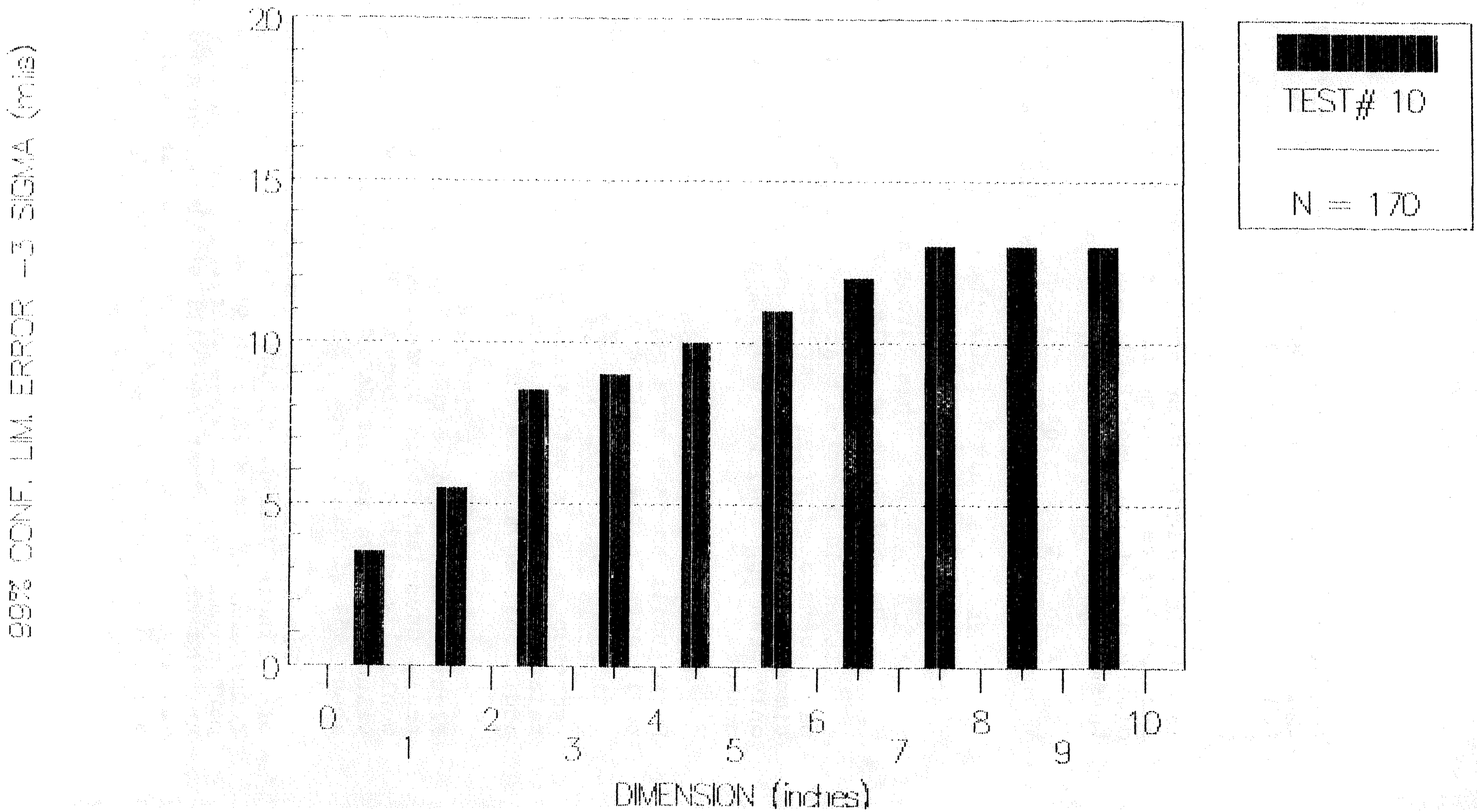

USERPART
REPEATABILITY
CUMULATIVE MEASUREMENTS (%)
0
20
40
60
80
100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
ERROR (mils)
TEST# 10
N = 170

FIGURE 4

USERPART

XB-5081-1 STARWEAVE



for the entire StereoLithography process is the error distribution function itself. This function, as well as the cumulative error function, which is derived from it, provides a realistic picture of the state of StereoLithography accuracy at this time.

In order to appreciate the remarkable progress which has been made in StereoLithography accuracy during the past year, one should examine **Figure 6.** This is a plot of the RMS error for all 170 dimensions of the User-Part, for resin XB-5081-1, when built with three different build methods.

* 50 mil 60°/120°/x triangular hatch. This was by far the most common build method as little as one year ago.

* WEAVE™. This build method, intoduced late in 1990, is now in widespread use.

* STAR-WEAVE™. This latest build method will be available to the user base in September 1991.

It should be noted that the data presented in Figure 6 are for parts generated after completing the iteration cycle a number of times. Thus, both linewidth and shrinkage compensation have not only been applied, but they have been optimized for each building method.

Also, we have chosen to plot the results for the "3 best" User Parts built to date as a separate grouping. This was done solely to illustrate the envelope of the present state-of-the-art.

It is clear from the results presented in Figure 6 that WEAVE™ represented a substantial advance in part building accuracy relative to triangular hatch, and that STAR-WEAVE™ represents an additional advance beyond WEAVE™.

Furthermore, it is important in interpreting the data of **Figure 6** to recognize that if the error distribution function were truly Gaussian, then approximately 68% of all the measurements would lie within a tolerance band between plus and minus 1 RMS value relative to the CAD dimenion, about 90% within 1.6 RMS and about 95% within 2 RMS.

Finally, it is not only important to characterize the accuracy of a single User-Part, but it also important to characterize the repeatability as well. In other words, if one gets an accurate part on Monday, and keeps everything as constant as possible, what are the chances that one will still get another accurate part on Tuesday? To answer this question, a series of 15 User-Parts were all built with the same SLA, the same resin, the same build technique and then cleaned, post-cured and measured as close to identically as possible. **Figure 7** shows the error distribution function for all 15 x 170 = 2550 measurements. **Figure 8** shows the cummulative error function for the same 2550 points. Note that **Figure 7** is very similar to **Figure 3** and that **Figure 8** is also very similar to **Figure 4**.

Analysis of the data shows that system repeatability for the 15 User Parts was within 1 mil RMS when using STAR-WEAVE™. This is excellent, and shows that once proper build methods and post processing techniques are used, the StereoLithography equipment is very repeatable.

USER PART IMPROVEMENTS

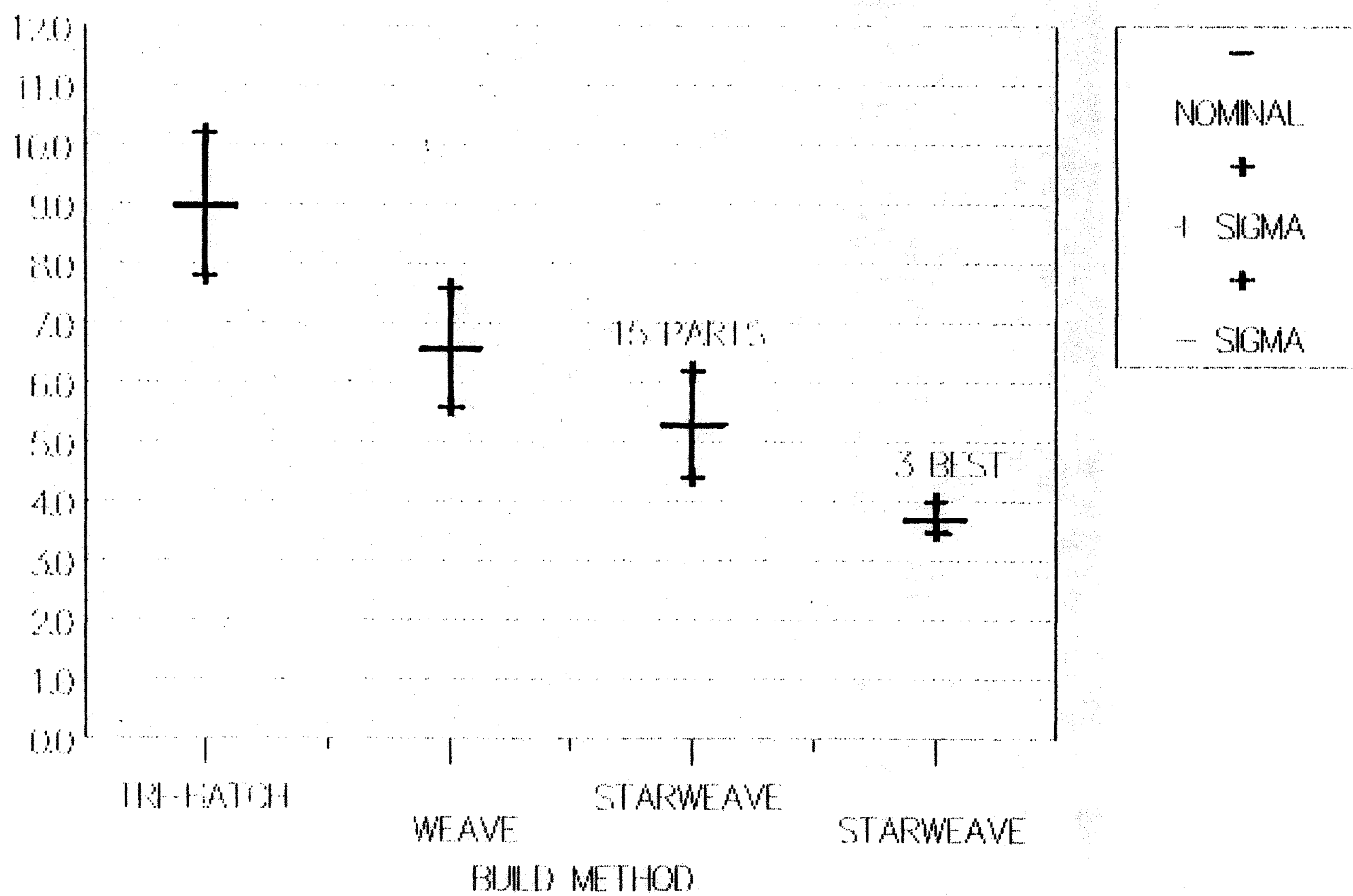
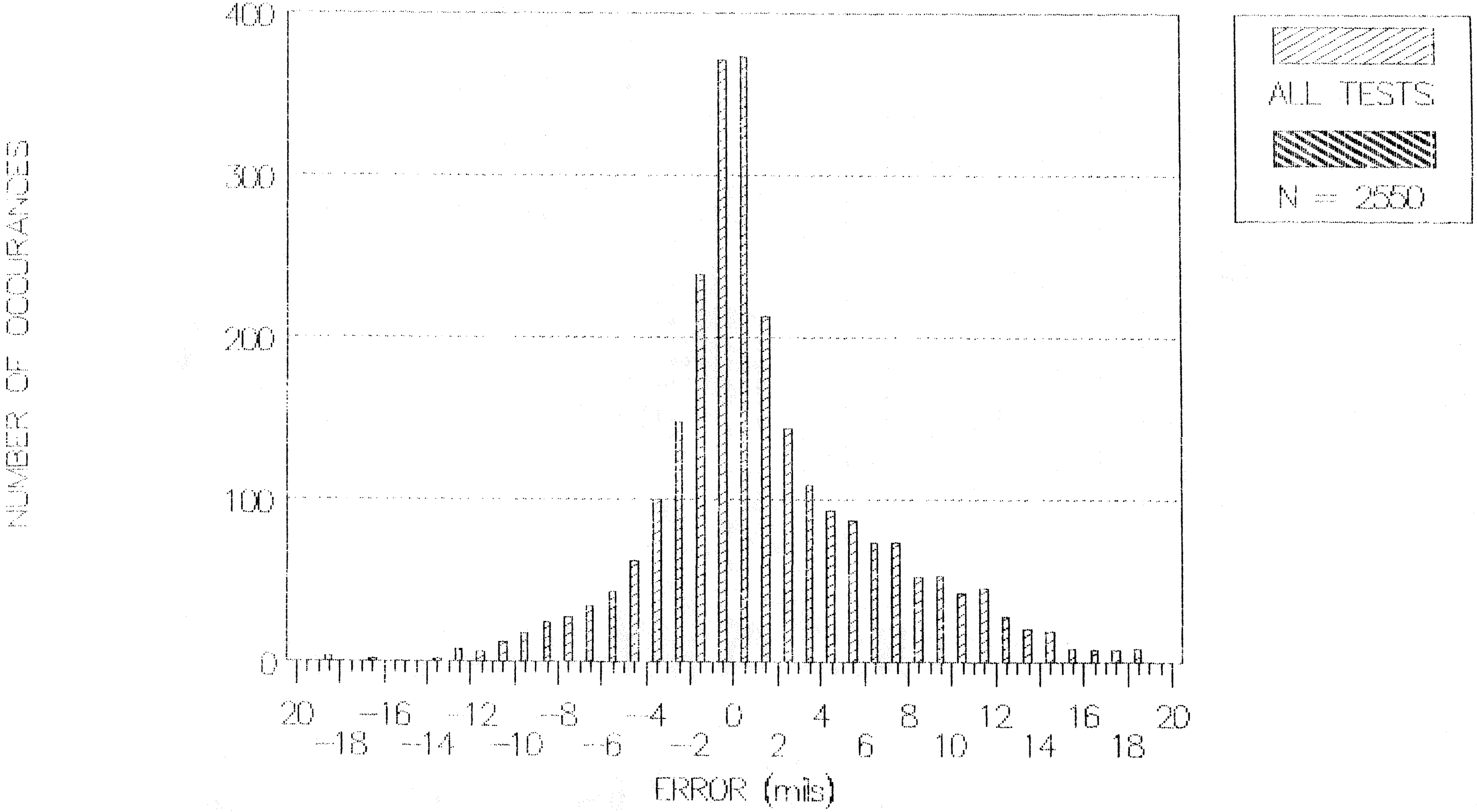


FIGURE 6

USERPART REPEATABILITY



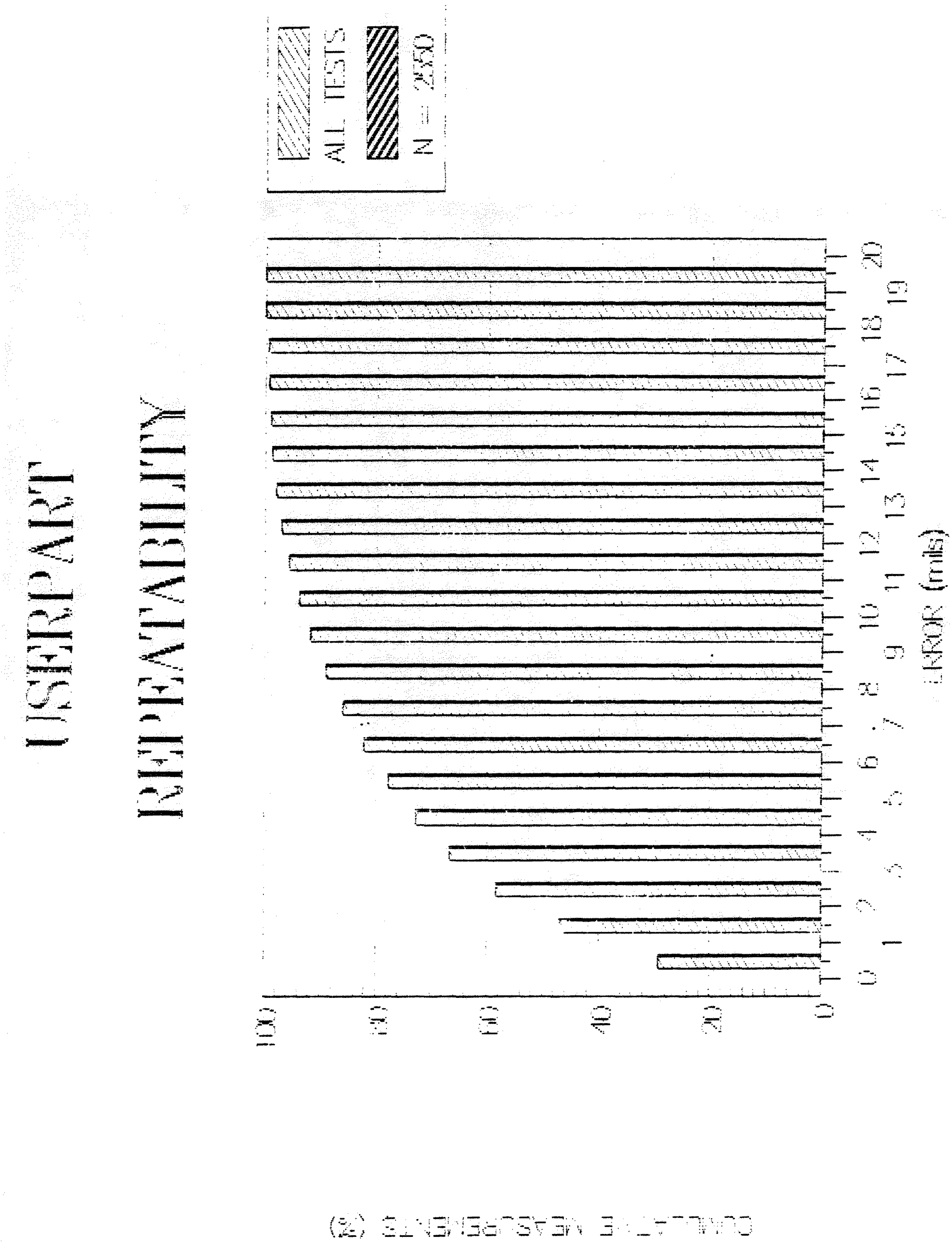

USER PART
REPEATABILITY
ALL TESTS
N = 2550
ERROR (mils)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
0 20 40 60 80 100

FIGURE 8

CONCLUSIONS

The following conclusions are appropriate based upon the data presented:

1. StereoLithography accuracy is best described by the error distribution function.

2. WEAVE™ is definitely more accurate, for all the resins tested, than 60°/120°/x triangular hatch.

3. STAR-WEAVE™ is definitely more accurate than WEAVE™ for all the resins tested.

4. For a part such as the User Part, StereoLithography can now reliably maintain 70% of all dimensions within ± 5 mils, using STAR-WEAVE™.

5. The 99% confidence limit errors scale, to good approximation, as the square root of the length of a given dimension.

6. System repeatability, based on a study of 15 User Parts, is typically within 1 mil RMS.