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PRELIMINARY WORK TOWARD THE DEVELOPMENT OF A DIMENSIONAL TOLERANCE STANDARD FOR RAPID PROTOTYPING

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INTRODUCTION

Rapid prototyping is a new technology for building parts quickly from CAD models. It works by slicing a CAD model into layers, then by building a model of the part one layer at a time. Since most parts can be sliced, most parts can be modeled using rapid prototyping. The layers themselves are created in a number of different ways - by using a laser to cure a layer of an epoxy or a resin, by depositing a layer of plastic or wax upon a surface, by using a laser to sinter a layer of powder, or by using a laser to cut a layer of paper. Rapid prototyping (RP) is new, and a standard part for use in comparing dimensional tolerances has not yet been chosen and accepted by ASTM (the American Society for Testing Materials). Such a part is needed when RP is used to build parts for investment casting or for direct use. The objective of this project was to start the development of a standard part by using statistical techniques to choose the features of the part which show curl - the vertical deviation of a part from its intended horizontal plane.

PROBLEM STATEMENT

Rapid prototyping has many uses. These are given in Table 1.

General use	NASA Application	Industrial Application
Visualization of a concept	Reusable Launch Vehicle (RLV)	Backup light cover (Used by BMW)
Checking fit of different parts	Space Station furnace	Texas Instruments
Models for direct use	Space Lab mockup parts	Injection molds
Molds for sand casting	None yet	Bearing housing (Reliance Electric)
Parts for investment casting	LOX resistant turbo pumps	Hip joint replacements (Clemson U.)
Functional prototypes	Wind tunnel test model	Gearbox housing (VW)

Table 1. Applications of rapid prototyping

Of these applications, only the first does not require some part accuracy. Accuracy means conformity to some standard of surface finish, linear dimension, twist, curl (hereby defined as the vertical deviation of a part from its intended horizontal plane), and the preservation of angles. Most physical standards are defined with reference to some accepted part geometry and some measurement process, but for rapid prototyping, neither a part nor a measurement process has been accepted by the American Society for Testing Materials (ASTM).

For a part to be useful as a standard, it should have at least four characteristics: (1) The geometry should be simple, so as to avoid unknown interactions between different types of dimensional deviations (2) It should be easy to measure the part for a particular type of dimensional deviation, preferably with only two or three measurements needed per deviation type. (3) It should be made of components each designed to indicate the magnitude of the deviation of one dimensional characteristic. In particular, the ultimate part should have components to measure linear dimension accuracy (when compared with the CAD drawing), surface finish, twist, curl, and the minimum angles it is possible to build in the vertical and horizontal directions.

In addition to the characteristics described above, the author and his NASA colleague felt strongly that a part used as a standard for rapid prototyping should perform the following functions:

(1) It should serve as a measure of accuracy for each of the dimensional parameters chosen.

(2) It should enable vendors to achieve part accuracy by being inexpensive to manufacture and easy to measure, hence easy to use in the optimal selection of RP process parameters and materials.

(3) It should enable a NASA branch or a company contemplating the purchase of a machine to evaluate the accuracy of different RP processes or materials.

(4) If a complex part is to be manufactured for NASA or for a company by an organization selling RP services, manufacturing this standard part should enable NASA contractors to demonstrate process accuracy without the manufacture of the complex part.

Developing a standard part for rapid prototyping would include the design of components to measure each of the dimensional distortion types given above. In order to demonstrate a methodology for the complete part, the author and his NASA colleague concentrated on the component that would best measure curl.

DEVELOPING THE PART AND DETERMINING ITS SIGNIFICANT ATTRIBUTES

The objective of this research was to determine design elements that would show curl so that these elements could be included in a standard part for rapid prototyping. The systematic design process used to select these design elements was to choose a part with many such elements, then to vary them and determine which elements were statistically significant. The part is shown in Figure 1 below.

The components of this part were chosen using the following logic:

<u>45 degree leg</u>: This feature tests whether curl is additive - i.e. whether the curl at the end of the 45 degree leg is the sum of the curl in the X and Y legs. This leg was present in all parts measured.

<u>X and Y ramps</u>: These test whether anisotropy in component mass makes a significant difference in the curl, in either the X or Y direction. Some parts measured in this project had the X ramp, some had the Y ramp, some had both, and some had neither.

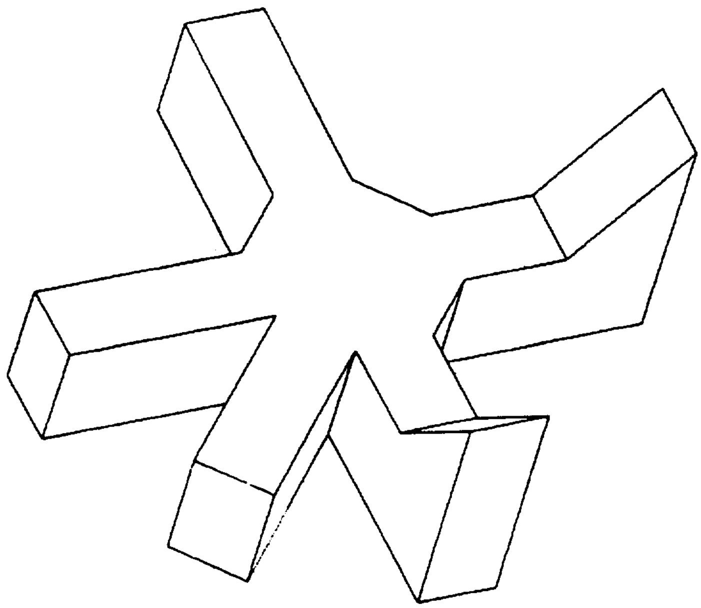

Figure 1. Geometry of test part

Radial offset: This was the distance from the center of the part to the center of the build platform of the RP device. Since some of the RP processes use lasers, and these impinge upon the build material at different angles at different parts in the build platform, it seemed reasonable that the location on the build platform might make a difference. Varying the radial offset from 0 to the corner of the platform tested whether offset from center of build platform was a significant factor.

Width: The width of a leg was varied to test whether spar width is a significant factor. The parameter varied was the horizontal aspect ratio, defined as the spar width/spar length. This parameter took on the values 0.10, 0.24, and 0.38 for test parts. When this parameter was varied, all the legs took on the same value. This procedure was also used for the thickness.

points for each part, with the mean of the five non-extreme measurements (of the seven) being used as the data point for the experimental analysis.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

One question was that of correlation among various measures of curl. The measures used were horizontal deviations at (1) the end of the X leg adjacent to the 45 degree leg, (2) the end of the Y leg adjacent to the 45 degree leg, (3) the end of the X leg opposite the 45 degree leg, (4) the end of the Y leg opposite the 45 degree leg, (5) the end of the 45 degree leg, (6) the point on angled leg where this leg is intersected by a line through the end of the adjacent X leg and parallel to Y leg, and, (7) the maximum of all curl values. This correlation matrix is shown in Table 2. This chart shows

	X leg adj	X leg opp	Y leg adj	Y leg opp	X part way	Leg end	Max curl
X leg adj	1						
X leg opp	.01366	1					
Y leg adj	0.6991	0.6132	1				
Y leg opp	0.7982	0.3550	0.6171	1			
X part way	0.9029	0.1084	0.6818	0.7256	1		
Leg end	0.9000	0.1036	0.7756	0.6558	0.8639	1	
Max curl	0.9068	0.3645	0.8023	0.8919	0.8452	0.8515	1

Table 2. Correlations among various measures of curl

	T/L	W/L	X Ramp	Y Ramp	Offset	Intercept
X leg $R^2 = .665$	.131 **	.032	-.0047	-.00492	.00378 *	.00265
X opp $R^2 = .534$	.080 **	.052 *	.00491	.00307	-.00329 *	.009183
Y leg $R^2 = .700$	.087 **	.062 *	-.00349	-.00797	.000015	.00717
Y opp $R^2 = .736$	.148 **	-.00234	-.00656	.00270	.00054	.0124
X part $R^2 = .431$	.0489 **	.0156	-.00461	-.00167	.001305	.002373
Leg end $R^2 = .665$	.0813 **	.0301	-.00485	-.0104	.00181	.0185
Max curl $R^2 = .748$	.135 **	.0139	-.0054	-.0052	.00188	.0190 *

Table 3. Regression coefficients from model. (* - Significant at $\alpha \leq .05$; ** = $\alpha \leq .01$)

that the X leg adjacent to the angled leg and the Y leg opposite to the leg are the most highly correlated with the maximum curl. A further analysis gives a correlation of 0.917 between the sum of curl in the X and Y legs and the curl in the leg between them.

A regression analysis was performed on the data, with results that are shown in Table 3. From these results, it is clear that the only factors that are statistically significant in determining the curl are the thickness - very significant - and the width - not so significant. From these results, the following conclusions can be drawn:

- Curl is most closely associated with thickness.
- Curl is associated, though less closely, with width.
- The presence or absence of X and Y ramps does not make a significant difference in the curl.
- Legs at 90 degrees from each other give curl measurements whose sum is significantly correlated to the curl of the leg half way between them, leading to the conclusion that curl is in some sense additive.

In addition to these conclusions from statistics, the build process leads any user to suspect anisotropic behavior parallel to the perpendicular sides of the build envelope. Therefore, the conclusions of this research are that the component of the final part used for a dimensional tolerance standard should include two legs at right angles, with each leg having at least the width and thickness used in this experiment, with the legs parallel to two perpendicular sides of the build platform.

Further research: To complete this study, more parts need to be made on machines other than the FDM - in particular, on machines using stereolithography, since that is the most commonly used process. The experimental design process shown here is useful and can profitably be used to design the other component of the standard part for rapid prototyping.

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