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IMPROVING THE DIMENSIONAL ACCURACY OF PARTS MADE BY RAPID PROTOTYPING(3D-PRINTING)

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Abstract - *Rapid prototyping is the process by which a three-dimensional CAD (Computer-Aided Design) file is made into a physical part which can be tested with respect to form, fit, and function. The goal of this researchis to improve planar dimensional accuracy for the 3D SystemsSpectrum Z-510 3D rapid prototyping machine. This objective has been achieved by first calculating a new bleed compensation factor (BCF) and then by utilizingthe standard industryEZ-Bleed Compensation Gauge™ provided by 3D Systems.In order to further improve and check the accuracy, a Calibration Cross was printed and measured to find the difference between the experimental and ideal cross lengths. Aseries of new BCFs were then created and tested. The significant results of this research experiment were decreases in the standard error by 69, 51 and 61% in the X, Y and Z dimensions, respectively, after four changes to the BCF.*

Keywords: 3D Printing, Bleed Compensation tor, Computer-Aided Design, Dimensional Accuracy, Rapid Prototyping

1. INTRODUCTION

Rapid prototyping is the process of making a three-dimensional solid object from a CAD model. 3D Printing (3DP) is one of many types of rapid prototypingmethods available on the market. It is an additive process where successive layers of material are laid down building the prototype up layer by layer [1]. The manufacturing industry is increasingly using rapid prototyping and manufacturing technology due decreased lead times, decreased cost and its capability of creating complex geometry such as small cavities and intricate curves [2].

1.1 Goal and Objectives

The goal of this paper is to describe and discuss improving the dimensional accuracy of parts made by a 3D Systems Spectrum Z-510 rapid prototyping machine. The specific objectives of this paper are to discuss (1) the introduction the rapid prototyping industry and the research conducted (2) the procedure followed (3) the results of the research (4) a discussion of the results (5) a conclusion of the research.

1.2 The Need

The usefulness of these prototypes relies critically on their accuracy to test the form fit and function of the prototype. Parts made by rapid prototyping are typically held a 0.127mm (0.005in) tolerance, greater than that of parts traditionally machined [3]. This tolerance varies depending upon manufacturer and model of rapid prototyping machine. Sometimes applications require the tight tolerance given by traditional machining and if rapid prototyping is to be used it need a similar tolerance. Sometimes the required tolerance is unachievable due to the imbedded error within the mechanical parts of a machine. Other times machines one can achieve the needed tolerance through a fine calibration; in this case, it was the fine calibration of the bleed compensation factor [4].

1.3 The Process

Prototypes such as these are produced by first importing a 3D CAD model and slicing it into thin cross-sectional areas which are in turn directed to the 3D printer. The printer creates the model one layer at a time by spreading a thin layer of ceramic powder and then inkjet printing a binder in the cross sectional shape of the part. The process is then repeated until the part is complete and ready to be removed [5]. The impregnation of the resin binder into the powder can result in parts that are larger or smaller than the ideal design dimensions. This can partially be explained by the accuracy of the equipment which has a resolution of 600 x 540 DPI, but is also due to environmental difference from the manufacturing to the user's location, such as changes moisture in the air. Adjusting the BCF can compensate for this by lowering the viscosity of the binder in order to infiltrate deeper into the powder bed. The determination of a bleed compensation factor specific for a machine and location will increase accuracy of rapid prototype samples. The goal of this researchis to find how accurate the 3D Systems Spectrum Z-510 3D Printer can make a part by manipulating the BCF. This goal will be achieved by using both the standard 3D Systems EZ-Bleed Compensation Gauge™ and a Calibration Cross.

1.4 EZ-Bleed Compensation Gauge

The bleed compensation gauge is a tool developed by Z-Corp to calibrate the BCF of individual users. It allows a rapid method of testing current bleed values and determining the degree to which correction values are needed [6].There are three bleed correction gauges – one for each axis (X, Y and Z). The gauges are initially connected in one solid part as seen in Fig 1. Once the gauges are broken apart in post processing they consist of a U-shaped body with an insertable plunger. These separate X, Y and Z gauges are then infused with an epoxy infiltrant for hardening. This is not necessary, but useful as the green strength of the parts is very low. There are markings embossed upon the surface of the plunger acting in conjunction with the reference plane to show by what value of addition or subtraction the BCF needs. This can be seen in Fig 2, on the right. There are a total of 15 grooves on the plunger, three indicating larger grooves showing a correction by a factor of 0.005 inches and 12 smaller grooves representing 0.001 in. When a plunger fits more

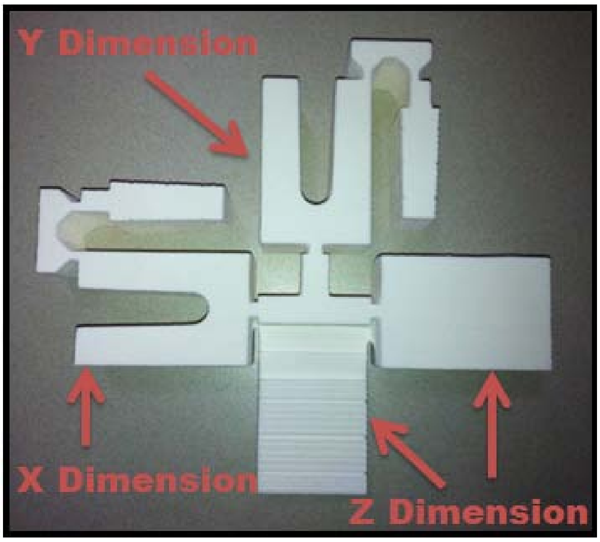

Fig. 1: EZ-Bleed Compensation Gauge™

than half way into the gauge, the new bleed value will be less than the current value. In the same manner, when plunger fits less than half way into the gauge, the new bleed value will be larger than the current value. The amount of correction is determined by counting the number of grooves the plunger fits into the gauge body above or below themid-point. When the plunger fits to half way the current bleed compensation is correct and no adjustment is needed for that axis [6].

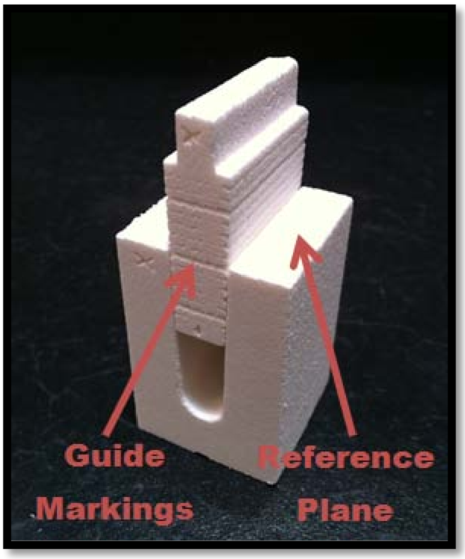

Fig 2: X Axis bleed compensation gauge

1.5 Calibration Cross

Since the EZ-Bleed Compensation Gauges™ use a built-in scale rather than requiring any measured instrument,it is difficult to quantitatively evaluate the improvement of changes to the BCF. Thus another means of measuring was needed to observe the changes to the BCF.A Calibration Cross, as seen in Fig. 3, was created and used as a method to analytically evaluate the change of the BCF and, consequentially, the effectiveness of the EZ-Bleed Compensation Gauge™. Fourteen separate measurements have been taken on every Calibration Cross.

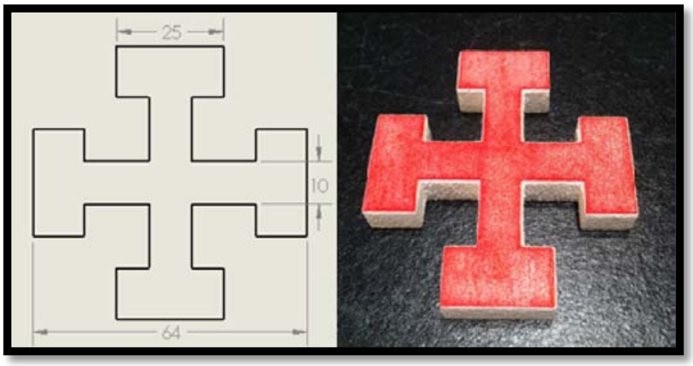

Fig 3: Calibration cross with measurements.

Fivemeasurementswere taken along the X and the Y axis and four along the Z axis. On the X axis one measurement has been taken of the top and bottom 25 mm length and one of the 10 mm necking point both above and below the cross section as seen on the left side of Fig. 3. These same measurements have been taken along the Y axis, but inverted 90°. The 10 mm depth of the cross has been taken once on each extrude to measure along the Z axis. These measurements have been taken for each new BCF including a part made without a BCF and a part made using the standard BCF. Using this information, the changes to the BCF could be numerically observed.

2. PROCEDURE

The equipment used for the research is follows:

i) Z-Corporation Spectrum Z™ 510 3D Printer

ii) Digital Calipers.

The experimental procedure is as follows:

- Create Control Calibration Cross
  - Load Calibration Cross into Z-Print software and verify the correct X, Y and Z orientation.
  - Justify center and print cross.
  - Gross de-powder, dry, fine de-powder and infuse cross epoxy infiltrant.
  - Measure and record length information.
- Repeat previous three steps with EZ-Bleed Compensation Gauge™.
  - Assemble part by inserting the plunger into the gauge for each dimension.
  - Note the correction value based on the difference between the groove locations aligned with the reference plane.
  - Create a new powder type with corrections.
- Continue using EZ-Bleed gauges until it is no longer effective.
- Print a new Calibration Cross with new BCF.
- Refine new powder type by estimating the needed addition or subtraction to the powder from previous Calibration Cross.
- Repeat previous two steps for increased accuracy.

Table 1. Standard Error for bleed compensation factor. Runs 1-4, none, and standard.

Axis	No BCF	Std BCF	1st BCF	2nd BCF	3rd BCF	4th BCF
X	0.277	0.117	0.079	0.074	0.037	0.043
Y	0.286	0.177	0.135	0.131	0.097	0.067
Z	0.335	0.085	0.029	0.042	0.033	0.056

3. RESULTS

The results of this project show the increase in accuracy of a 3D Systems Spectrum Z™ 510 3D Printer by changing the bleed compensation factor as seen in Table 1. The BCF was changed based upon indications from the EZ-Bleed Compensation Gauges™ and measurements taken from a Calibration Cross. The difference between the theoretical Calibration Cross and the printed model were taken and the standard error was found using the Eq. (1) where e_1, e_2, e_3 are the error factors for the various lengths along the Calibration Cross.

$$\text{Standard Error } E_t = \frac{\sqrt{e_1^2+e_2^2+e_3^2}}{3} \qquad (1)$$

Figure 4 shows the numerical decreasing trend, from the Calibration Cross, in the standard error starting with no BCF and ending upon the application of the fourth BCF. The difference between the first test, where no BCF was applied, and the second test wherethe factory standard BCF was applied shows three relatively large decreases illustrating the difference the application of a BCF has on the accuracy of a printed model in all three axes. The difference between the factory standard and the first BCF shows the decrease in error that was found using the EZ-Bleed Compensation Gauge™. The leveling out of standard error between the first and second BCF was due to another

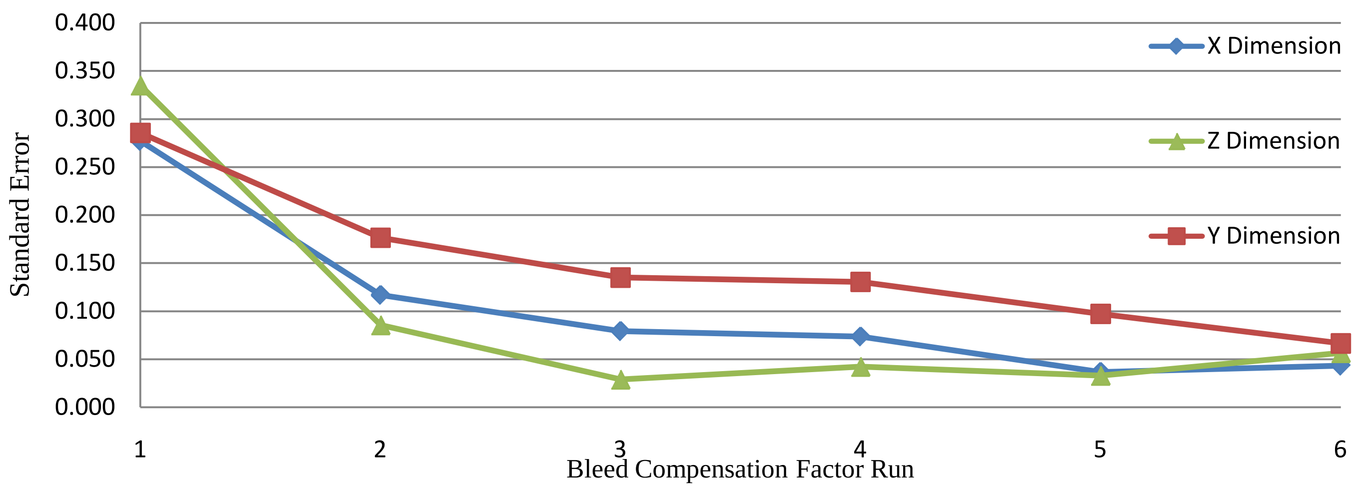

Fig 4: The standard error for each bleed compensation factors for the X, Y and Z axis.

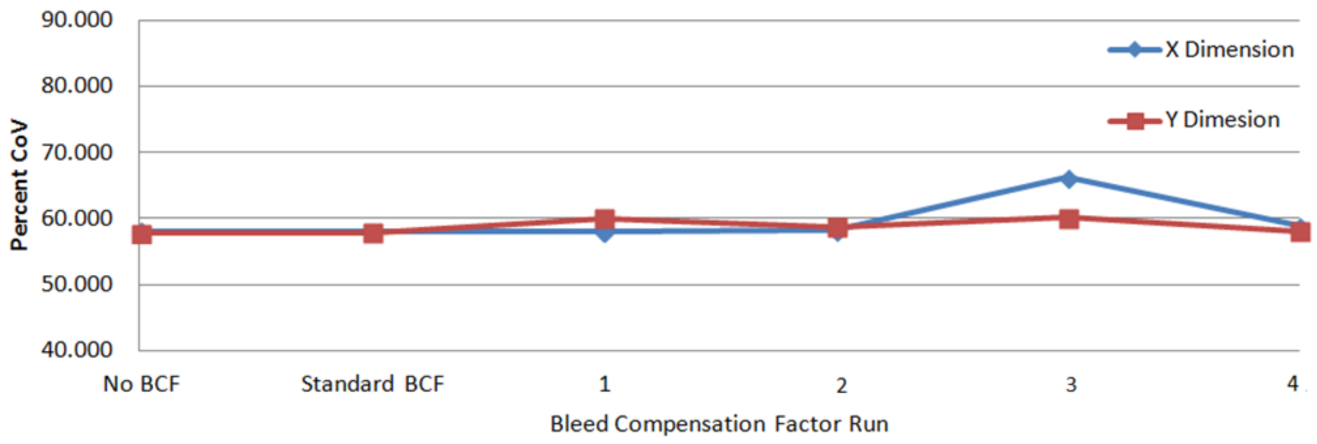

Fig 5: The **percent** coefficent of variance for each bleed compensation factors for the X, Y and Z axis.

iteration of the EZ-Bleed Compensation Gauge, but it reached the tests limit. The decrease from the second BCF to the third was calculated based upon the amount of deviation of the printed model of the Calibration Cross and its ideal CAD dimensions. The mixed results from run the third to the fourth BCF utilized the same method, but with mixed results.

In a similar fashion the decreasing trend can be seen through the percent error as seen below in Table 2. The error was not standardized, meaning that the error of different measurements on the Calibration Cross along the same axis was kept distinct. The nominal value of where the percent error was taken can be seen on the left of the table. This table demonstrates the larger the measurement, the less overall error is in the measurement and that there is some intrinsic error due to the accuracy machined parts that will not be corrected by changes in the BCF.

4. DISCUSSION

The 2nd and 4th BCF show the limits on both methods of creating a new BCF. The EZ-Bleed Compensation Gauges™ reached a limit to where it is difficult to read if a change is needed, or is due to limitations in the measuring system. The system requires two parts to be fitted into one another and for that measurement to be read by eye.

Table 2. Percent error of bleed compensation factors

Axis	Nom. (mm)	No BCF	Std BCF	1st BCF	2nd BCF	3rd BCF	4th BCF
X	25	2.19	0.82	0.58	0.59	0.34	0.37
	10	4.42	1.78	1.21	1.11	0.70	0.67
	65	0.68	0.34	0.22	0.19	0.02	0.09
Y	25	2.04	1.17	0.49	0.58	0.30	0.51
	10	4.78	3.22	2.53	2.30	1.63	1.18
	65	0.76	0.47	0.45	0.43	0.36	0.15
Z	10	3.35	0.86	0.29	0.43	0.33	0.57

Sometimes the plunger would get stuck higher than itought to have gotten struck and this is attributed to surface adhesion of the ceramic powder. The EZ-Bleed Gauges™ calibrated the BCF achieved the standard error of .127mm. With a small adjustment from the Calibration Cross the model measurements in each axis were under the .127mm threshold of accuracy. The accuracy of the part is linked to the expansion dimensions along the outside layers of the model. When measuring the overall length of the Calibration Cross along one axis compared to the length of one attachment there was little difference. While the error after the 1st BCF along the X axis of the 10mm length was 0.145, the error of the 65mm length was 0.144. These similar values show that the error is irrespective of the overall size of the part. This means that the larger the part is, the more accurate the part. This can be seen clearly in Table 2 where the error is not standardized. The percent error of the X dimension on the same run was 0.59 compared to 0.19 with respect to the 25 and 65mm measurements. Another verification of this is the horizontal and linear nature of the coefficient of variance (CoV) for each BCF as seen in Fig 5. The CoV found using Eq. (2) where $\bar{X}$ Mean is the average of the X, Y and Z axes.

$$\% \text{ COV} = \text{Standard Error} * \frac{100}{\bar{\text{X}} \text{ Mean X,Y Z}} \tag{2}$$

The lack of variation in the CoV shows how there was a very similar variance despite what the nominal dimensions of each measurement. The 65mm and 10mm measurements have similar error regardless of the large difference in their size. The CoV was not taken for the Z dimension because the standard error will be the same as the $\bar{X}$ mean. It should be noted that all of these measurements and calibrations were done to a single machine somewhere along its wear cycle. As parts in the machine degrade and need to be replaced, such as the print heads, the BCF will need to be recalibrated the new optimum BCF may be different.

5. CONCLUSIONS

The bleed compensation factor controls the accuracy to which the model can be printed. Without using a BCF, models printed with percent error up to 4.7% in the different areas of the model. Utilizing Z-Corp's standard method for calibrating, the EZ-Bleed Compensation Gauge™, models were reduced to the factory specifications of 0.127mm. A small amount of refinement using the Calibration Cross increased the accuracy to below this threshold.The combination of these methods decreases the standard error by 69, 51 and 61% in the X, Y and Z dimensions, respectively, after four changes to the BCF.

- The application and changing the BCF can drastically affect the accuracy of models created on a Z-510 3D Printer.
- Thinner samples will be more inaccurate than larger samples due to built-in inconsistencies with the hardware.
- It is speculated that using the new BCF will need to be recalibrated if parts are replaced and may need attention further along the machines life cycle.
- It is assumed that the average optimum BCF for a new machine is the factory standard, but a Bleed Compensation Gauge™ ought to periodically be used to recalibrate the machine.

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