ACCURACY IMPROVEMENT IN RAPID PROTOTYPING MACHINE (FDM-1650)

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ABSTRACT

Over the past few years, improvements in equipment, materials, and processes have enabled significant improvements in the accuracy of Fused Deposition Modeling (FDM) technology. This project will investigate the present in-plane accuracy of a particular FDM machine using the benchmark "User Part" developed by the North American StereoLithography User Group (NASUG) and show the effect of optimal Shrinkage Compensation Factors (SCF) on the accuracy of the prototyped parts.

The benchmark parts were built on the FDM-1650 prototyping machine and a total of 46 measurements were taken in the X and Y planes using a Brown & Sharpe Coordinate Measuring Machine (CMM). The data was then analyzed for accuracy using standard formulas and statistics, such as mean error, standard deviation, residual error, rms error, etc. The optimal SCF for the FDM-1650 machine was found to be 1.007 or 0.7%.

INTRODUCTION

Rapid Prototyping (RP) is the f abrication of a physical, three-dimensional part of arbitrary shape, directly from a numerical description (typically a CAD model) by a quick, highly automated, and flexible process. RP technology has made many contributions to the manufacturing industry mainly by reducing the time to produce prototype parts and improving the ability to visualize part geometry. The physical prototype allows for earlier detection and reduction of design errors and the capability to compute mass properties of components and assemblies [1,7]. Also, it is very advantageous to present a design in client presentations, consumer evaluations, bid proposals, and regulation certification. This concept was first introduced in 1988, and since then the growth of Rapid Prototyping has been exponential every year.

RP also has some challenges that must be improved upon and one of the main challenges is part accuracy. This is the main concern of countries like Japan, which are not willing to incorporate RP to there manufacturing process [1-3]. The parts produced tend to warp and/or shrink from its given dimensions forcing the user to run several trials of a part to reach its ideal dimensions or settle for a slightly inaccurate part. Another concern is the build time; it can often take several days to prototype certain parts depending on the size.

When Rapid Prototyping was first introduced, the materials used to produce the parts had low yield strength. Through the advancement in material science, the photopolymers and thermoplastics used now have much higher yield strength. The strength of RP materials is sufficient for some applications, but does not always satisfy the strength requirements for wind tunnel testing. The use of stronger materials in the future such as metal-based powders will enable RP to produce parts to satisfy these requirements.

The purpose of this engineering research project is to make a contribution towards the accuracy improvement of Rapid Prototyping machines. This can be accomplished by finding the most optimal shrinkage compensation factor (SCF). The Shrinkage Compensation Factor determines the amount an object should be enlarged so that it can approach the desired dimensions of the user during the shrinking process.

THEORY AND ANALYSIS

In this engineering project, the rapid prototyping technology used was a Fused Deposition Modeling machine (FDM –1650), built by Stratasys. The machine uses a 3D CAD drawing that is converted to a Stereolithography file (.STL) and then it is sliced into a series of closely spaced horizontal planes [2,7,8]. The file is then sent to the machine as a build file and production of the part begins. The machine has a build area of 10x10x10 in. and produces hard solid prototypes that may be used in many applications.

The FDM technology uses a spool of ABS thermoplastic filament with a diameter of .070 inches to build a part. The filament is heated to above its melting point and then extruded through a nozzle on a delivery head and onto a build platform. When one layer is finished the platform is lowered and a new layer is formed on top of it.

The overall inaccuracy of the parts being built by RP technology has been one of the major challenges that need to be overcome. Errors due to shrinkage and warpage dominate the inaccuracy of the part. The thermoplastic ABS material used in FDM machines experiences a volume change when it is heated and then extruded onto a build platform. “Each prototype made is slightly smaller than its designed dimensions”[3,5,8]. SCF is one of the variables that can be controlled by the operator to influence the overall accuracy of the part. When prototyping, the shrinkage is compensated by multiplying the dimensions by a SCF through the build software. Through research, the optimal SCF can be found and the prototype can be built within the specified build accuracy of the machine.

To test the build accuracy of a prototyping machine, a user part was developed by the North American StereoLithography User Group (NASUG). It is an in-plane benchmark part, which covers the extent of the build platform and allows for the measurement of the part’s X and Y dimensions. This particular part (Fig. 1) was chosen because of: (1) its large amount of independent surfaces, (2) a variety of balanced measurements ranging from .125 to 9.5 inches, and (3) an almost equal amount of inside and outside measurements. These three characteristics made the part ideal for performing measurements because it reduced biases on certain measurements, making all of the factors in producing the part just as important [4-5].

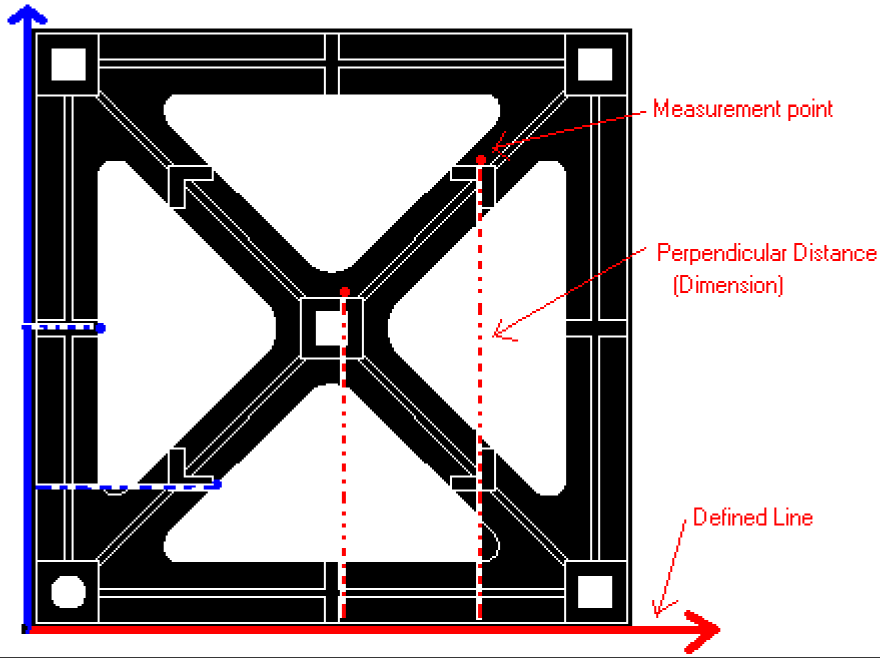

Figure:1NASUG "User Part" and the CMM measurement technique

To calculate the SCF, 46 measurements were taken in the X and Y plane [9]. These measurements were input into an Excel program and from these points, 27 outside and 21 inside dimensions were calculated. After obtaining this data, statistical equations were used to determine the overall accuracy of the part.

First the dimensional data is converted to the differences relative to the CAD dimensions. The error in each of the dimensions is calculated by,

$$\text{Actual error} = a - c \qquad (1)$$

where *a* is the measured dimension and *c* is the CAD Dimension.

Many statistical data analysis computations were derived from the 21 inside dimensions and 27 outside dimensions. The slope of the best-fit regression line of actual error vs. ideal dimension was calculated to get an idea of the accuracy of the part and to determine the new SCF. The slope is determined by,

$$\text{Slope} = \frac{(42+54)*(A+B) - (C-D)*(E-F)}{\text{Constant}} \qquad (2)$$

where A = Σ(Inside Ideal Dimension)*(Error), B = Σ(Outside Ideal Dimension)*(Error), C = Σ(Outside Ideal Dimension), D = Σ(Inside Ideal Dimension), E =Σ(Error Outside Dimensions), and F = Σ(Error Inside Dimensions). The constant is determined by,

$$\text{Constant} = (42+54)*(\Sigma(G^2)+\Sigma(H^2)) - (\Sigma(H) - \Sigma(K))*(\Sigma(M) - \Sigma(K)) \qquad (3)$$

where G = Inside Measured Dimension, H = Outside Measured Dimension, K =Inside Ideal Dimension, and M = Outside Ideal Dimension.

Next a y-intercept value must be determined to complete the equation for the least-square regression line for which the slope was found above. This equation is used to find the expected error in each of the dimensions and when that value is compared to the actual error, we can determine the residual error in the part. The equation for the intercept is given by,

$$\text{Intercept} = \frac{(\Sigma(A)^2 + \Sigma(C)^2)*(\Sigma(E) - \Sigma(G)) - (\Sigma(I) + \Sigma(L))*(\Sigma(C) - \Sigma(A))}{\text{Constant}} \qquad (4)$$

where I = (Outside Ideal Dimension)*(Error), L = (Inside Ideal Dimension)*(Error), C = Outside Ideal Dimension, A = Inside Ideal Dimension, E = Outside Error, and G = Inside Error.

Now with the slope and intercept defined, the predicted value for the error, given an ideal dimension, can be found by the equation,

$$y\ (predicted) = mx + c \tag{5}$$

where m = slope, x = ideal dimension, and c = intercept.

This process of finding the slope, constant, and intercept is performed for both the x and y dimensions and the two results are averaged at the end.

The predicted value of error is used to determine the residual square, which squares the difference between the measured dimensions and the predicted value:

$$Residual\ Square = (Difference - Predicted)^2 \tag{6}$$

With the result from equation 6, the residual error in the part can be calculated. The residual error defines the overall difference of the measured values from the predicted error values [6]. The equation for residual error is defined by,

$$Residual\ Error = \sqrt{\frac{(M + N + O + P)}{121}}$$

where M = Residual Square (Inside Y Dimensions), N = Residual Square (Outside Y Dimensions), O = Residual Square (Inside X Dimensions), and P = Residual Square (Outside X Dimensions).

Finally the SCF can be derived. The SCF is an indication of the numerical percentage of how small or large the user part is compared to the actual CAD dimensions. The SCF equation incorporates the initial shrinkage compensation factor, which was used in the beginning of the build process. The equation to determine the SCF is,

$$SCF\ (X) = 1 - (1 - (Slope))*(1 + SCF(X)\ OLD) \tag{8}$$

$$SCF\ (Y) = 1 - (1 - (Slope))*(1 + SCF(Y)\ OLD) \tag{9}$$

RESULTS & DATA ANALYSIS

After several trials of making the "User Part", FDM-1.007 [1] exhibits the lowest Mean, RMS, and Residual Error indicating that so far, a SCF of 1.007 gives the lowest error and the most accuracy for the user part.

A scatter graph of the difference between the measured and desired dimension (error) plotted against the desired (CAD) dimension was used in the calculation of the SCF and the Total Shrinkage (TS) for the "User Part". The Total Shrinkage is the slope of a "least squares" regression line of the Error vs. Ideal (CAD) dimension graph. It gives an indication of how far off the SCF that was used to create the part is to the SCF that will produce the most accurate part. A negative TS means the part was made too small and a positive TS means the part was made too big. The lowest TS value is desired for the most accurate part. FDM-1.008-P2[2] had the lowest Total Shrinkage value, but it was not the most accurate part as indicated by further statistical calculations performed on it. As Figure 2 summarizes, the greatest total shrinkage of

[1] FDM refers to the build method, 1.007 is the SCF, and I (if used) refers to the first measurement for the part

[2] This is the second part made with a SCF of 1.008, due to questionable results given by the first part

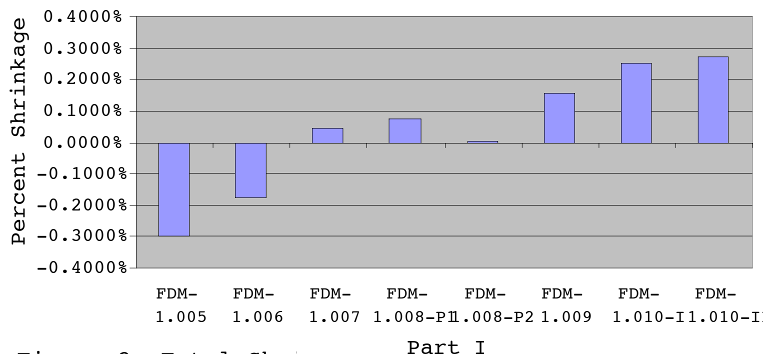

Figure 2: Total Shr

-0.2966% and 0.2744% was achieved from parts FDM-1.005 and FDM-1.010-II, which indicates that the optimum SCF is not close to those SCF. Part FDM-1.007 showed the second least shrinkage of 0.0453%, but further calculations proved this was the most accurate part.

The Shrinkage Compensation Factor (SCF) is related to Total Shrinkage because the value for Total Shrinkage is subtracted from the initial SCF, to get a new, more accurate SCF. As Figure 3 illustrates, calculations performed on the measurements revealed that a new SCF that should improve the accuracy for a part made on a FDM machine lies between 0.65% and 0.75%. Part FDM-1.007 was the only part that could be made in this range and it was this part that turned out to be the most accurate.

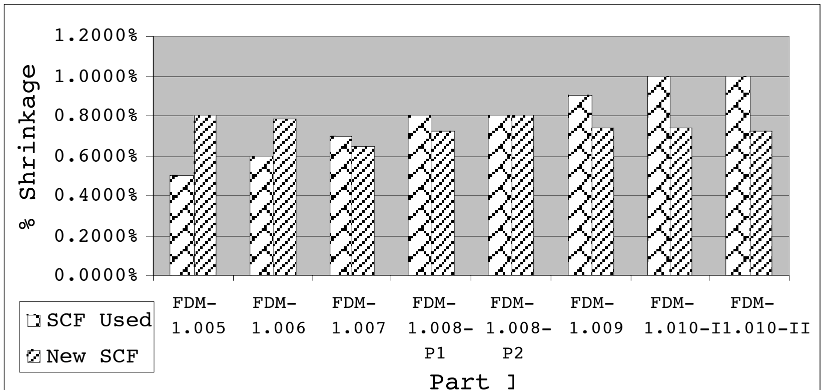

Figure 3: Used & New Shrinkage Compensation

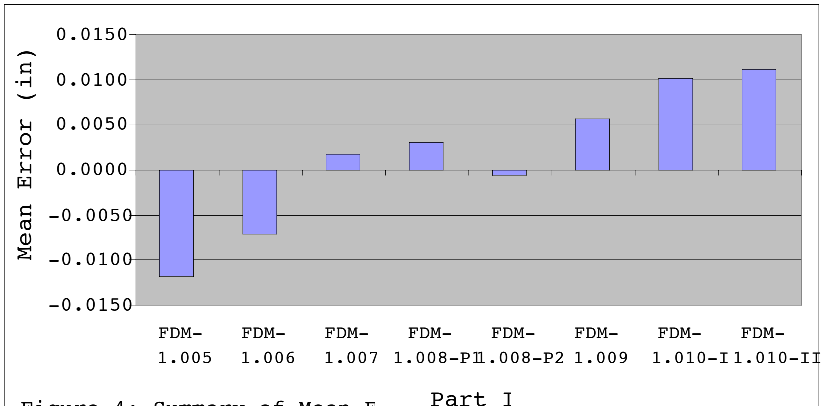

Figure 4: Summary of Mean E

The mean error is calculated to get an indication of the error in the part and to determine whether the dimensions were within the machine specified accuracy **[6]**. The graph for mean error shows a similar trend to the Total Shrinkage graph and thus gives similar information. A positive mean error indicates that most of the measured dimensions were greater than the CAD dimensions, and a negative mean error indicates that most of the measured dimensions were smaller than the CAD dimensions. The FDM parts with shrinkage factors set from 1.005 to 1.010 had mean errors ranging from –0.0119 inches to 0.0110 inches, giving an even spread about zero. As Figure 4 shows, FDM-1.007, FDM-1.008-P1, & FDM-1.008-P2, produced mean errors, which satisfied the machine specified accuracy of ±0.005 in. However, the mean error can be influenced by negative and positive error values, and needs to be used in conjunction with other statistical calculations to find the best part.

The standard deviation was also calculated to get an indication of the spread of errors around the mean and really understand the meaning for the value of mean error [6]. A low mean error and a low standard deviation will provide a good indication of the accuracy of a user part. The standard deviation data varied from 0.0096 inches to 0.0246 inches with the full results represented in Figure 5. Parts FDM-1.007, FDM-1.008-P1, and FDM-1.008-P2 all had mean errors very close to zero. However, when these values were matched with the standard deviation values, FDM-1.007 had the lowest spread of errors around the mean and this is another reason for the high accuracy of this part.

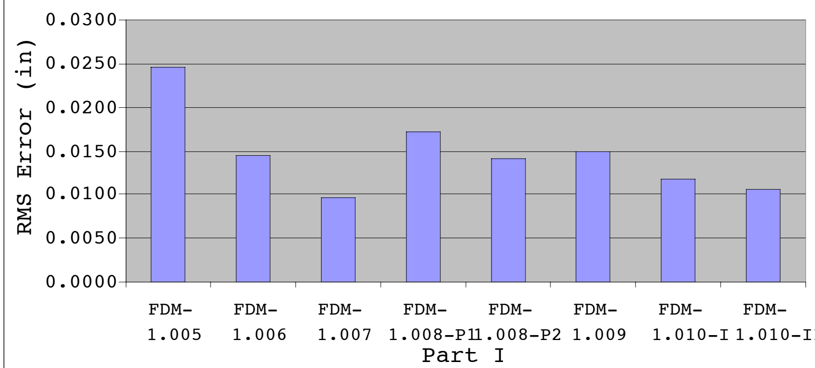

Figure 5: Summary of Standard Devi

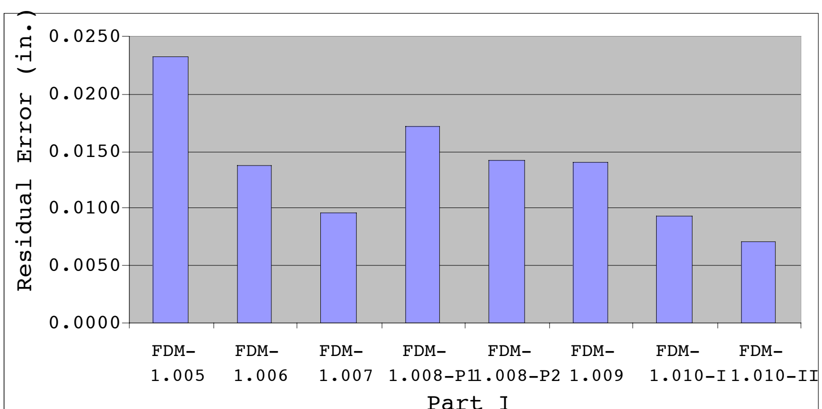

Figure 6: Summary of Residual

Calculating Residual Error for the user part allows the measurement of the errors in the part, which are not caused by shrinkage. These are random errors in the machine, material, and measurement that are much harder to measure and control. Overall, the Standard Deviation and Residual Error (Figure 6) for each user part had similar values, indicating that the error in the part due to shrinkage is very small and it is the random errors, which contribute greatly to the inaccuracy of the part. The lowest Residual Error of 0.0096in. for FDM-1.007 was the same as its Standard Deviation, indicating the error in the part due to shrinkage was extremely small and all the errors were random errors that are harder to control.

The most important of all the data calculated is the RMS Error (Figure 7) as it gives a better indication of the size of the error in each part. It is a better approximation than the mean error, which can be influenced by positive and negative error values [6]. The lowest RMS Error would indicate the most accurate part. It is FDM-1.007, which gives the lowest RMS Error value indicating its greatest accuracy and verifying the previous results, which indicated that it was the most accurate part. Part FDM-1.008-P2 had lower Total Shrinkage and Mean Error values than FDM-1.007, but its Standard Deviation, Root Mean Square Error and Residual error values verified its inaccuracy.

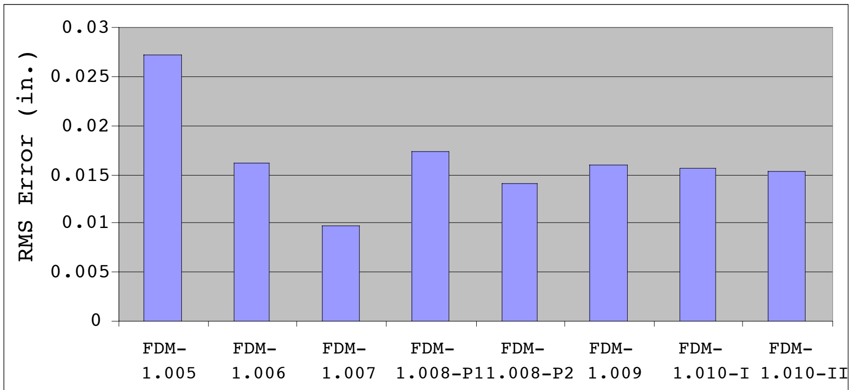

Figure 7: Summary of RMS Er Part I

Part ID	Slope	SCF Used	New SCF	Mean Error (in.)	SD (in.)	Residual Error (in.)	RMS Error (in.)
FDM-1.005	-0.2966%	0.5000%	0.7981%	-0.0119	0.0246	0.0232	0.0272
FDM-1.006	-0.1752%	0.6000%	0.7800%	-0.0071	0.0145	0.0137	0.0160
FDM-1.007	0.0453%	0.7000%	0.6500%	0.0017	0.0096	0.0096	0.0097
FDM-1.008-P1	0.0739%	0.8000%	0.7253%	0.0030	0.0172	0.0172	0.0174
FDM-1.008-P2	0.0006%	0.8000%	0.7993%	-0.0006	0.0142	0.0142	0.0141
FDM-1.009	0.1551%	0.9000%	0.7442%	0.0057	0.0150	0.0141	0.0159
FDM-1.010-I	0.2543%	1.0000%	0.7400%	0.0102	0.0118	0.0093	0.0156
FDM-1.010-II	0.2744%	1.0000%	0.7200%	0.0110	0.0107	0.0071	0.0153

Table 1. Summary of FDM-1650 Results

Conclusions and Recommendations

The objective for this research project was to find the optimal shrinkage compensation factor for the FDM-1650 prototyping machine and produce the most accurate part. From the data that was analyzed, the best SCF for the FDM-1650 was:

SCF = 1.007, or (0.7%)

There are a few recommendations arrived upon for future accuracy research on the FDM-1650. Firstly, varying temperature and build speed during the build process could affect the accuracy of the parts. These parameters might help minimize the amount of warpage that the part undergoes due to the amount of time it is exposed to heat. Also, building different percent sizes of the part can be used as a test to compare the effects of shrinkage on a small and a large part. Another recommendation is for more accurate SCF inputs, which contain 4 to 5 decimal places. This would allow for accuracy research of parts with SCF's between 1.0065 to 1.0075, the region where the results point to as having the best SCF. The machine should also allow for inputs in both the X and Y direction instead of the one shrinkage factor that can presently be input into the build software. The addition of these inputs and added accuracy in the decimal place should produce a more accurate part that is even closer to its desired dimensions. Finally, the support material that is currently in use with this machine should be changed because it is difficult to remove. A water-soluble support material would make it easier to remove and clean the part, saving valuable time.

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