Journal of
INDUSTRIAL TECHNOLOGY

Volume 26, Number 1 - January 2010 through March 2010

# Three-Dimensional Printing Build Variables That Impact Cylindricity

By Dr. Troy Ollison & Dr. Kevin Berisso

*Peer-Refereed Applied Papers*

**KEYWORD SEARCH**

CAD
CAM Manufacturing
Materials and Processess
Rapid Prototyping

The Official Electronic Publication of The Association of Technology, Management, and Applied Engineering • www.atmae.org

# Three-Dimensional Printing Build Variables That Impact Cylindricity

By Dr. Troy Ollison & Dr. Kevin Berisso

Dr. Troy Ollison is an Assistant Professor of Technology and Engineering Technology at the University of Central Missouri in Warrensburg, Missouri. Ollison has been teaching both graduate and undergraduate courses for eight years. He is also an active member of the Society of Manufacturing Engineers as well as the Association of Technology Management and Applied Engineering (ATMAE). His primary interest and research areas are in metrology, rapid prototyping and materials processing and testing.

Dr. Kevin Berisso is the Director of the AIDC Lab at Ohio University as well as an Assistant Professor in the Department of Industrial Technology. He received his BS in Industrial Technology from Ohio University and a MS in Industrial Technology from Indiana State University before taking a position with Applied Tactical Systems, a warehouse management software company. While at ATS, Dr. Berisso worked as a project engineer with companies such as Colgate-Palmolive and TRW. He then went to work for Delphi Automotive as a manufacturing engineer in the automotive battery division. In 2003 Dr. Berisso received his PhD in Technology Management from Indiana State University. He then proceeded to teach at Central Missouri State University before returning to OU in the summer of 2005. Included in Dr. Berisso's research interests are RFID, direct part marking and the integration of AIDC with manufacturing processes and automation."

## Abstract

Rapid prototyping (RP) technologies have become more than just a fast and inexpensive way to produce prototypes. Today RP is widely used to produce functional prototypes, end-use parts and tooling as well as visual prototypes. When RP is used for end-use parts with interconnected moving assemblies or for producing metal casting molds which must have sufficient material for machining tolerances, accuracy is very critical. However, in general, accuracy of the finished RP parts is relatively low compared to parts produced by traditional manufacturing processes. The understanding of why some of these accuracy differences exist is either unknown or not well documented. The first step in determining this understanding is to find out the effects of process parameters on part accuracy for RP processes. The goal of this research was to determine the effects of build orientation, printhead life and the diameter of the 3D printed part on their cylindricity when using ZCast® build material with a ZCorp 310 printer.

An analysis of variance (ANOVA) study was conducted using a Zeiss Contura® G2 CMM. Eleven sample batches, for a total of 132 specimens, were produced and measured. Each batch of printed parts consisted of twelve specimens of two different diameters and three different build orientations. In addition, printhead life was recorded before each of the eleven batches. During measurement, each of the 132 specimens was held in a fixture and measured at three axial levels with fifteen discrete measurement points at each level. The results of this study indicate that the build orientation was the only parameter which had a significant affect on the cylindricity of 3D printed parts using ZCast® build material.

## Introduction

Rapid prototyping (RP) technologies continue to pervade manufacturing. As these technologies become more sophisticated through increased machine and software precision and new layering materials, the applications of RP technologies seem limitless. RP technologies are now being used to produce functional end-use products and parts as well as visual models (Wohlers, 2003). Many of the products that are produced have interconnected moving parts and require great precision during production. However, even with these new breakthroughs, RP has some significant obstacles to overcome before it can reach its full potential. Some of these obstacles are: durability of parts produced, cost of equipment and materials and accuracy of finished parts (Wohlers, 2003).

There have been several spin-offs from rapid prototyping technologies. One such spin-off is rapid tooling (RT). Originally coined when RP technologies began to be used in the foundry industry, RT is an additive process that uses 3-D Computer Aided Design (CAD) programming to produce patterns and molds for prototypes and small batches of cast parts (Jetley & Low, 2006; Rooks, 2002). This process is commonly used to produce molds for metal casting or for the purpose of low to medium volume production runs of plastic injected pieces where the ability to use RT technologies result in a fast prototype which could help secure business for a company ("Direct Metal Laser-Sintering," 2006). Currently, almost one-third (29.5 percent) of all rapid prototyping activity is used for tooling or pattern related applications. These parts are used for and include prototype tooling, metal casting and plastic injection molds (Wohlers, 2006). In addition, several RT techniques can be cost effective for production volumes of between 1,000 and 100,000 parts (Twarog, 2006).

As RT becomes more prevalent, the accuracy of the finished parts becomes increasingly important. The relatively rough surface finish and inherent inaccuracies traditionally common with RP technologies are of little concern when producing parts as visual aids or for aesthetic evaluation. When these components are used for tooling, precision fits with other parts require accurate and precise parts (de Beer, 2002; Folkestad & Johnson, 2001; Kietzman, 1999). One of the fastest growing RP technologies capable of RT is three-dimensional printing (3DP). However, the accuracy of 3DP can be difficult to determine because it depends on the part's geometry and the resolution of the printer (Connolly, 2000). 3DP technology is a relatively new rapid prototyping process compared to other more established methods such as stereolithography. With the introduction of newer technologies, newer materials are being offered. One such material by ZCorp is their ZCast material, a plaster-ceramic material designed for producing mold cavities and cores to be used in the casting of many non-ferrous metals. The advantage of ZCast is that it allows for the production of cores in a one-step process. However, due to 3DP's relative newness, especially ZCast parts, there is currently a limited amount of research available that addresses 3DP processes and procedures as compared to other more established RP processes.

Recently, metal casting philosophy has shifted from overcompensating for machining allowances towards the elimination of this excess material. This allows metal-casters to save on material and machining costs ("Tightening the Reins", 2004). The results of this study will enable those implementing the ZCorp 310 Printer with ZCast® build powder to more precisely produce cylindrical mold cavities or cores by determining the optimal build orientation, diameter and printhead life.

Three research questions were developed to help define the scope and scale of this study. The first asks if the cylindricity of 3D printed parts made by the ZCorp 310 Printer utilizing ZCast® build powder and zb56 binder will be affected by rotating the build orientation about the X axis (0, 45 and 90 degrees). The second asks if the cylindricity is affected by printhead life and the third asks if the cylindricity is affected by the diameter of the printed part. The following null and alternative hypotheses, and their associated interactions, were tested. For all hypotheses, an alpha of 0.05 was selected.

1. $H_{o1}$: μ 0 degrees around X = μ 45 degrees around X = μ 90 degrees around X.

   $H_{A1}$: μ 0 degrees around X ≠ μ 45 degrees around X ≠ μ 90 degrees around X.

2. $H_{o2}$: μPrinthead life start = μPrinthead life end.

   $H_{A2}$: μPrinthead life start ≠ μPrinthead life end.

3. $H_{o3}$: μ 1 inch diameter = μ 0.750 inch diameter.

   $H_{A3}$: μ 1 inch diameter ≠ μ 0.750 inch diameter.

To allow for a practically sized study, the following assumptions were applied in an attempt to ensure the feasibility of this study:

- That, based on the build procedures used, cylindricity was not related to the mix consistency of the virgin and recycled ZCast® build powder.
- Because specimen size was randomized within the build chamber, it was assumed that this did not have an effect on the cylindricity of the specimens.
- The ZCorp 310 worked as intended and that all shrinkage calculations, layer thickness settings and material characteristics were as advertised by ZCorp.
- Since a single layer thickness was use, it was assumed that variations in layer thickness did not exist and did not have an effect on the cylindricity of the specimens.
- It was assumed that the curing time between batches was consistent and adequate and did not have an effect on the cylindricity of the specimens.
- That the measurement technique and selected equipment worked as expected and that all efforts to reduce measurement variation were sufficient to ensure that they did not have an effect on the cylindricity of the specimens.

## *Review of Literature*

Rapid prototyping is widely used to evaluate a design before expensive mass production takes place. The process of verifying and evaluating a "successful" design has several aspects which include: correct shape, correct size and adequate strength (Kietzman, 1999). These aspects are often referred to as form, fit and function. Form deals with those aesthetics of the part that are essential to capturing the design's intent. Fit deals with the shape and dimensional accuracy of the part to ensure proper mating of surfaces or features. Function is the ability of the part to be used and function as well as a production part (Mackie, 2006; Raquet, 2005). The ability to quickly produce an RP part and evaluate it for form, fit and function, has the potential to reduce manufacturing lead time of a product up to 30-50% (Pandey, 2003). Therefore, industry is currently placing increasing demand on functional RP models and prototypes which in turn is putting a lot of pressure on the development of prototyping techniques (de Beer, 2002).

Due to its relative infancy, as compared to other manufacturing processes, RP has some limitations which include; size envelopes, limited material properties, varying accuracies between the X, Y and Z planes and poor surface finish (Huxley, 2002). These limitations are of little significance when using RP to evaluate a design strictly on form or the aesthetic aspects of a part. However, when evaluating designs on fit and function or application for end-use products, these limitations can be detrimental (Curtis, 2006b). In order to improve the shortcomings of RP, improvements need to be made in the areas of accuracy and range of materials (Kulkarni, 2000).

Over the past decade most RP research has focused on the so-called high-end processes such as sterolithography (SLA) and selective laser sintering (SLS). Most of this research dealt with process control, material property improvement or non-cylindrical testing (Dimitrov, Schreve & deBeer, 2006; Kim & Oh, 2008; Mackie). However, other contemporary research areas include: improving design aids by incorporating finite element analysis, developing optimized processes for indirect and direct RT for casting and molding processes and tissue engineering in the medical field (Dimitrov et al.). Much of the existing research deals with process planning and optimization which are beyond the scope of this paper (Pal, 2007; Vosniakos, Maroulis & Panteli, 2007).

Limited research is available on many RP processes. It has been found that questions pertaining to accuracy, surface quality or strength are avoided in case studies and equipment manufactures' websites. At most, this information is stated in the vaguest form (Dimitrov et al., 2006). There are many books currently available which cover the basics of RP technologies. However, a great deal of the important details pertaining to RP is only available in papers, patents, or proprietary corporate documents. Therefore, standardized methods for evaluating the accuracy, surface quality, and mechanical properties of RP parts have not been developed. Independent test data on commercial processes can also be extremely difficult to find (Curtis, 2006a; Kietzman, 1999).

As was mentioned earlier, the accuracy of a RP part can be very important. However, the process of determining the dimensional accuracy of parts produced by various RP systems is not a simple task. There are currently no standards available for the evaluation of dimensional accuracies when using various RP systems (Mueller, 2006; Wohlers, 2006). Many factors contribute to the inaccuracy of RP/additive fabricated parts due to the numerous phase changes an RP part must go through when being produced. These phases include converting a CAD model to an STL file; a printhead applies binder to selected areas of a powder bed which binds the powder particles together; the part is cured at room temperature or in an oven and finally, after curing, post processing may take place which can involve sanding/shaping and/or infiltrating with an adhesive to harden the part.

Because of the layering process innate in all RP processes the parts are left with non-isotropic properties and residual stresses. Due to this phenomenon, parts often lack dimensional accuracy due to the differing coefficients of thermal expansion in the X, Y and Z directions (Curtis, 2006b). Also, the layering process causes what is known as a staircase effect as shown in Figure 1. All RP parts have this staircase effect which cannot be totally eliminated. These stepped edges may lie completely inside or outside the CAD model and can be very noticeable on curved surfaces. This leads to a distortion of the shape referred to as a containment problem. However, the staircase effect can be reduced by refining the build layers or possibly eliminated by changing the orientation of the part (Bablanl, 1995; Pandey et al., 2003).

A study published in 2001 by Cooper, Williams and Pat Salvail compared

***Figure 1. Staircase effect. This effect is common on curved or angled RP parts***

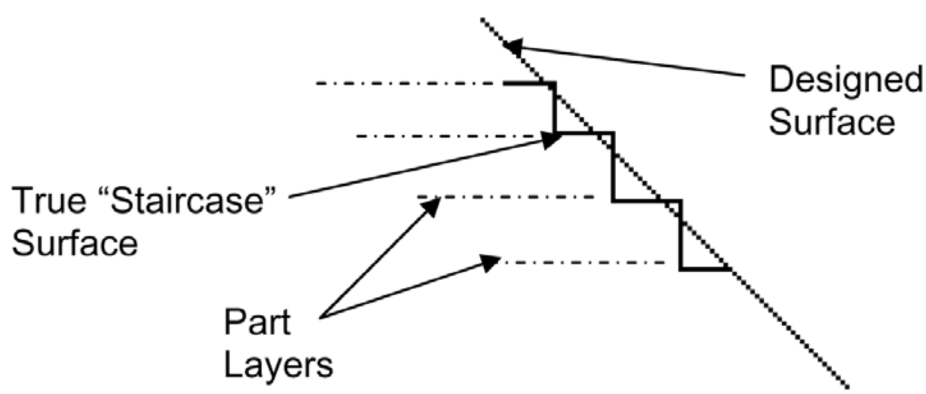



***Table 1. Comparison of Various Rapid Prototyping Technologies. The following table derived from the Cooper et al. study, displays the results of various RP technologies compared.***

| **Comparison of Various Rapid Prototyping Technologies** | | | | |
|---|---|---|---|---|
| **Technology** | **Multi-jet Modeling** | **Fused Deposition Modeling** | **Selective Laser Sintereing** | **3D Printing** |
| **Material** | Wax-like plastic | ABS | Polystyrene | Plaster |
| **Accuracy (in.)** | 0.013 | 0.014 | 0.018 | 0.025 |
| **Build Time** | 437 min | 2530 min | 411 min | 340 min |
| **Cost (USD)** | $146 | $421 | $268 | $113 |

several common RP technologies for the creation of patterns for casting a diverter valve component. Table 1, displays the materials used, accuracy, build time and cost of the systems investigated.

Today manufactures offer a wider range of materials than ever before. Materials range from traditional photopolymers and ABS plastic to carbon fiber-based materials, stainless steel and ceramic composite powders (Wohlers, 2006). Despite this continued growth, minimal data on build materials, the quality of RP parts is strongly affected by the material properties and process parameters (Albert, 2002).

The literature has indicated that the orientation of the RP part while being built may affect its accuracy (Bablanl, 1995; Kulkarni, 2000). Orientation can be related to many aspects of the model creation, build characteristics and finished part properties of the part. The factors dependent on part orientation include support generation, mechanical properties, shrinkage tolerances and build time (Kulkarni, 2000).

It is suggested that in powder-based RP processes, the orientation of parts may affect accuracy due to the displacement of layers and the compressibility of the powder. Dimensional accuracy may decrease as the number of layers increase. It is suggested to orientate parts where they are shortest vertically to minimize layer displacement (Bablanl, 1995; Dimitrov & deBeer, 2002; Lee, 1995). However, depending on the complexity or features of the part, vertical orientation may not be possible. Bablanl also offers some general guidelines for proper orientation of parts which include: 1) the height in the build direction should be minimized, 2) curved surfaces should be in the horizontal plane for higher resolution of the surface, 3) planes should be built parallel to build direction and 4) parts with internal voids or geometry should be orientated so that trapped build material can be easily removed. The aforementioned may very well be viable general guidelines. However, these guidelines do not provide specifically detailed information pertaining to certain RP processes, materials or geometric forms resulting in limited use for those users who are in need of more comprehensive information. It is up to the designers and operators of this equipment to make the proper choices for the particular need at hand (Kulkarni, 2000).

As mentioned previously, accuracy is very important for fit and function, pattern making and tooling for a variety of molding and forming processes. Investigations conclude that accuracy is dependent on a variety of factors which include system calibration, printing technique, material used, binder and binder mechanism, nominal dimensions, build orientation, geometric features and their topology, environmental conditions, elapsed time, post treatment procedures, and infiltration agents (Albert, 2002; Dimitrov et al, 2006; Grim, 2004). Overall system accuracy can be a difficult thing to conclude because it depends on the geometry of the part and the resolution of the printer (Connolly, 2000). In general, 3DP parts have few errors in accuracy in the X and Y direction. However, if process parameters are not set correctly, the Z-axis could be a source of accuracy problems (Albert, 2002). The potential accuracy problems in the Z-axis stem from variations in the packing of the build powder which causes a loss of registration between previous and new layers (Charnnarong, 1996; Lee, 1995).

Tolerance and precision are obviously important factors when choosing an RP process. 3DP is continuing to improve but it still is unable to hold the accuracy levels that CNC machining can (Fidan, 2004). A realistic accuracy expectation of 3DP systems without using part finishing techniques or changing build parameters is ± 0.010” to 0.030”. Three-dimensional printer vendors claim accuracies of ± 0.005” which are not realistic for all features on all parts (Grim, 2004). In order to exploit the strengths of 3DP, process capability profiles which include recording characteristics such as accuracy, surface finish, strength, elongation, build time and cost must be determined (Dimitrov et al., 2006).

The quality of RP parts are strongly affected by the powder properties and process parameters such as binder saturation values and saturation levels, layer thickness, shrinkage, and location of parts in the build chamber (Albert, 2002). It is assumed that powder held together by binder is less likely to experience layer displacement (Charnnarong, 1996; Lee, 1995). Investigations have revealed that substantial inaccuracies can occur due to compression of the support powder. This problem was somewhat addressed through ZCorp’s new slicing software which allows for optional support structures to be added automatically (Dimitrov et al., 2006).

Shrinkage in 3DP, however small, can lead to effects such as distortion and delamination between successive layers of a part. Drying shrinkage occurs due to capillary stresses which appear as the binder dries. This places the liquid under tension (suction). This tension results in movement of the build medium as it dries. Because 3DP builds parts layer-by-layer, shrinkage not only affects the final dimensions but also part integrity and strength (Charnnarong, 1996).

As was previously mentioned, it is known that different build orientations may influence model characteristics for different geometric designs. Numerous studies (Bablanl, 1995; Dimitrov et al, 2002, 2006; Kulkarni, 2000; Lee, 1995; Raquet, 2005) have indicated that orientation might affect the accuracy of 3DP parts. However, there is little research pertaining to different dimensional tolerances, build materials and processes in this area (Dimitrov et al., 2002).

The literature has suggested that as the size of the RP/additive fabrication part increases its accuracy proportionally decreases (Wohlers, 2003). However, there is little information or research pertaining to this relationship. The literature suggests that part size has little effect in the X and Y axis directions but a significant effect in the Z axis direction (Connolly, 2000). This may be due to the compressibility of build material and displacement of layers (Dimitrov et al., 2006; Lee, 1995).

## Methodology

Two part designs (see Figure 2), one for each diameter being tested, were created and imported into ZCorp's ZPrint software. The parts were copied and rotated in the ZPrint software for each of the three orientations and then built (see Figure 3). The finished parts were extracted, cleaned off and kept in a sealed container to minimize any environmental changes. Once all of the parts were completed, they were automatically measured on a Zeiss Contura® G-2 coordinate measuring machine with an appropriately sized probe. Two programs were written, one for each diameter. Based on the recommendations of the current literature (Berisso, 2003; Chang, 1991; Choi, 1998; Dowling, Griffin, Tsui & Zhou, 1997; Hocken, 1993; Jackman, 1998; Jiang & Chiu, 2002; Summerhays, 2002; Weckenmann, Heinrichowski & Mordhorst, 1991), fifteen sample points were chosen for the circumference sampling of each of the selected three axial planes of measurement for both the 1.00 inch and 0.75 inch diameter specimens (see Figure 4 and 5).

A 2 X 3 X 11 ANOVA statistic was chosen because this study involves the simultaneous comparison between two diameters (1.00" and 0.750"), three build orientations (0°, 45°, 90°) and eleven printhead life categories with regard to the cylindricity of the built part. One advantage to the ANOVA statistic is robust to violations of homogeneity as long as the sample sizes are equal and largest variance is no more than 4 or 5 times that of the smallest variance (SPSS Guide, 2007).

## Results

After the data collection was finished, a complete descriptive analysis of the data was undertaken. Eleven batches of twelve specimens (for a total of 132 parts) were produced with existing mate-

***Figure 2. Specimen Design. This illustration was obtained via a screen shot in SolidWorks version 2006. The specimen's cylindrical dimensions are: 1" diameter X 3" and 0.750" X 3".***

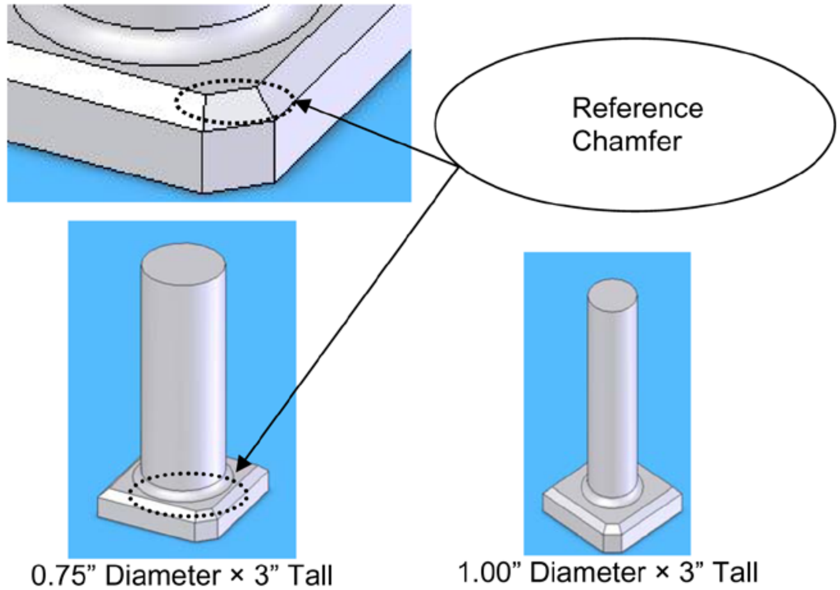
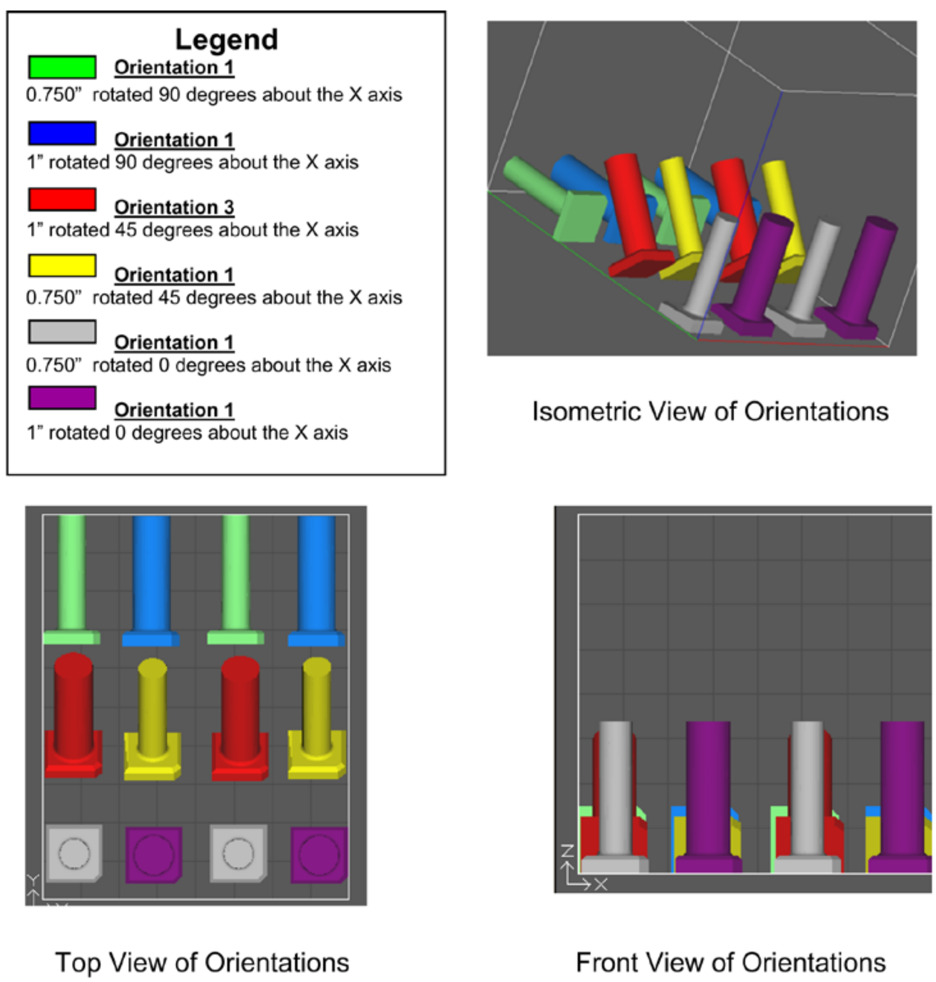



***Figure 3. Build orientations of each batch. Each color represents a different build orientation and diameter.***



rials, resulting in an adjusted R squared value for the study of 0.724. Since, according to Coddington (2002), low level correlations have a Pearson R value of less than 0.60; mid level correlations are at 0.60 to 0.79; and strong level correlations are at greater than 0.79, this study has a midlevel correlation.

The ANOVA analysis was run on the collected data (see Table 3). Of the three hypotheses tested only the first null hypothesis, that there was a difference in build orientations, could be rejected. The build orientation variable results, F = 159.405, p = .000, resulted in a rejection of the first null hypothesis. The analysis shows that there is a statistically significant difference in the cylindricity of 3DP parts and their build orientation at a 0.05 level of significance. These results objectivly indicate to those who produce rapid tooling with ZCorp 310 printers and ZCast® build material that the build orientation of 0, 45 and 90 degrees rotation about the X axis will significantly affect part cylindricity. In many cases a choice can be made as to which build orientation to use during the printing of a 3DP core or mold. If cylindricity is of great importance build orientation needs to be considered.

Based on the ANOVA analysis, there was a failure to reject the remaining null hypotheses. The implications of this are that printhead life, diameter and the resulting interactions of the three independent variables will not statistically impact the cylindricity of a 3DP part.

## Conclusions

As stated in the introduction, the objective of this study was to analyze the effects of build orientation, diameter and printhead life on the cylindricity of 3D printed parts using the ZCorp 310 printer and ZCast® build material. The results of this analysis are a first step in the determination of the optimal conditions and build orientation for cylindrical mold cavities, features or cores used in rapid tooling. In the realm of rapid casting, the accuracy of the finished mold or core is very important. Completed castings which do not have sufficient machining or heat treating allowances are not usable. On the other hand, castings which have excessive material to remove require additional time, machine wear and cost additional money to finish.

The results of this study indicated that the build orientation variable had a statistically significant effect on the cylindricity of 3D printed parts. This should tell those who operate and program ZCorp 310 printers using ZCast® build material that if cylindricity is of great concern, the orientation of the cylindrical features must be considered. Many times a choice can be made to

***Figure 4. Circumference measurement points. These arrows designate the measurement points which were sampled around the circumference of each specimen. As shown, fifteen evenly spaced points were sampled at three specified levels.***

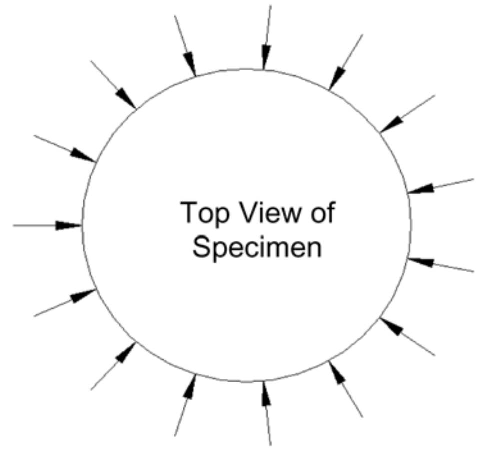



***Figure 5. Axial measurement planes. This illustration designates the three axial measurement planes which will be sampled for each specimen. As shown, three axial planes (fifteen points each) will be sampled in the following locations in inches relative to the top of the specimens.***

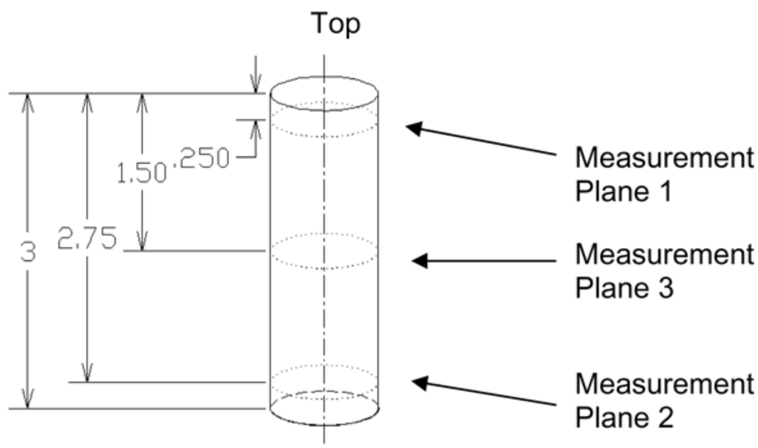



***Table 2. Cylindricity Descriptive Statistics. The following table shows the descriptive statistics for the cylindricity data collected.***

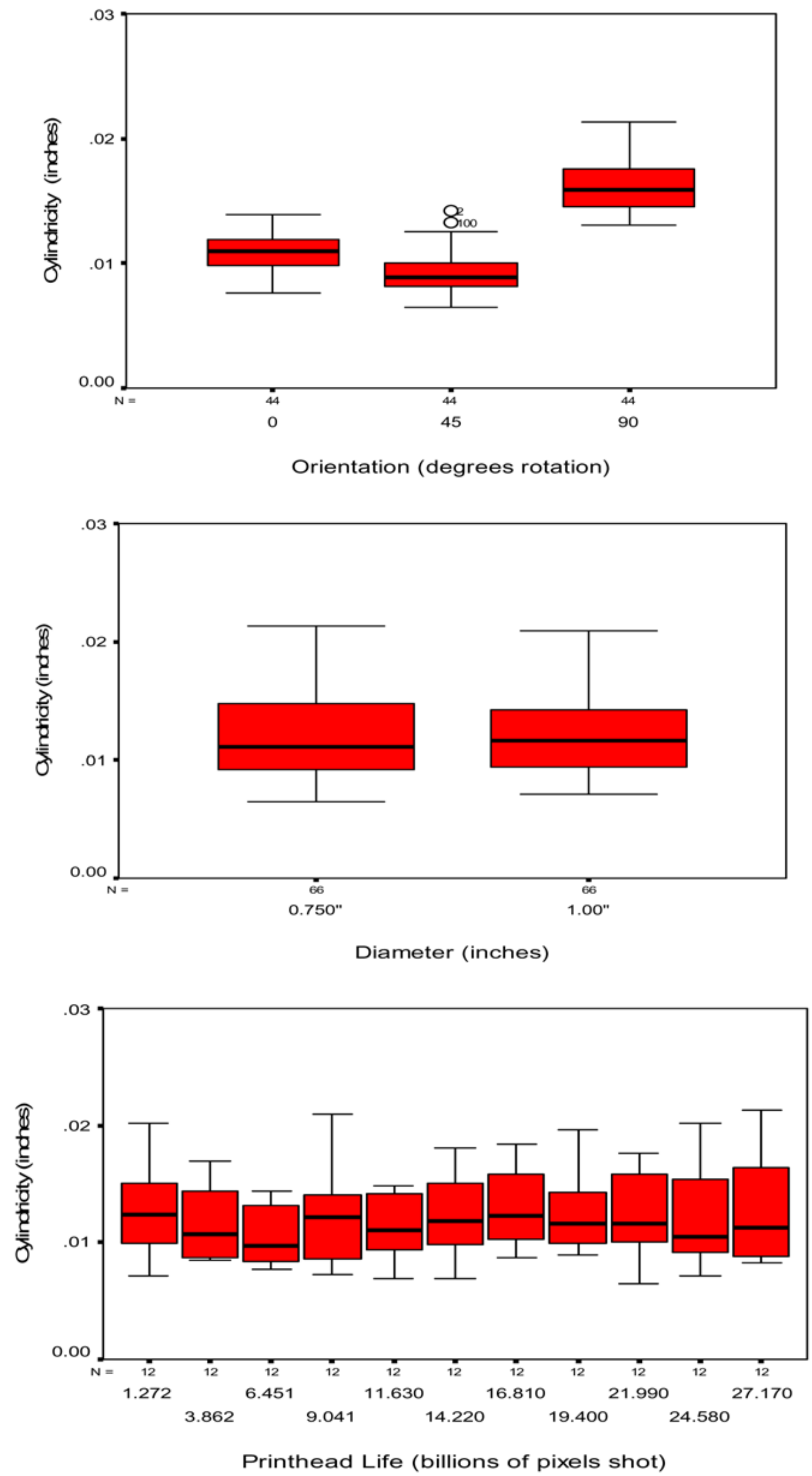
| Descriptive Statistics for Cylindricity | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Std. | | Skewness | | Kurtosis | |
| | N | Min | Max | Mean | Dev. | Var. | Value | Error | Value | Error |
| Cylindricity | 132 | .0065 | .0213 | .1012 | .0035 | 0 | .619 | .211 | -.401 | .419 |

orientate a part in different ways within the build chamber. An examination of the resulting box plots (see Figure 6) for the orientation the most accurate cylindricity measurements in this study were the 45 and zero degrees (vertical) rotation. These results are possibly due to the compressibility of the build powder below the specimens during the build. The specimens which were built vertically (zero degrees rotation) had little compression of the build powder because each successive layer was built upon material which was previously bound together. On the other hand, the specimens which were built horizontal (90 degrees rotation) had less support from bound powder resulting in a distortion of the specimen which would exponentially become greater as the build layers increase. Additional studies need to be conducted to determine the optimal build orientation for cylindricity accuracy.

As shown in the results, there appears to be no statistically significant difference in cylindricity based on the printhead life or diameter of the part. However, only two diameters were investigated during this study. In order to capture a more complete picture of how diameter may affect cylindricity a wider range of diameters should be investigated beyond the diameter of 1.00" and below 0.750" as well as increments between 1.00" and 0.750".

The cylindricity throughout most printhead life data sets remained fairly consistent during the study. The last data set at 27.170 billion pixels of beginning printhead wear displayed a noticeably larger variance than the previous data sets. This might indicate that after 27-30 billion pixels have been shot variability will increase thus resulting in less cylindricity accuracy. This correlates with ZCorp's recommendation that after 30 billion pixels have been shot through the printhead, surface finish and accuracy may be degraded. Extending the printhead life well beyond 30 billion pixels may present a clearer picture of how printhead life may affect cylindricity.

***Figure 6. Box-plots of the variables. This figure displays the amount of variability for each group of data.***



The operators and programmers of 3D printing equipment will be able to utilize the results of this data very effectively. Those that use ZCorp 310 printers with ZCast® build material now have definitive data concerning cylindricity and how it is related to orientation, printhead life and the diameter of printed parts. As mentioned earlier, this is very important for those developing metal casting molds and cores.

Those in the metal casting industry can utilize the results of this research to feel more confident and informed about the advantages and disadvantages of rapid tooling/casting processes. Previously, those in the metal casting industry may not have known the benefits of rapid tooling techniques or may have dismissed the advantages because of unknown inconsistencies in required cylindricity. Now that the results of this research have been published, those in the metal casting industry now know that when using ZCast® in a ZCorp 310 printer, build orientation is very important and should be considered when trying to obtain the most cylindrical features.

***Table 3. ANOVA Results. The following is an SPSS output for the data collected. A significance less than 0.05 results in the rejection of the null hypothesis.***

Dependent Variable: CYLINDRICITY

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Corrected Model | 1.42036E-03 | 67 | 2.11994E-05 | 6.118 | 0.000 |
| Intercept | 5.69236E-06 | 1 | 5.69236E-06 | 1.643 | 0.205 |
| TEMPMEAS | 3.22696E-06 | 1 | 3.22696E-06 | 0.931 | 0.338 |
| HUMMEAS | 1.05047E-07 | 1 | 1.05047E-07 | 0.030 | 0.862 |
| ORIENT | 1.10468E-03 | 2 | 5.52338E-04 | 159.405 | 0.000 |
| DIA | 1.53190E-08 | 1 | 1.53190E-08 | 0.004 | 0.947 |
| LIFE | 3.29877E-05 | 5 | 6.59755E-06 | 1.904 | 0.106 |
| ORIENT*DIA | 4.30608E-06 | 2 | 2.15304E-06 | 0.621 | 0.540 |
| ORIENT*LIFE | 4.71046E-05 | 20 | 2.35523E-06 | 0.680 | 0.831 |
| DIA*LIFE | 2.01715E-05 | 10 | 2.01715E-05 | 0.582 | 0.823 |
| ORIENT*DIA*LIFE | 6.25537E-05 | 20 | 3.12768E-06 | 0.903 | 0.585 |
| Error | 2.21760E-04 | 64 | 3.46500E-06 | | |
| Total | 2.09858E-02 | 132 | | | |
| Corrected Total | 1.64212E-03 | 131 | | | |

[a] R Squared = .865 (Adjusted R Squared = .724)

## *References*


Albert, Y., Tseng, Y.C. (2002). A robust process optimization for a powder type rapid prototyper. Rapid Prototyping Journal, 8 (3),180.

Bablanl, M. (1995). Quantification of Errors in Rapid Prototyping Processes, and determination of Preferred Orientation of Parts. Transactions of NAMRI/SME. Vol. XXIII Society of Manufacturing Engineers.

Berisso, K. (2003). A comparison of measurement variations for selected probe head configurations for coordinate measuring machines. Dissertation Abstracts International, 64 (08), 3989. (UMI No. 3102997).

Chang, Sung Ho. (1991). Statistical Evaluation and Analysis of Form and Profile Errors Based on Discrete Measurement Data. Published doctorial dissertation, The University of Michigan, Ann Arbor.

Choi, W., Kurfess, T. R. & Cagan, J. (1998), Sampling uncertainty in coordinate measurement data analysis. Precision Engineering, 22 (3), 153-163.

Charnnarong, J. (1996). The drying shrinkage in three-dimensional printing and its dependence on the properties of the powder and the binder . Dissertation Abstracts International. 57 (08), 5256. (UMI No. 0597215).

Coddington, C.E. (2002). ITEC 6112: Analytical Studies and Planned Experimentation in Industry. Online course taken through East Carolina University in the fall of 2002.

Connolly, J. (2000). Have 3-D Printers Found Their Place in the Mold-Making World? Time-Compress. Retrieved March 17, 2004, from http://www.timecompress.com/magazine/archives.cfm.

Cooper, K., Williams, G. & Salvail, P. (February, 2002). Evaluating RP Methods: NASA's Side-by-Side Comparison. Modern Casting, 92 (2)28-30.

Curtis, W. (March 2006a). Truly Functional Prototypes. Time Compression Technologies, 9 (2) 46-52.

Curtis, W. (May 2006b). Additive Prototype Material Properties: A Well Kept Secret. Time Compress Technologies, 11 (3). Retrieved January 27th, 2007 from the World Wide Web: http://www.timecompress.com/magazine/archives.cfm.

de Beer, D. (2002). The Role of RP in Design and Development Defined Through Successful Case Studies. Technical Paper. Society of Manufacturing Engineers PE02-238.

Dimitrov, D. & de Beer, N. (2002). 3-D Printing-Process Capabilities and Applications. Technical Paper, Society of Manufacturing Engineers MS02-212.

Dimitrov, D., Schreve, K., & de Beer, N. (2006). Advances in Three Dimensional Printing – State of the Art and Future Perspectives. Rapid Prototyping Journal. 12 (3), 136-147.

Direct Metal Laser-Sintering Makes a Speedy Delivery. (2006). Modern Casting, 96 (8).

Dowling, M. M., Griffin, P. M., Tsui, K. L. & Zhou, C. (1997). Statistical issues in geometric feature inspection using coordinate measuring machines. Technometrics 39, 3-17.

Fidan, Ismail. (2004). Bench marking studies for 3D printing processes. 1st Annual Manufacturing Technology Summit – 2004: TP04PUB258: Dearborn, Michigan.

Folkestad, J. E. & Johnson, R. L. (2001). Resolving the Conflict between Design and Manufacturing: Integrated Rapid Prototyping and Rapid Tooling (IRPRT). Journal of Industrial Technology, 17 (4).

Grim, T. (January 2004). Rapid Prototyping Benchmark of 3-D Printers. Time Compress Technologies, 9 (1). Retrieved January 27th, 2007 from: http://www.timecompress.com/magazine/archives.cfm.

Hocken, R. (1993). Sampling Issues In Coordinate Metrology. Manufacturing Review, 6 (4), 282-294.

Huxley, M. & Weisberg, S. (August 1st 2002). Rapid Prototyping Cuts Time to Market. Cadalyst. Retrieved January 27th, 2007 from the World Wide Web: http://www.cadalyst.com/cadalyst/article/articleDetail.jsp?id=97261.

Jackman, J. & Park, D. (1998). Probe Orientation for Coordinate Measuring Machine System Using Design Models. Robotics and Computer-Integrated Manufacturing, 14, 229-236.

Jetley, S. & Low, D. K. (2006). A Rapid Tooling Technique Using a Low Melting Point Metal Alloy for Plastic Injection Molding. Journal of Industrial Technology, 22 (3).

Jiang, B., & Chiu, S. (2002). Form Tolerance-Based Measurement Points Determination With CMM. Journal of Intelligent Manufacturing, 13, 101-108.

Kietzman, J. (1999). Rapid Prototyping Polymer Parts VIA Shape Deposition Manufacturing. Dissertation Abstracts International, 60 (04), 1815. (UMI No. 9924574).

Kim, G. D & Oh, Y. T (2008) A benchmark study on rapid prototyping processes and machines: quantitative comparisons of mechanical properties, accuracy, roughness, speed, and material cost. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 222 (2), 201-215.

Kulkarni, P, et al. (2000). A Review of Process Planning Techniques in Layered Manufacturing. Rapid Prototyping Journal, 6 (1), 18.

Lee, S., Sachs, E. & Cima, M. (1995). Layer position Accuracy in powder-based rapid prototyping. Rapid Prototyping Journal, 1 (4), 24-37.

Mackie, M. (2006). How Are RP Processes Alike and How Do They Differ? Time-Compress.11 (6), 7-9.

Mueller, T. (September 2006). Accuracy in Rapid Tooling. Time Compression Technologies,5 (5). Retrieved January 27th, 2007 from the World Wide Web: http://www.timecompress.com/magazine/archives.cfm.

Pal, D.K.. (2007) Rapid tooling route selection for metal casting using QFD-ANP methodology. *International Journal of Computer Integrated Manufacturing*, 20 (4), 338-354.

Pandey, Pulak, et al, (2003). Slicing procedures in layered manufacturing: a review. Rapid Prototyping Journal, 9 (2), 274.

Raquet, J. (2005). An investigation into the material properties and precision of rapid prototyping technology. Dissertation Abstracts International, 66 (01), 513. (UMI No. 3161851).

Rooks, B. (2002). Rapid Tooling for Casting Prototypes. Rapid Prototyping Journal, 22 (1), 40-45.

SPSS Guide (2007). ANOVA. Retrieved September 27, 2007 from: http://academic.reed.edu/psychology/RDDAwebsite/spssguide/anova.html.

Summerhays, K. D. et al. (2002). Optimizing Discrete Point Sample Patterns and Measurement Data Analysis on Internal Cylindrical Surfaces With Systematic Form Deviations. Precision Engineering, 26, 105-121.

Tightening the Reins on Dimensional Tolerances in Aluminum Green Sand Castings. (2004). Modern Casting, 94 (12).

Twarog, D. (2006). How Die Casters Prove Rapid Tooling Has Benefits. Design News, 61 (17).

Vosniakos, G-C., Maroulis, T & Panteli, D. (2007) A method for optimizing process parameters in layer-based rapid prototyping. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 221 (8), 1329-1340.

Weckenmann, A., Heinrichowski, M.& Mordhorst, H. J. (1991). Design of Gauges and Multipoint Measuring Systems Using Coordinate-Measuring-Machine Data and Computer Simulation. Precision Engineering, 13 (3), 244-252.

Wohlers, T. (2003a). Wohlers Report 2003. Wohlers Associates, Inc. Fort Collins, Colorado.

Wohlers, T. (2006). Wohlers Report 2006: RP, RT, RM State of the Industry. Time-Compress Technologies. 11 (6).