INVESTIGATION OF SAMPLES ACCURACY TO MODEL THE PROCESSES IN 3D PRINTING

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Abstract: *3D printing also called Layer based technology, Freeform fabrication, Additive manufacturing or Rapid Prototyping technologies has undergone significant development over the last decades. The growth is related to the expansion of the range of materials used, application areas, and range of possible sizes from nanometer to tens of meters as well as increasing machine accessibility. There is a growing consensus that 3D printing technologies will be at the heart of the next major technological revolutions. At present there are some technological specifics and associated difficulties in 3D printing one of which is the accuracy of the manufactured product. Research in this area would allow modelling of 3D printing processes.*

The article describes the possible types and sources of inaccuracies in 3D printing processes. The various types of test pieces used in practice are examined to quantify the errors in shape and sizes after building. Test pieces with predefined discrete points and methodology are provided to calculate inaccuracies. The results are presented in the terminology of "linear" and "shear" deformations. This gives opportunity to determine the variations in the shape and dimensions of the parts built by 3D printing. On the basis of the discreet results obtained, the possibility of 3D printing process modelling is discussed and presented.

Keywords: 3D PRINTING, ACCURACY, MODELLING, TEST PART, GRID METHOD

1. Introduction

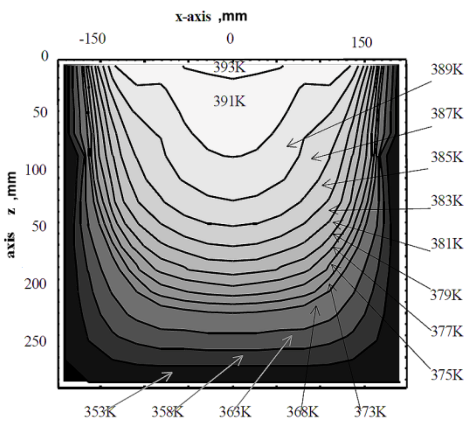
Additive Manufacturing (AM or commonly known as 3D printing and before that rapid prototyping - RP) undergone significant development during the past decades in terms of production volume and technological achievements. However the AM industry only began to grow substantially after 2009 probably because the last major AM patent for Fused Deposition Modeling (FDM) expired in 2009. This way 3D printers could be produced without infringing on intellectual property, creating a newfound interest and investment in 3D printing [1]. This is particularly valid for the introduction of affordable consumer 3D printers into the general market on the basis of so-called RepRap (affordable open source replicating rapid prototyper). Hence the main drivers for the rapid growth are the reduction in cost to access the technology, an increase in applications [2] as well as expanding of the range of materials used and printed dimensions. Additive manufacturing has been called a disruptive technology [3] that will fundamentally influence many processes in production. Predicting of the future of AM on economic and social implications is constantly on the focus of the researchers [4, 5] and companies [6]. There is a growing consensus that 3D printing technologies will be one of the next major technological revolutions [7].

Although AM is a breakout technology, the implementation of it is still in infancy. There are numerous challenges in applying AM. One major obstacle is lower accuracy relative to other technologies [2]. The errors in sizes and shapes of produced component reflect various reasons during the build up stage. A possible general classification of error sources common for most popular AM processes comprises the following [8]: errors caused by laser scanning system; errors caused by material shrinkage; errors caused by spot size and heat effected zone; errors caused by Computer Aided Design (CAD), tessellation and slicing; random errors. The thermal nature of most of the process leads to shrinkage, distortion and warping of the built part. All of these factor can contribute to significant errors in the final component. Therefore it is especially important to perform an accuracy analysis that systematically reveals the type of errors, their sources and magnitudes, so that improvements in the production practice can be implemented. If enough data about accuracy of a given process is gathered, the process can be modeled in terms of its accuracy performance.

2. Prerequisites and means for solving the problem

The manufacturing parameters in AM have great significance on the part integrity, strength, density, surface quality and shrinkage for different processes and materials. The analysis of process parameters is therefore one of the main streams of RP research. Once an optimum set of parameters are established they are kept as a material's "profile". In particular cases of unexpected changes to part quality, adjustments to the parameters can be made according to the experience of the machine operator or platform manufacturer recommendations. In most cases of AM it is practical to set the build parameters for optimum part strength, surface quality and build time. On this basis the accuracy in size and shape of the part can be targeted by applying scaling factors, beam offset compensation, part orientation and arrangement in the building chamber. As the manufacturing conditions at different areas of the build chamber vary, the overall accuracy of the process or platform is not uniform. The research in [9, 10] (Fig. 1) shows that the temperature variations of a SLS machine are considerable. It can be expected that the differences in shrinkage to room temperature and the ultimate accuracy of the build part will reflect these variations.

a)



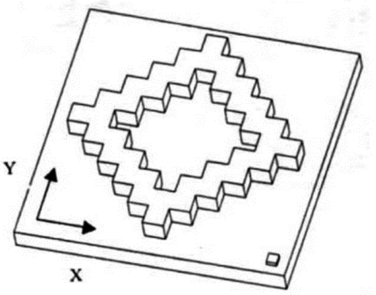
b)

Fig. 1. *Temperature distribution in the part bed - a) reported by [9] and b) reported by [10].*

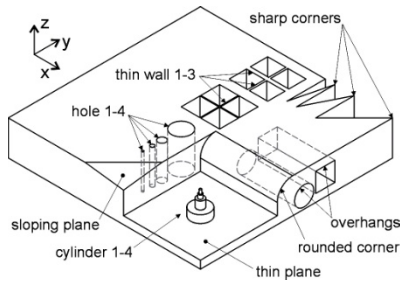
Essentially the practice of accuracy research in AM requires the building of various test parts or series of parts and evaluating the differences between their nominal and actual dimensions and shapes. Linear and angular dimensions, point's coordinates and surface roughness are the basic entities that are used to assess part geometry.

The elements that distinguish between different methodologies for accuracy studies of RP processes are test parts and the related measured geometrical entity. The most common types of test pieces can be classified as: pyramids (staircase); specifically designed parts; real parts. Typical examples of these are shown in fig. 2.

Pyramid (staircase) [11]



Specifically designed part [12]



Real parts [13]

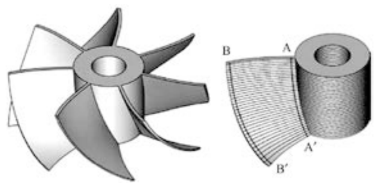


Fig. 2. *Typical examples of test parts.*

One of the drawback of all test pieces is that they don't cover entire surface of the part bed. Additionally they usually cross areas with different temperatures or with other manufacturing variations. As a result a continuous distribution of accuracies cannot be achieved. In case of the most popular type of test part - pyramid, the methodologies for accuracy investigation are based on measurements of the staircase dimensions and calculation of the material shrinkage in x, y or z direction. The measurements m_i are shown on fig. 3.

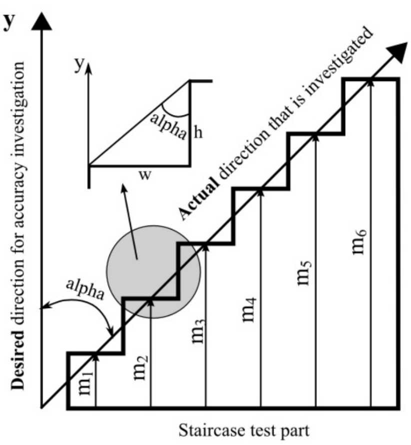


Fig. 3. *Lengths and directions for measurements of pyramid shape test part.*

The idea of such measurements is usually to determine the difference between the nominal dimension l_n and the final dimension l_f (produced by the machine) usually called the error (E):

$$E = L_f - L_n$$

The *distribution* of the errors E varies over the part bed defined as a plane (x, y). Geometrically the error is a function of two variables x and y:

$$E = f(x, y)$$

As illustrated in fig. 3, the direction in which the pyramid stairs advance is the "**actual** direction" defined by the angle α:

$$\alpha = \tan^{-1}\left(\frac{w}{h}\right)$$

This may not necessarily be the "**desired** direction" for investigation. Failure to observe this correctly can result in misleading directional results, particularly if z direction is investigated by vertical pyramid - fig. 4.

Vertical pyramid

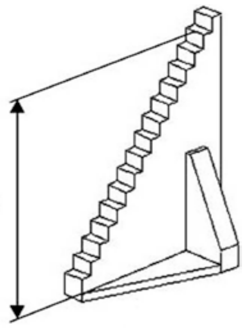


Fig. 4. *Vertical pyramid for z accuracy investigation.*

The most common approach of using the pyramid type of test piece is to compare the nominal (as in CAD model) and actual size of the steps as shown in fig. 5 [14]. The comparison of the results in coordinates "nominal dimensions - actual dimensions" is represented by an interpolation graph which slope is interpreted as the scaling factor. It has to be applied to the CAD model in order to achieve closer real part dimensions to the nominal. The intercept that the interpolation line cuts from the vertical coordinate axis of the graph gives the size of the systematic error due to the size of the extruded plastic jet or laser beam spot.

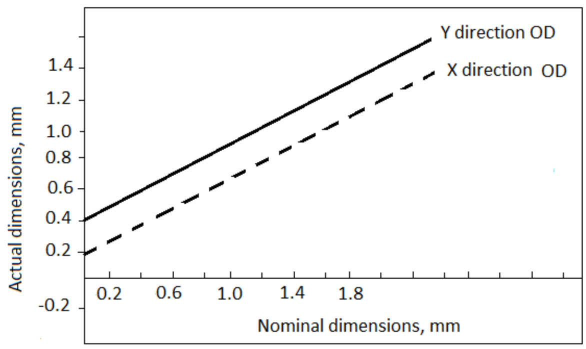


Fig. 5. *Linear interpolation "nominal size - actual size" of the outside (OD) in X and Y direction of the pyramid.*

In general practice it is important to know the length changes either in any directions or in some particular directions. In order to model the total accuracy of the AM process or specific platform or material behaviour in terms of shrinkage, constructing a map of entire field of distortions is essential. It is not achievable by utilising the test parts and measurement approach described above.

3. Solution of the examined problem

Regardless of the cause, it can be assumed that the change of dimensions or shape of a body manifests itself in the same geometrical appearance as strain. Strain is defined as being linear (ε) or angular (γ). The angular change in a right angle, known as shear strain, is defined as the change in angle between two line segments which were previously mutually perpendicular. An advantage of describing the inaccuracy of parts manufactured by AM processes in terms of strains, is the possibility it allows to combine analysis of dimensional and shape deviation from nominal.

The analysis methodology that is proposed in this study for accuracy modeling of AM processes is based on measurment of coordinates x, y or z at many points throughout a test piece in the form of a flat plate. To expose the strains, a reference grid in some form is applied to the CAD model of the test piece beforehand. After the plate is manufactured the actual coordinates of grid points is measured and compared with the CAD model. As the produced grid differs from the nominal CAD grid it can be considered as deformed and therefore the strains calculated. Several ways to estimate the strains of a deformed object are known however the Coefficient or Square Grid Method is utilised here. This method was introduced by Bredendick in [15, 16].

The advantage of such a methodology is the simple geometry of the test part - a plate with reference points in form of hole, cross or other spot mark. The plate can be arbitrary in size, location and orientation within the build chamber (fig. 6). It is also suitable for handling and automatic measuring as well as being representative of various engineering parts.

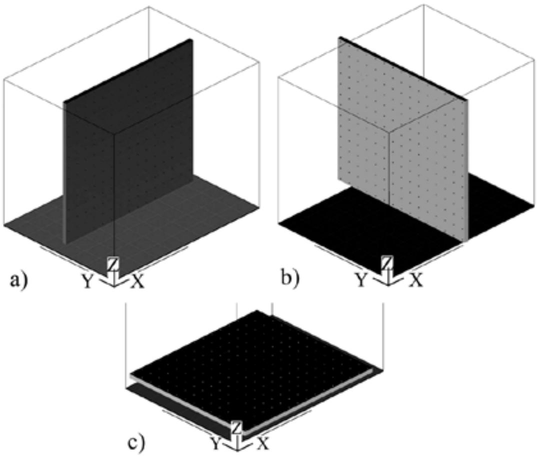


Fig. 6. *Examples of test plate orientation.*

If the plate is built horizontally the deviations ε_x and ε_y (fig. 6c) can be determined, if positioned vertically then either ε_z and ε_x (fig. 6a) or ε_z and ε_y (fig. 6b) can be calculated together with associated angular strains - γ_{xy}, γ_{zx}, γ_{zy}. By building a set of plates with a given orientation and in different positions in the build chamber, a three dimensional concept and model of the distribution of dimensional deviations over the entire build envelope can be created - fig. 7.

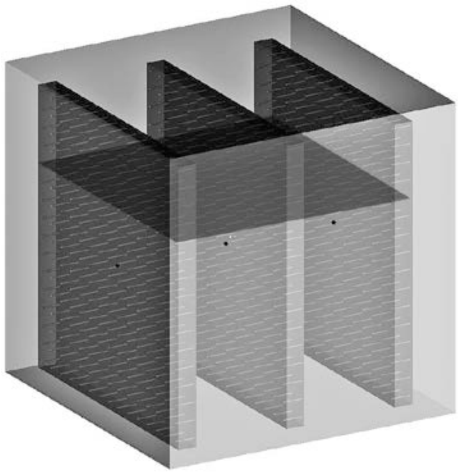


Fig. 7. *Set of test parts for 3D concept and model of the accuracy distribution.*

Accumulating a data from experimental set up similar to that shown on fig. 7 will allow interpolations of deformations from plates oriented in (z - y) to other directions by combining the points from different plates and forming virtual plates in perpendicular direction - the transverse surface on fig. 7.

4. Results and discussion

The experimental test plate was built by Selective Laser Sintering (SLS) process on DTM 2500 *Plus* machine according the settings on fig. 6a. The material used was polystyrene Castform. The hole centres was measured routinely by coordinate measuring machine (CMM) Mitutoyo QuickVision *Pro*. For that purpose a specialised software was developed that allows, together with Mitutoyo software, the total measurement to be done within minutes after the initial datum point and axis are set. The setting and the screenshot of the measuring software action are shown in fig. 8.

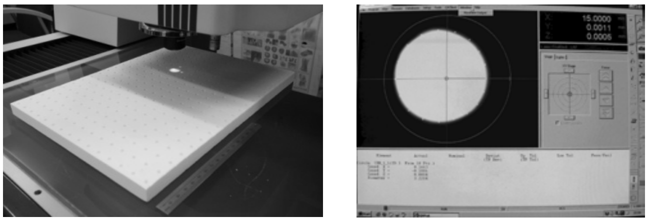


Fig. 8. *Plate measuring process and screen shot of software window.*

The accumulated data of x and y coordinates of grid points as holes is used as input data for linear and angular deviations from nominal calculations. For this purpose a VBA program for MS Excel spreadsheet was developed. The next step in data processing includes a MatLab program that was developed to analyse the results and to generate a 3D visualisation of the distributions of linear and shear deformations over the test part surface. The results are shown on fig. 9 and fig. 10.

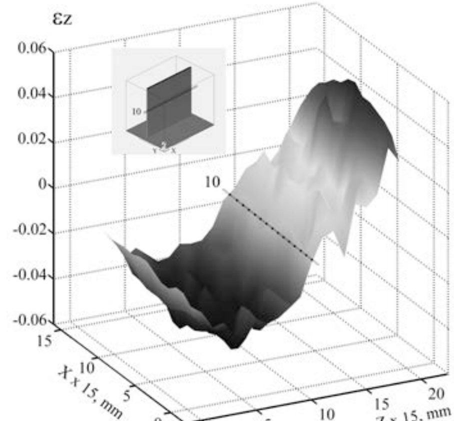


Fig. 9. *3D visualisation of ε_z (vertical size deviations from nominal) distribution in the (x, z) plane.*

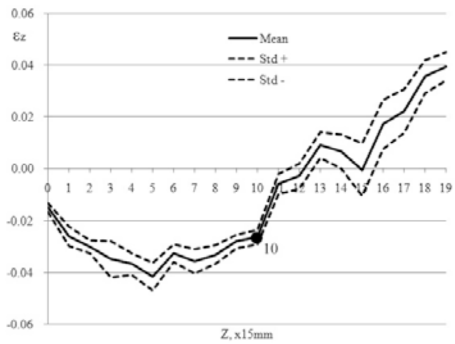


Fig. 10. *Distribution of ε_z -vertical deviation of the sizes from nominal.*

The mean value of all reference points along each row of the plate gives a point of the line shown on fig. 10. As an example the highlighted row “10” from fig. 9 gives the position of the point “10” on the fig. 10.

The results show that a single test piece and routine measurement procedure can be utilised to estimate the distribution of linear and angular deviations from the nominal sizes of AM parts. The geometry of the utilised test piece has advantages over the stair case (pyramid) type test pieces since it gives correct data about inaccuracy distribution along a particular direction or particular axes. The routine automatic measurements and data processing are possible due to the simple geometry of the samples and feasible software development.

5. Conclusion

Some estimates about accuracy of a process or platform can be done even with a single test piece. As it can be seen from fig. 9 and fig. 10 the described methodology can present the continuous distribution of distortions described in terms of linear and angular strains which can be interpreted as deviations from nominal in size and shape.

The data connection from several plates by interpolations is a step forward that can allow modelling of the entire build envelope, process or material accuracy. For that purpose a sufficient number of test plates over the entire build volume has to be produced and analysed.

The modelling of distribution of deviations from nominal, creates a possibility to reduce these deviations. One approach is a pre-deformation of the part data contrary to the expected defect. This can be implemented by using a free-form deformation (FFD) approach [17]. The FFD deforms the surrounding cuboid of an object in order to adapt the embedded object. Thus, an increased size and shape accuracy can be achieved by choosing suitable parameters for the FFD.

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