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AN INVESTIGATION FOR PROCESS CAPABILITY IN ADDITIVE MANUFACTURING

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ABSTRACT

This work presents an investigation for process capability in additive manufacturing (AM). Fused Filament Fabrication (FFF) is the additive manufacturing method, which is based for this verification. The typically layer-upon-layer building method in FFF has special effects to the geometrical quality and is important for comprehending the challenges in the additive manufacturing. But the continuously increasing of manufacturing quality in AM methods has enlarges the applying from rapid prototyping to rapid manufacturing or even to rapid tooling. The reliable applying of AM methods in these areas needs an evaluation and validation for process stability and is part of this paper. The necessary tolerance specification for purposing the process capability is common in mechanical engineering and is considered in results.

Index Terms - additive manufacturing, Fused Filament Fabrication, process capability

1. INTRODUCTION

The term of additive manufacturing (AM) was started with the idea for Stereolithography (STL) of Alain Le Méhauté, Olivier de Witte and Jean Claude André in 1984 [1]. Also the patent of Charles W. Hull "Apparatus for Production of Three-Dimensional Objects by Stereolithography" [2] has started a new age for manufacturing processes. He defined Stereolithography as a method for making solid material in ultrathin layers on top of the other and the solidification of the photopolymer is effected by ultraviolet light. Here is identifiable the difference to usual subtractive manufacturing methods, where material is removing in cutting-, drilling- and milling- processes to get a manufactured object. The indicator for additive manufacturing is the opposite, raw material is added. The template for an additive manufacturing process is a digital designed model in CAD. Additive manufacturing is a technology that builds objects by adding layer-upon-layer of material in 3-D. The material for layer process might be plastic, metal, food, cement or one day human tissue. These offers of material make additive manufacturing part in nearly every sector of industry. At the beginning of AM it was to be used for visualization of models in rapid prototyping processes. Now AM is being used to create customer products in aircraft, dental restorations, medical implants, automobiles and even fashion products. The development is increasing in almost every part of industry. Additive manufacturer means to create highly customized products for consumers and professionals alike. The aim is to involve AM for industrial tooling beside the classical manufacturing methods.
Manufacturing requirements are necessary for industrial tooling. A basic requirement is a stable manufacturing process with statistical controlled process results within tolerance and normally distributed attributes. The verification passes with helping of quality control charts and it is evaluated with statistical process control. The quality checks provide the evidence for the customer specifications.

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2. ADDITIVE MANUFACTURING

2.1 Methods in additive manufacturing

In general manufacturing methods are classified in subtractive and additive methods. The main groups are defined in DIN ISO 8580 and summarized in:

1. master forming
2. forming
3. cutting
4. assembling
5. coating
6. modify material property

Group 1 – 4 are changing the geometrical form of a workpiece and the last two groups have influence to the material property.
A categorization for additive manufacturing is difficult, but in literature it is mostly classified to master forming. AM is the opposite of subtractive manufacturing and how it named, material will be added. The layer-upon-layer building in additive manufacturing fabricates a solid 3-D object. The manufactured object is directly created after the 3-D modeling process in CAD. The complete workflow is shown in Figure 1.

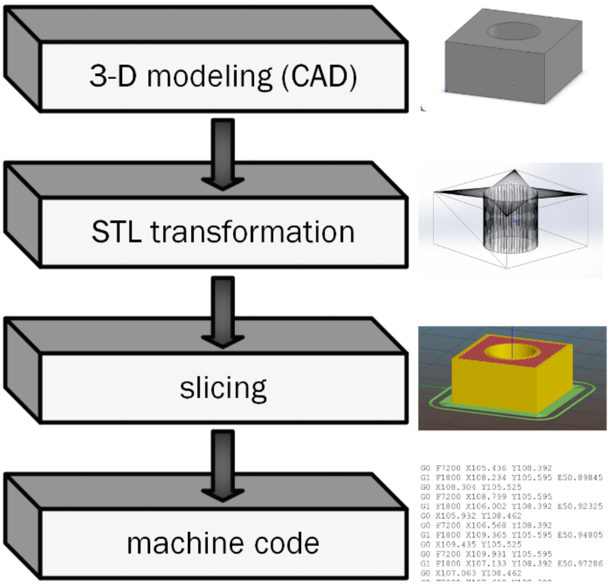

Figure 1: Workflow for additive manufacturing

Consequently a complex designed object structure is simple for manufacturing. The STL export has to follow after the completed modelling process in CAD. STL is a file format for describing the surface in tessellation of the designed object and is generally used in additive manufacturing. The slicing process is following and slices the object in horizontal layers. The result is a machine readable file, which contains all necessary commands for creating the object in additive manufacturing process. This workflow allows to manufacture object structures, which aren't possible to create with subtractive manufacturing [3].
The most popular additive manufacturing methods are Fused Filament Fabrication (FFF), Polyjet, Stereo Lithography Apparatus (SLA), Selective Laser Sintering (SLS) and Laser Metal Deposition (LMD). The name for this AM methods could be different in reason for brand names of manufacturing companies.

2.2 Layer building in Fused Filament Fabrication

Material in form of filament or granulate is melted in a nozzle and is coated the first layer on a building platform in Fused Filament Fabrication. After finishing of the first layer the platform moves in z-direction and increases the distance to nozzle. The shift in z-direction determines the next layer height. The material manufacturing temperature is short over the melting point and consequently the solidification starts quickly in cooling down period.

The manufactured object is forming layer by layer. The layer concept has many advantages, for example to build complex structures, but also a lots of disadvantages like the restriction of the extrusion width of the melted material. This process value limits the geometrical resolution of AM for thin structures. Furthermore the layer structure influence the quality of the surface. The layer thickness determine the characteristic of the aliasing effect, which is obviously visible on overhang or bevel structures (Figure 2). The reduction of layer height reduces the influence of step effect, but it isn't possible to halt the effect.

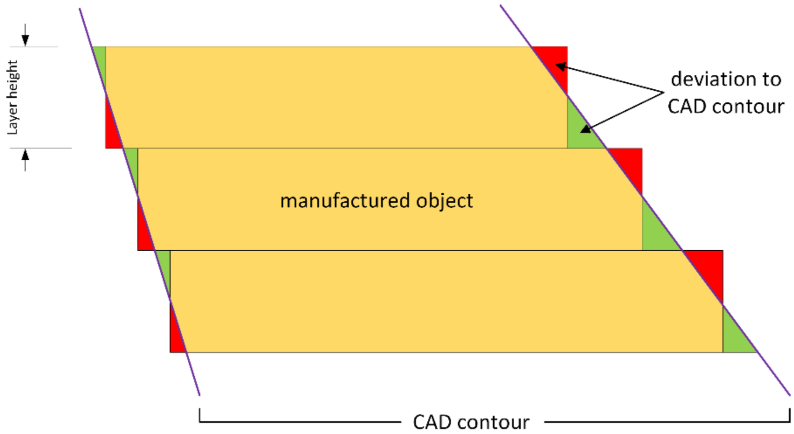

Figure 2: step effect in layer-upon-layer manufacturing

These attributes have influence for the geometrical manufacturing precision. The adjusting of these parameters is doing during the slicing process, which follows after the CAD modelling process. The slicing process gives the decision for high precision or a fast additive manufacturing process. Almost every parameter adjusting represents a compromise between accuracy and speed in the manufacturing process. The parameters for the additive manufacturing process are also dependent from the used melted material (Filament).

2.3 Additive manufacturing machine for experiments

This investigation provides a statistical analyses in form of a process capability for a Fused Filament Fabrication (FFF) process. The manufacture machine for processing analysis is a standard Ultimaker 2 extended+ (Figure 3). It is a midrange prized AM machine, which is well established in educational institutions, private houses or also used in companies for developing of prototyping parts. The transformation from CAD to machine readable files is doing by CURA, which is developed for the Ultimaker to execute the slicing process. The parameters of manufacturing can be adjusted and the user get a preview of the sliced object with informations about manufacturing time. Ultimaker ensure a manufacturing accuracy in x and y direction of 12.5 µm and in z-direction an accuracy of 5 µm. The used Filament for this investigation is polylactic acid or short named PLA. PLA is a synthetic polymer with suitable mechanical properties like a high surface hardness, high stiffness and tensile strength.

Furthermore the Ultimaker 2 extended+ can manufacture with different filament materials. The common materials are polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), but also co-polyester (CPE), thermoplastic polyurethane (TPU) and a lots of more differentiated materials.

Figure 3: Ultimaker 2 extended+

Material differences are in mechanical properties like surface hardness, stiffness and thermal effects. Material contraction in cooling down period has influence to geometrical attributes and is possible to consider in slicing process. PLA is chosen for the process capability, because it doesn't need a heated manufacturing space and the relative low melting temperature preserve the nozzle. Furthermore the PLA handling is safe and can be used for a broad range of objects.

3. PROCESS CAPABILITY IN ADDITIVE MANUFACTURING

3.1 Quality checks and tolerances

Quality checks should provide the proof for customer specifications. Therefor a complete economical and technical check of all material characteristics isn't necessary and reasonable [4]. The checks depend for the intended use and specific attributes of the product are limited in tolerances. The customer defines the specific attributes. The tolerances have to choose for the product function and the form elements. Standard tolerances can be choose for form elements to simple the variety. These standard tolerances are for length and angle values, but also for form and positioning values. They are defined in norm DIN ISO 2768-1 and DIN ISO 2768-2.

3.2 Pretests and capability of measurement equipment

For a correct process capability some pretest are necessary. For this purpose a designed test cube is created and additive manufactured with PLA. This cube is be used for researching the process capability for geometrical attributes and to define a tolerance category for DIN ISO 2768. In this case the medium tolerance category is chosen, which means for a cube with 30 mm edge length a tolerance of ±0.2 mm. Geometrical attributes in this case are the distance between the parallel surfaces of the cube.
Every measurement equipment has uncertainty and deviations in measurement results. A quality evaluation is only possible with a validation of the measurement equipment. Aim is to get a safe declaration for suitability of equipment. Potential methods are the GRR and the c_g/c_{gk} procedures [5]. The c_g/ c_{gk} procedure is used for this work, because the GRR method needs a number of manufactured parts, which isn't reasonable for the chosen additive manufacturing method in this work.
Furthermore the pretests are necessary to verify a convenient measuring equipment. Pretests have shown, the required geometrical tolerance after DIN ISO 2768 are achieving with a micrometer gauge.

The check is to perform with a suitable measurement equipment and the measurement resolution should be smaller than 10% in comparing to defined tolerances (1).

$$0.1 \geq \frac{uncertainty\ of\ measurement}{manufacturing\ tolerance} \qquad (1)$$

3.3 Process capability

The following main test is performed with another test object, which has a pyramid design (Figure 4). The pyramid has three levels, which consists of two six-corner-polygons and a cube at the top. The object design is chosen for an investigation of the manufacturing reproducibility in x- and y- direction in different z heights. Geometrical features are to investigate and should show some possible differences between the manufacture machine axes.

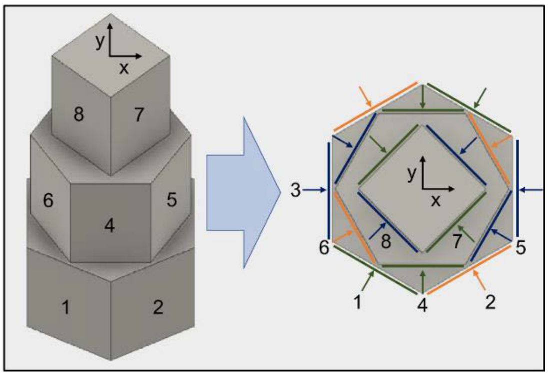

Figure 4: Pyramid object

The eight relevant pyramid surfaces have all a different angle to the y- direction and are showing deviations to the specific size. The pyramids are manufactured separately and successively for investigation of process control. The 16 surfaces are measured to the parallel counterpart and four measurement points are defined for each surface pair. In result 32 values are given for each pyramid and an iteration of this steps of 5 should reduce measurement failures. In summary 25 objects are manufactured and measured for process capability.
The chosen measurement equipment is the micrometer gauge CIM55059. The manufacturing settings are constant for all manufacturing parts and are listed below (Table 1):

Table 1: Parameter settings for manufacturing process

settings	Value
nozzle temperature	200 C
platform temperature	60 C
layer height	150 µm
retraction distance	0 mm
retraction speed	0 mm/s
cooling fan speed	100 %

For retraction speed and distance is chosen value 0, because the nozzle flow of melted PLA is low and has no influence for quality. At once manufacturing time can be reduce in this case.

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4. RESULTS

Generally the measurement analysis shows a shrinkage in all dimensions during the manufacturing process. Very few values are measured higher than the nominal value. Highest deviations are determined in first level of the pyramid and especially in surface 2 and 4 with a value of 0,263 mm and rather 0,256 mm. All manufactured objects presents this effect. Figure 5 shows the quality control chart of measurement point 4.2. A constant linear trend over all 25 objects is recognizable, but the value is lower than the lower limit value (LLV). A calibration should help for this problem.

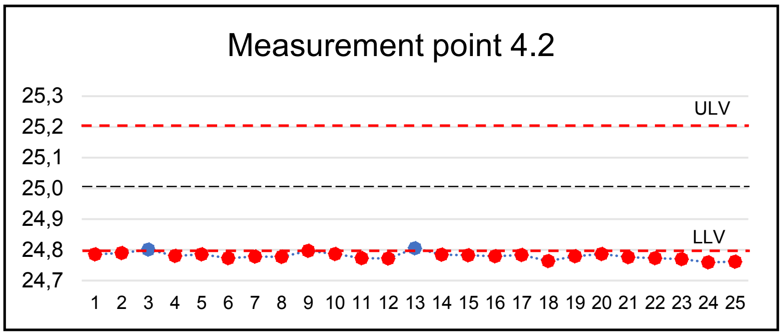

Figure 5: Quality control chart

This case lets interpret an unstable process in the first layers of manufacturing or rather the first three layers. The earlier pretests have shown the same effect of shrinking. The rest of measurement points are in tolerance and the third level of the pyramid shows fewest deviations in comparing to nominal values.
The results indicates a higher geometrical deviation with direction in y. Besides all manufactured objects are too small in dimensions, which is also reasonable in shrinking material after cooling.
For process capability a quantitation is necessary and the general calculation is the following:

$$c_p = \frac{ULV - LLV}{6 \times \sigma} \qquad (2)$$

The standard deviation σ is calculating with the separate values of measurement points:

$$\sigma \approx \hat{\sigma} = s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (3)$$

The process capability is in stable conditions if value $c_p > 1.33$. For a value between 1.0 and 1.3 the process is qualified, but the reasons for it has to research and an iteration of measurements is recommended. Two geometrical attributes have a value of 1.17 and 1.18. Otherwise the rest of the geometrical attributes have partly a process capability, which is also in limit of the smaller tolerance class.
In summary all geometrical deviations are in tolerances for DIN ISO 2768 in and the process capability is given for the Ultimaker 2 extended+.

5. CONCLUSION

The presented research provides proper results for the Ultimaker 2 extended+. The manufacturing process is stable and suitable for medium geometric requirements in DIN ISO 2768. A suitable measurement tool was selected and the ability was verified. Further investigations with higher requirements for DIN ISO 2768 and smaller geometric tolerances have also present proper results with limited capability.

The presented work provides a proof for additive manufacturing as industrial tooling. The manufactured results have adequate geometric precision for many cases in industry. Objects with only purpose for visualization the manufacturing accuracy are sufficient and objects with smaller structures and requirements for fitting are might also manufactured. The further development of mechanical parts, drive trains and slicer algorithm will increase the accuracy in FFF manufacturing process. Currently sold FFF manufacturing machines are more capable then the used Ultimaker 2 extended+ and in future the process capability will getting higher.

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