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Investigation on precision of laser powder bed fusion process using statistical process control

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Abstract

Laser Powder Bed Fusion (L-PBF) process is one of the cutting-edge technologies in the field of Additive Manufacturing (AM). L-PBF offers the advantage of manufacturing complex geometries in reduced time; however, its use for high precision applications and the achievement of good dimensional accuracy are still challenging. The aim of the current study is to investigate the precision of L-PBF process using Statistical Process Control (SPC) and assess the capability of the manufacturing process. A benchmark artefact was designed and fabricated by L-PBF process to evaluate the dimensional accuracy. The artefact consists of slender cylinders with variable internal diameters of 0.8 mm, 1 mm and 1.5 mm as a function of different wall thicknesses and inclinations of 90°, 60°, 45° and 0°. The material used for manufacturing the artefact was Inconel 718. Investigation on the impact of part positioning on the base plate and the impact of part orientation on dimensional accuracy were studied. To verify the process repeatability and part reproducibility using statistical process control, all the cylinders have been positioned in five different locations on the base plate. Impact of re-coater collision on the parts has been investigated by fabricating the parts with hard and soft re-coaters. The results presented in this work explain a design approach to fabricate slender parts successfully and the deviation in dimensional accuracy of cylinders from the actual design intent, involving the internal and external diameters of the cylinders, to verify the consistency of the process.

Keywords: Laser Powder Bed Fusion, Additive Manufacturing, Benchmark Artefact, Dimensional Accuracy, Inconel 718, Part Orientation, Statistical Process Control.

1. Introduction

Additive Manufacturing (AM) refers to several manufacturing methods with a range of materials that can be used. The conventional subtractive manufacturing methods cannot handle intricate designs with complex substructures to be manufactured [1]. In general, AM is defined as a manufacturing process where objects are made from 3D CAD model by joining materials, usually layer upon layer, as opposed to subtractive manufacturing technologies [2,3,4,10]. Laser powder bed fusion (L-PBF) process is one of the widely used additive manufacturing method for metals. As the name implies, the metal powder bed is irradiated layer-by-layer by a laser source. The continuous interaction between the metal powder and the laser causes the powder material to melt and the next layer of metal powder is applied, and the process is repeated till the part id built [5].

Over the years, there have been rapid developments in the additive manufacturing process leading to the evolution of several fabrication methods based on various working principles, using a wide range of materials. Therefore, assessment on capabilities and limitations of these methods is important [6].

This paper focuses on investigating the precision of L-PBF process by designing and fabricating a geometry specific benchmark artefact and hence assessing the capability of the manufacturing process itself.

The results discussed in this paper are related to a combination of printing parameters chosen for this artefact and not used for other purpose. Such parameters have not been optimized to improve the process capability itself and are different from the ones used for BHGE parts. The parts produced were measured using suitable measurement techniques and the same quantities were measured more than once by different techniques to minimise the repeatability errors. Furthermore, statistical process control method was used to quantify the manufacturing process (L-PBF) capability using control limits and thereby propose a suitable approach to evaluate the quality of parts based on the dimensional accuracy

2. Methodology

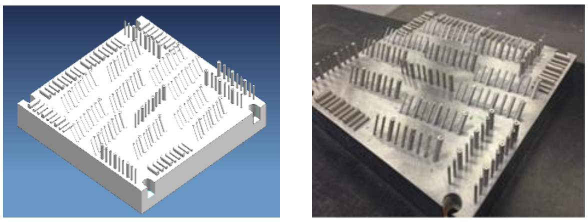
2.1. Design of benchmark artefact

A novel benchmark artefact was designed to be manufactured by L-PBF process. The artefact was designed to investigate the precision and capability to fabricate holes with and without axis inclined as a function of varying wall thickness. Different wall thicknesses were assigned around the hole to investigate on the impact of wall thickness on hole diameter accuracy.

Table 1 represents the design guidelines and dimensions of the benchmark artefact.

Table 1 Design guidelines for benchmark artefact

Hole Diameter (mm)	Wall thickness (mm)	Inclination Angle (°)	Feature Repetition	Height (mm)
0.8	0.8 / 1 / 2	90/60/45/0	5	19.2
1	0.8 / 1 / 2			
1.5	0.8 / 1 / 2			



(1a) (1b)

Figure 1. Benchmark Artefact (a) CAD Design (b) Fabricated part

From Figures 1(a) and 1(b), it can be seen that the artefact consists of slender cylinders that are positioned around the building platforms at different locations. The cylinders are designed with holes based on the dimensions provided in Table 1 as function of varying wall thickness and inclination angle. The parts are aligned tilted rather than being positioned in a straight line. This rule was applied to avoid part failure during manufacturing due to mechanical impact of the re-coater [7]. Every cylinder has been positioned at 5 different locations on the building platform, to investigate the process repeatability, to manufacture the geometry with specified dimension. As suggested in [4], bores and holes are essential design features. Therefore, it is important that geometrical features such as holes should be incorporated in the part design while assessing the process capability.

2.2. Metrological Inspection

The external and internal (hole) diameters were measured as a first step. In this paper the results obtained from measuring hole with 1 mm hole diameter with different wall thickness and inclinations will be discussed.

The external diameter of the cylindrical features was measured using Zeiss ConturaG2 Coordinate Measuring Machine (CMM) and Zeiss COMET 6 8 MPixel fringe projection system, while the hole diameters were verified using calibrated gauge pins. In figure 2, the deviations of the measured external diameter have been plotted against the nominal dimension. For confidentiality reasons, the results have been scaled and does not represent any ratios and dimensional units. A set of nine cylinders (comprising of all hole diameters with different wall thickness) for every inclination angle from a particular position on the building platform was chosen and the analysis was performed.

The nominal external diameters of the chosen cylinders of all inclinations are the same. From the graph, it can be inferred that the magnitude of deviation of the measured values against the nominal are quite the same for all the parts, irrespective of the inclinations when measured with CMM and fringe projection system. On the other hand, the deviation from nominal is larger for inclined features (60° and 45°) when compared to the uninclined (90°) and features that are horizontally attached (0°) to the building plat form. For the inclined features, the geometry at the down-facing surface will be impacted due to dross formation resulting to larger from actual geometry [5]. The huge deviations can be verified further, by investigating the form of the fabricated part. The measured data is provided as a feedback to the designers and manufacturers that will help in understanding the manufacturing process capabilities and their impacts on the final part [8,9].

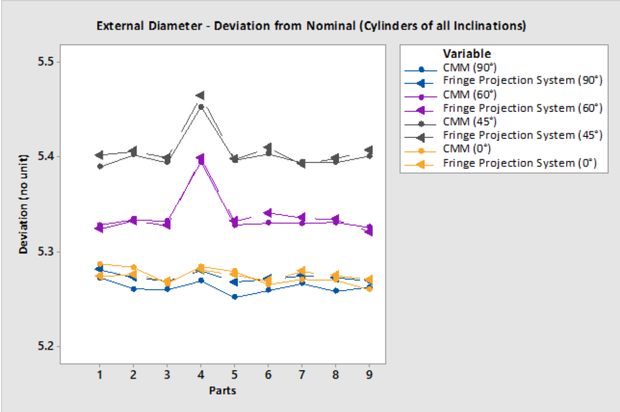


Figure 2. Deviation of measured external diameter from nominal

2.3. Application of Statistical Methods

To investigate the precision and accuracy of the process to manufacture holes, Statistical Process Control approach was chosen. Process capability index was used to quantify the precision and accuracy of the manufacturing process. The hole diameters were divided in 3 subgroups based on the wall thickness.

Table 2 Subgroup classification for hole diameters

Subgroup number	Wall thickness (mm)	Hole diameter (mm)
1	0.8	1
2	1	
3	2	

Table 2 represents the subgroup classification of the parts based on the wall thickness around the hole. The hole diameters of all the parts were measured twice by two different operators to avoid knowledge bias and repeatability issues. Process capability analysis was performed for all the parts with nominal hole diameter of 1 mm with different degrees of inclinations, to investigate the hole diameter accuracy with varying wall thickness and inclination angles.

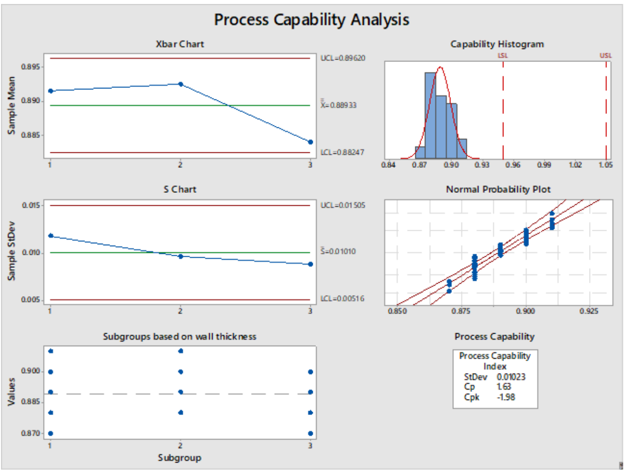


Figure 3. Process Capability Analysis for 90° cylinder: $Ø_{hole}$ = 1 mm

Figure 3 illustrates the results obtained from the process capability analysis to manufacture holes with nominal diameter of 1 mm without the hole axis being inclined (90°). From the process capability plot, it can be inferred that the manufacturing process is not accurate and is offset from Upper and Lower Specification Limits (USL, LSL). In this case, the process capability index (Cp_k) must be chosen to quantify the process capability. This is because Cp index is used when the process is well within the specified control limits. However, obtaining a positive Cp value greater than 1 for a process lacking accuracy refers that the precision (repeatability to manufacture) of the process is good. Furthermore, it can be noticed that there are no impacts on hole diameter accuracy with respect to the wall thickness.

Figures 4 and 5 illustrate the process capability analysis performed with the same subgrouping methodology for hole with a nominal diameter of 1 mm but with the axis of the hole inclined to 60° and 45° from the vertical.

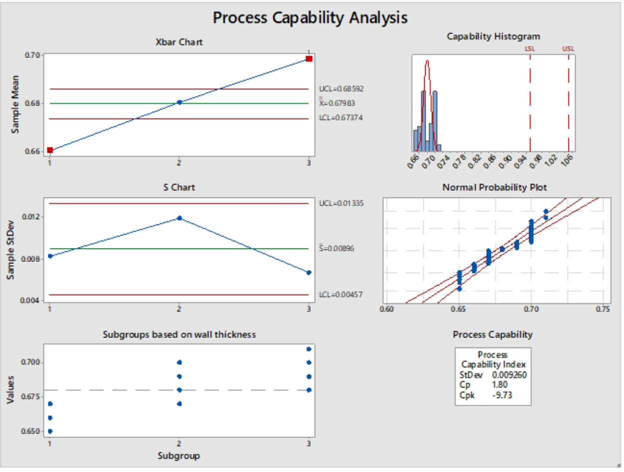


Figure 4. Process Capability Analysis for 60° cylinder: $Ø_{hole}$ = 1 mm

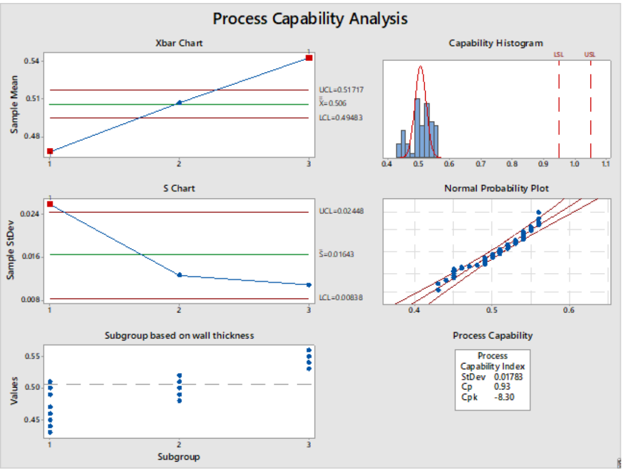


Figure 5. Process Capability Analysis for 45° cylinder: $Ø_{hole}$ = 1 mm

The accuracy of the process to manufacture holes with inclined axis is further decreased. From figures 4 and 5, the hole diameter accuracy is decreasing when the angle of inclination is increased. Furthermore, the accuracy of the hole diameter increases with increase in the wall thickness. As suggested in [5], the stair-case effects on the up facing surface and dross formation on the down-facing surface on the internal sections of the hole has a greater impact in measuring the hole.

In terms of process capability, from the process capability index, the process is lacking precision and accuracy. This is because of the variation in the measured values with respect to the wall thickness. Since the same subgrouping methodology was used, the variations due to wall thickness reflects on the process capability with lesser precision and accuracy.

Further process capability analysis was performed to evaluate the precision of holes that were fabricated in cylindrical parts that were attached horizontally to the base plate (0°). From the capability plot and histogram of figure 6, we can see a widespread distribution in the process capability.

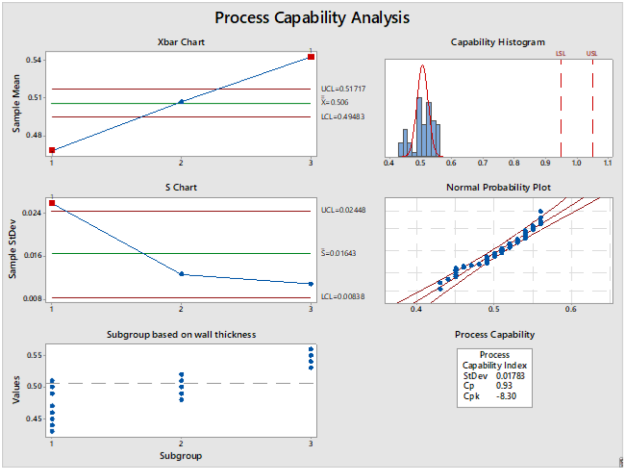


Figure 6. Process Capability Analysis for 0° cylinder: $Ø_{hole}$ = 1 mm

This trend is observed because some of the holes in these parts were completely blocked and were unmeasurable at a particular position. Since the measured diameter values were different for same dimensioned parts at different positions of the build platform irrespective of the wall thickness, the positioning of the parts on the build platform had an impact on the hole diameter accuracy. The process capability analysis also indicates that the measured data is unstable and failed the normality test due to defects on some parts.

3. Results and Discussions

The results that are discussed in the paper are related to the process parameters that the author designed for this research, and do not reflect the actual BHGE AM capability. For confidentiality reasons the company did not disclose the actual manufacturing capability and process parameters.

The results from the process capability analysis indicates that the capability to manufacture holes with axis uninclined is better than manufacturing holes with inclined axis. This is due to the absence of stair-case effects and dross formations on the internal surfaces. However, the manufacturing process lacks accuracy, irrespective of the angle of inclination.

On further investigation, it can be noticed that the method of subgrouping the parts with an inclination angle of 60° and 45° based on wall thickness, does not hold good to evaluate the process capability index. This method may lead to under or overestimating the actual manufacturing process. Therefore, the process capability index must be evaluated individually for every wall thickness.

In addition, unfavourable manufacturing orientation for L-PBF process is found from the results of the parts that were horizontally attached (0°) to the build platform. Manufacturing parts with this orientation will not only have poor dimensional accuracy but also poorer surface texture. This is because the first layer of the metal powder is loose, and the laser must irradiate larger area and therefore there is a high possibility of melt pool spattering [4].

There is a firm possibility that there could be a deformation on the shape of the hole, when it is measured more than once using calibrated gauge pins. The form of the hole not only on the top surface but also internally can be deformed and therefore should be investigated further.

Based on the overall analysis, it can be concluded that the manufacturing process corresponding to the set of assigned AM process parameter lack accuracy while the precision to print the parts is consistent.

4. Future Work

Further investigation will be performed to investigate the internal sections of the holes to detect the form and surface. Additional studies will be carried out to understand the impact of part positioning on the build platform related to the surface morphology and geometrical deformations. The geometrical form of the parts will be evaluated to develop compensation modelling methods to reduce geometrical deformations based on the feedback from metrological inspections.

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