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Planning for Metal Additive Manufacturing

Mariana Dotcheva[a],*, Julie Favrot[b], Krassimir Dotchev[a], Jurgita Zekonyte[a]

[a]*University of Portsmouth, School of Mechanical and Design Engineering, Anglesea Building, Anglesea Road, Portsmouth PO1 3DJ, United Kingdom*
[b]*The École nationale d'ingénieurs de Saint-Étienne, 58 Rue Jean Parot, 42100 Saint-Étienne, France*

* Corresponding author. Tel.: +44 (0)23 9284 2361. *E-mail address:* Mariana.Dotcheva@port.ac.uk

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Abstract

The implementation of Additive Manufacturing (AM) technologies simplifies the process planning and manufacturing of parts with intricate geometry. This is because the AM can directly fabricate a part with complex geometry using variety of materials with required mechanical properties such as strength, hardness, and certain behaviour under load. The advantages of AM become apparent in many industrial applications not only for prototyping purposes, but also for making end-use products. Therefore, the necessity to plan the design and manufacturing process chain is now vital for making AM a reliable and efficient technology that can achieve the required part quality. This paper presents research on quality assessment of parts fabricated via Selective Laser Melting (SLM) as a starting phase of new process-planning model. SLM samples were manufactured, several methods for quality assessment applied, and the outcomes evaluated. The results are used in the "design for SLM" and inform the whole process planning methodology when SLM is considered for production. In addition, they will be further employed in predictive modelling and design optimisation of precision parts made via metal AM.

Keywords: Selective Laser Melting; Additive Manufacturing; Process Planning; Part Quality; Design for 3D printing.

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1. Introduction

The application of Additive Manufacturing (AM) technologies (aka 3D printing) lead to simplification of the process planning and manufacturing of intricate parts, which possess the final geometrical forms with accurate dimensions, and required mechanical properties such as strength, hardness, and certain behaviour under load. As this technology becomes more popular among many industries and the number of applications increases, the need of planning the design and manufacturing process chain for a specific AM technology becomes vital for making the AM more reliable and efficient in making parts of good quality.

Selective Laser Melting (SLM) is a metal powder based layer manufacturing or an AM process that makes metal parts. The implementation of SLM (or metal AM) opens up new product solutions and provides new opportunities for many industries. Thus, in the last years, the use of metal AM, as a standard manufacturing strategy for production of end-use parts, has become a major challenge attracting a lot of research. In many applications, the ultimate aim is manufacturing of high precision metal parts. However, the quality of the components fabricated by SLM process is still not good enough for direct use. Poor surface integrity, marks from removed support structures, partially sintered powder to overhanging surfaces, staircase effect on inclined features are some of the reasons why additional machining needs to be involved. The metal printed parts require post-processing and further finishing of all functional surfaces. Therefore, a careful planning of the whole process chain, from the design phase to the final product, and considering all implications should be implemented.

Employing metal AM as a main production method requires close integration of the design and manufacturing planning processes. This requires in-depth understanding of the specific AM process and expected quality of fabricated parts. A process is considered successful if the required productivity and accuracy are achieved.

To achieve these goals the assessment of the of part quality

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including dimensional accuracy, surface quality, density, tolerance analysis and finishing process optimisation will be essential.

In this paper an approach for qualitative and quantitative analysis of parts produced by SLM (metal AM) process, as an essential phase of planning for SLM manufacturing, is presented. The emphasis is on the importance of creating efficient process planning for the designed component. The paper considers the SLM process, however the proposed approach is general and can be applied to any metal AM machine.

2. Literature review

As metal AM becomes more popular, there are a number of studies reporting work on design, process planning and manufacture of precision parts. Some research works [1, 2, and 3] propose an integration of some manufacturing technologies and inspection processes in a single hybrid system. In the centre of this system is a metal AM technology, which produces near-net-shape parts. The next process stage finishes the part to the required accuracy employing subtractive manufacturing methods and quality inspection. This approach eliminates the need of setting the part on different machines. It starts with a prefabricated or existing work piece, which saves time. The use of the same set-up for manufacturing and inspection processes also eliminates some errors. However, such approach is only applicable when metal deposition methods are used and does require new hybrid machines to be developed.

Another method to achieve better geometric tolerances is to optimise the part orientation, as it has been introduced in [4], and find a compromise between the support structure volume and geometric accuracy. In many cases the support structure is considered as unwanted or even negative addition to the original part because it requires additional time to build and to post-process and remove after the build. However, in many cases it can improve part accuracy.

One important aspect of AM, that needs to be taken into account in the process planning, is the staircase effect [5, 6]. Research has been done on modifying the original CAD model, optimising build orientation, and implementing variable slicing algorithms in order to reduce its impact of surface finish and accuracy.

For the purpose of the research presented in this paper the part's aesthetics and the staircase effect on non-functional surfaces are neglected. The surface roughness is considered only after post-processing and the staircase effect is be taken into account when the minimum cutting allowance for finishing is estimated.

There are several works on process planning for AM and some authors consider different aspects of it starting from the CAD model [8], slicing [5], the AM process parameters optimisation, hatching strategies [7], and post-processing.

The research of the published papers shows that there is a gap in the field of study, i.e. on process planning for AM especially how to approach the part's finishing phase. A new, complex approach is needed that should consider carefully the design requirements, specifics of the AM, and plan the finishing and inspection processes in order to achieve the required quality. This new process planning will lead to modifications of the part model. None of the reviewed papers looks at the designed part in the context of a complete manufacturing planning.

3. Process planning model

Planning for AM is a multifaceted process. A detailed diagram of the proposed process-planning model for metal AM is shown in Fig.1. The main activities, their association within the model, and the workflow are also presented. The model has three main areas:

- In the first area of activities, the 3D model has been already modified (corrected) for printing and finishing.
- The second area represents the quality assessment and inspection activities proposed for the metal AM.
- The third area is planning of necessary finishing processes.

The process starts with the 3D CAD model preparation for 3D printing (see Fig.1, area 1). It consists of the main design geometry that is modified to accommodate the following factors: material allowances for finishing, modifications required by the build (3D printing) orientation, SLM (or other metal AM) specific rules influence, machine capability influence (i.e. shrinkage, distortions across the building envelope, etc.), and SLM (3D printing) parameters influence.

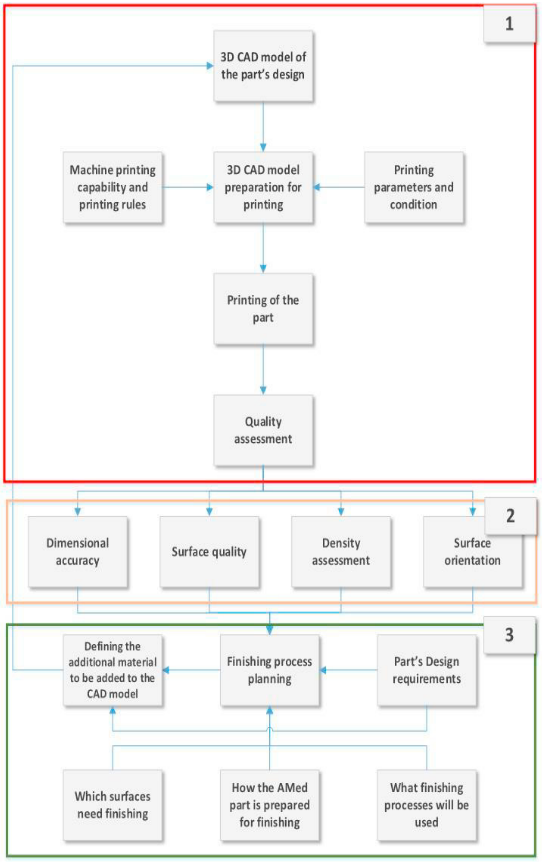

Fig. 1. Process-planning model for metal AM.

The first area of the diagram in Fig.1 represents the traditional approach of AM parts fabrication that is still used in many industries. Sometimes the parts quality of more demanding applications are not adequate to the design requirements. It is because of impossibility to predict in advance, or even theoretically estimate, the exact influence of each of the above listed factors on the part quality, and subsequently apply corrections to the model geometry. Therefore, test parts or the actual parts, whichever is more efficient, need to be printed, their properties measured (see Fig.1, area 2), the quality analysed, and corrections applied back to the 3D model (see Fig.1, area 3).

The finishing of functional surfaces is a part of the overall process planning in Fig.1, area 3. It is influenced by the level of success and inputs of all previous activities. The current practical approach is to add generous allowances of material to the surfaces that are supposed to be finished by material removal operations in order to cover for all expected and unexpected imperfections. This method generally works, but it is resource consuming and often cancels out the advantages of AM. Increasing the size of the CAD model, by adding allowances, means that more material (expensive metal powder in SLM), energy, and time will be consumed in the AM process ultimately leading to extra cost. In addition, the printed extra material should be machined, to achieve the expected geometry and quality, which adds to the expenditure.

The idea of this research is to plan and make the processes more efficient without sacrificing the design requirements. The first phase is to establish the quality of the 3D printed parts (see Fig.1, area 2). Qualitative and quantitative analyses are applied to outline the main activities (see Fig.1, area 3). These activities provide additional inputs (to the usual design rules) for a specific AM process.

The results from the inspection should be used in the activities from the third area for planning the required finishing operations and their influence on the CAD model.

The main aim of this research in a long-term is to develop an expert platform for design and manufacturing of precision components using the SLM technology as a main shape-forming process. This platform should deliver:

- Resource-efficient finishing process plan for precision parts by influencing the 3D CAD modelling process and/or modifying the conventionally designed parts;
- Development of a more complex process planning system utilizing the best-fit SLM with optimised process parameters and achieving the desires part quality, reliability, and repeatability.

This paper presents and evaluates the results from 3D printing of test parts using ProX300® SLM machine. The objective is to establish what are the main considerations required in the context of the main research aim – process planning for manufacturing of precision metal components.

4. Experimental setting

A commercial ProX300® SLM machine made by 3D Systems Corp. and loaded with nitrogen gas atomized 17-4 PH Stainless steel pre-alloyed powder, with a nominal 80% particle size of < 50 µm, were used for specimen fabrication.

The composition of the metal powder is given in Table 1.

The specimens were fabricated in a nitrogen (N_2) gas backfilled build chamber.

The SLM process parameters used in sample fabrication are: Laser power: ~ 0.11 kW; Scanning speed: ~ 1200 mm/s; Back-and-forth scan strategy; Nominal scan spacing: ~ 50 µm, and Melt layer thickness of ~ 40 µm, as recommended by 3DSystems®.

This type of metal powder (aka Laser Form® 17-4PH) is widely used in aerospace, petrochemical and chemical applications because of its corrosion resistance and good mechanical properties.

Table 1. 17-4 PH Stainless steel powder characterisation.

Element	Chromium Cr	Nickel Ni	Copper Cu	Silicon Si	Manganese Mn	Niobium (Nb)
Weight, %	15-17.5	3-5	3-5	<1	<1	0.15-0.45

Several samples of 10 mm solid cubes and 10 mm cubes with internal lattice structure, shown in Figures 2 and 3, were 3D printed and inspected. The model of the sample with internal lattice structure has been designed using the software Creo® Parametric 4.0. A sectional view of this model is shown in Fig. 3. The lattice type is a cubic body centered lattice with beams and balls at the nodes. The horizontal beams have been removed to avoid generation of the SLM support structure.

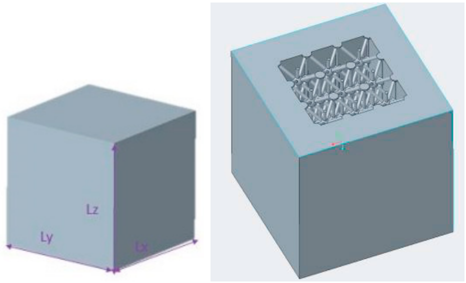

Fig. 2. Experimental samples: solid (left) and with lattice (right).

No geometrical corrections have been applied to the sample models during the preparation phase in order to estimate all deviations from the nominal after the printing.

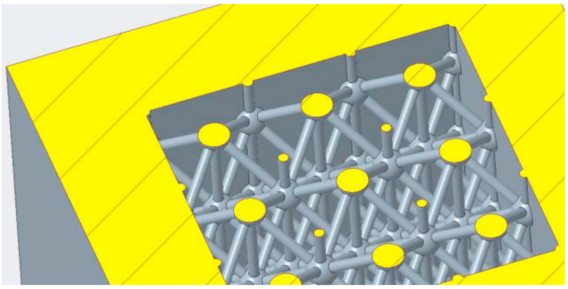

Fig. 3. A section of the 3D CAD model showing the internal lattice structure.

4.1. Sample inspection

A number of inspection methods have been selected to measure accurately the size, shape, porosity, and surface roughness in order to create a better picture and understanding of the printed samples quality.

The dimensions in X, Y, and Z directions of all samples after the build have been measured using Mitutoyo CRYSTA - Apex S 776 Coordinate Measuring Machine (CMM), with a resolution of 0.0001mm.

The samples with lattice structure have been scanned using Xradia 520 Versa (Carl Zeiss) X-Ray Microscope and compared with the nominal 3D CAD model geometry. After the scanned part data and 3D CAD model have been superposed, a comparison analysis was performed based on the Hausdorff distance. The best-fit option has been used for alignment of the scanned data with the 3D CAD model and the results of one sample are shown in Fig. 4.

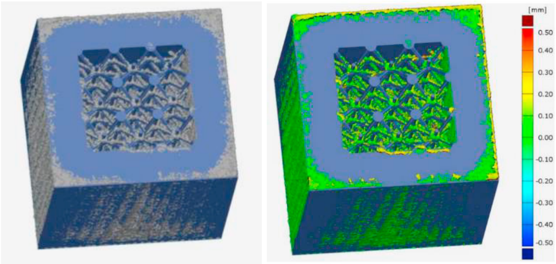

Fig. 4. Comparison of a scanned sample with the 3D solid model.

The real printed surfaces are grey colour and the 3D CAD model is dark blue colour (left image in Fig.4). In many regions, the samples' surfaces are below the nominal (3D CAD surface). A quantitative estimate of the printed surface shape deviation from the nominal is given in Fig. 4, the right image. It should be noted that the samples with different locations in the building envelope exhibit different shape distortion. These results highlight the fact that investigation of the placement and orientation of the printed surfaces is needed if the finishing allowance is going to be optimised.

A deeper analysis shows that not only the surface regions deviate from their nominal in a non-uniform manner, but also within one region, there are small spots either over or under the nominal position (Fig. 5).

The over positioned spots can be removed with the finishing operation. As long as their deviation is not significantly above the finishing cutting allowance, they will not compromise the finishing operation. The spots below the nominal indicate that it will affect the quality of the finished surface if the cutting allowance is insufficient (Fig. 5). Quantitative and qualitative assessments of the printed parts needs to be linked with the design requirements. To reduce the influence of the printed surface imperfections enough additional material should be added on the precision part's features. In the example shown in Fig. 5 the range of the imperfections is -0.50 ÷ 0.25 mm.

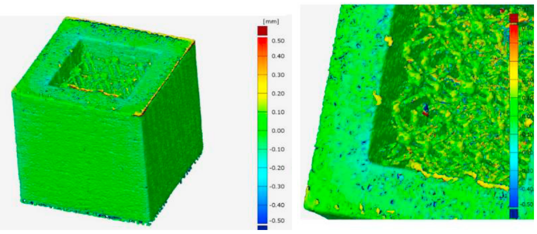

Fig. 5. Comparison of a scanned sample with the 3D solid model.

All nine 10 mm solid cubes and the two 10 mm cubes with internal lattice structures were inspected. The overall dimensions of samples were measured on the printing substrate (plate) before and after their removal from it. The results from these measurements are presented in Table 2. When the samples are separated from the substrate (plate), their dimensions are marginally smaller due to the residual stress and additional shrinkage. The deviations (off the plate measurements) from the nominal were calculated and compared to the IT tolerance grading system [13] in order to compile the process dimensional capability. Therefore the calculated accuracy for ProX300 SLM system for small parts is in X direction: the standard deviation is 0.032 mm; 95% accuracy - +/-0.060 mm, and in Y direction: the standard deviation is 0.045 mm; 95% accuracy - +/-0.080 mm.

Table 2. Measured dimensions of the solid cubes.

Sample		Lx, mm	Ly, mm
1	On plate	9.972	9.964
	Off plate	9.953	9.955
2	On plate	9.961	9.970
	Off plate	9.963	9.963
3	On plate	10.061	10.102
	Off plate	10.054	10.091
4	On plate	9.965	9.980
	Off plate	9.954	9.973
5	On plate	9.962	9.950
	Off plate	9.957	9.948
6	On plate	9.963	9.974
	Off plate	9.955	9.960
7	On plate	9.964	10.005
	Off plate	9.956	9.990
8	On plate	9.958	9.972
	Off plate	9.957	9.960
9	On plate	9.972	9.965
	Off plate	9.961	9.946

These results fall within the IT9-IT10 tolerance grade. For larger parts, the dimensional accuracy is +/- 0.2% of the nominal.

One solid cube and a cube with lattice centre were compared. The dimensions at three levels, top level (a), middle (b), and bottom (c), were measured on all four vertical sides of the cubes as illustrated in Fig. 6.

The results from all measurement presented in Table 3 show that the dimensions are lower than the nominal. All samples have shrunken except the one in the centre of the substrate. The solid samples demonstrate slightly lower shrinkage than the one with the lattice structure. However, in all cases the standard deviations are similar from 0.016 mm to 0.020 mm indicating a good consistency. As the metal AM is a perfect technology

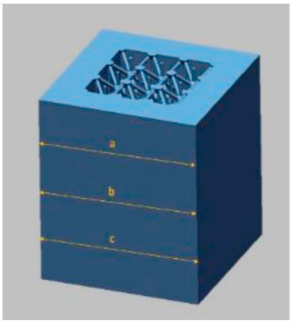

Fig. 6. Comparison of a scanned sample with the 3D solid model.

for building hollow parts or parts filled with cellular structures, the accuracy results demonstrate the need for further in depth investigation of such components.

Table 3: Measured dimensions of the samples at three vertical levels.

Sample	Level a: top (mm)	Level b: middle (mm)	Level c: bottom (mm)
Lattice cube: side 1	9.938	9.938	9.940
Lattice cube: side 2	9.907	9.894	9.907
Lattice cube: side 3	9.940	9.944	9.946
Lattice cube: side 4	9.927	9.928	9.931
Solid cube: side 1	9.946	9.956	9.951
Solid cube: side 2	9.950	9.958	9.946
Solid cube: side 3	9.932	9.939	9.937
Solid cube: side 4	9.961	9.923	9.925

The consistency of the calculated deviations indicates that it is possible to compensate them by appropriate scaling of the model and offsetting the surfaces finishing in the positive direction of adding material. These experiments provide data for applying a systematic compensation to the model during the planning phase. The compensation should be at least in the region of the accuracy capability of the metal AM machine, i.e. within the IT9-IT10 tolerance grade positive direction in order to cover the cases with negative deviations.

4.2. Porosity

Porosity refers to the level of solidity achieved in a metal printed part. This is an important characteristic of any part manufactured by a specific AM process, machine, and material - in this case ProX300® SLM with Stainless steel metal powder.

Some studies demonstrated that the quantity and size of the pores affect part mechanical properties such as structural strength, elongation to rupture, and fatigue resistance [9]. In addition, the pores create higher stress concentrations under load. The SLM process parameters such as the Laser power, Scanning speed, Layer thickness, and other have direct impact on the part porosity, in particular pore dimensions and morphology. The SLM process parameters need to be optimised not only for a machine and a material, but also for every part to avoid pores due to lack of sufficient melting [10, 11].

All samples have been inspected and their overall porosity estimated by using X-ray Computer Tomography (CT) with Xradia 520 Versa from Carl Zeiss.

The porosity of the nine solid samples (cubes) and their position on the machine substrate are shown in Fig. 7. These results demonstrate that the porosity varies insignificantly from 1% to 1.5%. Similar were the results for the samples with lattice structure.

Two horizontal sections from the reconstructed X-ray CT data of a sample with cellular centre and a solid sample are illustrated in Fig. 8 (left) and Fig. 8 (right). The sample 3D models were built using image segmentation of the X-ray computed tomography data in order to create black-and-white picture of the sections and the whole part. The white colour represents a solid area and the black colour shows the areas with voids (Fig. 8). Visually, the distribution of the voids is random and not clustered in specific regions. Therefore, the porosity is uniform in both cases of solid samples and samples with internal lattice. In addition, this is valid for the regions close to the outer surfaces.

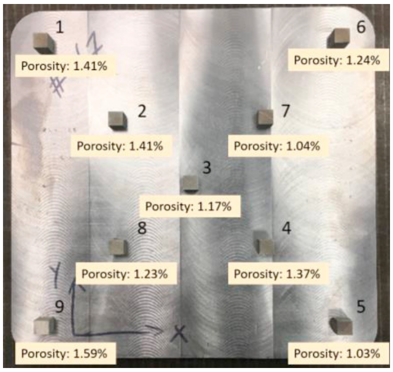

Fig. 7. Position of the samples on the substrate and their porosity.

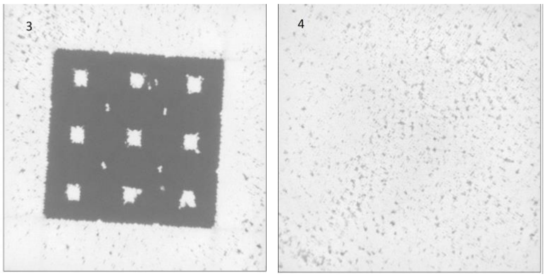

Fig. 8. Distribution of voids in a sample with lattice (left) and solid sample (right).

Another observation from Fig. 8 is that the porosity in both pictures looks excessive compared to the estimated values of 1-1.5% given in Fig. 7. This impression is due to the given threshold value or resolution in the construction of the 3D image out of the CT data. Hence, in the generation of the porosity distribution pictures, even the very small size of pores are visualised.

Although the internal porosity is important for the part mechanical properties, it could be ignored as not relevant for the quality of the functional surfaces. Due to the voids random distribution it is unlikely that it will influence directly the dimensional accuracy and therefore the cutting allowance for finishing.

4.3. Surface roughness

Surface roughness is a part quality characteristic that questions the use of AM processes. Generally, the surface quality of the as-build parts is not acceptable for direct use in precision components. This is an inherent problem in all AM technologies and the best solution is to plan the finishing operations in order to improve the geometrical accuracy and surface roughness.

A simple experiment has been conducted in order to estimate what is the minimum allowance (extra material) that could be finished to achieve better surface roughness.

A prismatic part with dimensions 25 mm x 25 mm x 3 mm has been printed vertically with its wider side along the Z-axis of the machine. The initial visual inspection quality of the surfaces visually inspected. After the removal from the build substrate, the part vertical surface has been divided into four zones as shown in Fig. 9. The initial surface roughness in each zone has been measured in two directions: horizontal and vertical. The four areas were ground at progressively increasing depths of cut to determine the minimum stock that needs to be removed. In the end, the sample has been hand polished with a sandpaper grit from 800 to 24000 and given a final finishing with metal polishing compound.

The surface roughness in the four zones has been measured using the Mitutoyo SV-3200 Surface Roughness Tester. The results are provided in Table 4 below.

Table 4: Surface roughness in horizontal and vertical directions.

Zone	Horizontal direction, Ra(µm)	Vertical direction, Ra(µm)	Thickness, mm	Process
1	9.76	9.66	3.050	As build
2	9.52	9.86	3.055	
3	9.82	10.20	3.075	
4	9.90	9.59	3.065	
Average	9.75	9.83	3.061	
1	1.49	2.07	3.010	First hand polishing
2	1.59	2.06	3.010	
3	2.96	2.54	3.015	
4	1.66	1.27	3.020	
Average	1.93	1.99	3.014	
1	0.26	0.47	2.995	Second hand polishing
2	0.39	1.79	3.000	
3	1.05	0.25	3.000	
4	0.26	0.40	3.010	
Average	0.49	0.73	3.001	
1	0.05	0.05	2.980	Third hand polishing
2	0.06	0.06	2.955	
3	0.08	0.09	2.980	
4	0.06	0.06	2.970	
Average	0.06	0.06	2.971	
1	0.04	0.04	2.950	Compound polishing
2	0.05	0.04	2.950	
3	0.04	0.04	2.960	
4	0.04	0.04	2.960	
Average	0.04	0.04	2.955	

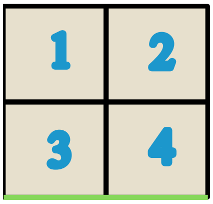

Fig. 9. The four zones of finishing and surface roughness measurement.

These experiments demonstrate that by removing an average of 0.05 mm of material, the surface roughness could be reduced (improved) five times from Ra 9.75 µm to Ra 1.93 µm. When the polishing process continues and the total removed material is down to 0.1 mm the surface roughness can be improved more significantly to Ra 0.04 µm.

The distance between the highest peak and lowest valley has been measured on every vertical side of an unfinished sample. The profile measurements were taken on each side along three lines, one in the middle of the surface and the other two closer to the edges of the side, in vertical Z direction normal to the printed layers. Two additional profile measurements were taken at the top sample surface. The sampling length is according to BS ISO 4288:1996 [12]. The maximum distance between the highest peak and lowest valley on each side are: Side1 isn 67.65 µm, Side2 - 71.20 µm, Side3-71.97 µm, Top side1 - 58.85 µm and Top side2 - 47.32 µm.

These values are quite consistent and indicate what allowance should be introduced to the model when the requirement is only a level of surface finishing.

An example of the surface profile measurements is shown in Fig. 10.

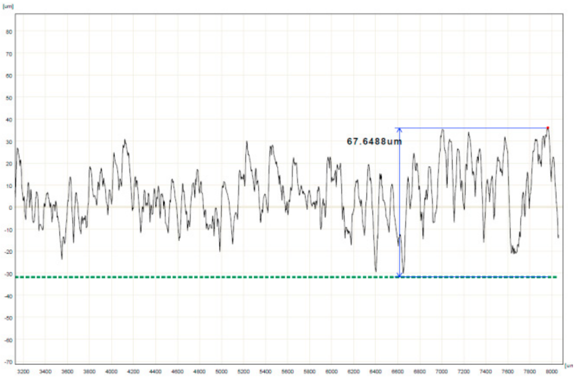

Fig. 10. Surface profile measurement.

5. Conclusions

The work presented is the first phase of a longer-term project on planning for metal Additive Manufacturing. The presented results help to understand better how the quality of the “green” (as-printed) parts may influence the finishing operations.

An initial literature review on metal AM process planning has been conducted. It has been concluded that there is a gap in the research in the area of analysis, planning, and optimisation of the finishing operations for metal AM parts.

A novelty in this paper is the introduction of a detailed and systematic process-planning model for precision parts manufactured by SLM process. The paper discussed the activities from the areas two and three of the model shown in Fig.1 and performed experimental part quality evaluation.

A number of test samples have been designed, fabricated, measured, and analysed. Several inspection techniques have been applied as efficient tools for obtaining preliminary results for the analysis of the shape distortion, dimensional accuracy, porosity, and surface finishing of the metal AM parts.

The shape distortion is influenced by the residual stresses and shrinkage after the sample removal from the substrate. For the 10 mm cubes it is within the range -0.50 ÷ 0.25 mm. The best accuracy that could be achieved in the SLM process for macro features is within the IT9 to IT10 tolerance grades.

The porosity of the SLM (ProX300 machine) process is quite consistent and varies insignificantly from 1% to 1.5% and does not have significant influence of the surface quality.

The surface roughness on vertical walls is affected by the layers in the AM process and the maximum distance between the highest peak and lowest valley can be 60-70 µm. A hand finishing experiment demonstrated that the surface finishing can be improved from Ra 10 µm to Ra 0.04 µm with the removal of about 100 µm material thickness.

The results from the quality evaluation provide input data for optimal modification of the 3D model (Fig. 1) and correction of those surfaces that are expected to have high precision. The material compensation (allowance) should be at least in the region of the accuracy capability of the metal AM machine, i.e. in this investigation, within the IT9-IT10 tolerance grade positive direction in order to cover the cases with negative deviations.

Also, the reported results and experiments help to evaluate the stability and repeatability of the process. The test samples demonstrate a good consistency and similar dimensional accuracy, surface roughness and porosity.

The results from this research provide a confidence in the successful application of process planning for design and manufacturing of precision components using metal AM (SLM) technology.

This project considered test parts form a single machine. A future work needs to investigate the quality and repeatability of parts build on multiple builds on a single machine and parts in builds on multiple machines. Also, the results from this work help to identified areas that may have influences to the part quality and require more in-depth investigation.

Although the paper reports on the SLM manufactured parts, the results can be generalised for any metal AM process. The research contributes to a better integration of the design and manufacturing of precision metal AM-ed components. It facilitates product designers to anticipate potential pitfalls and improve their design for AM.

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