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Study of the influence of filter material on the roughness evaluation by means of CT

N. Ortega[1], S. Plaza[1], A. Pascual[2] I. Holgado[2], L.N. López de Lacalle[1]

[1]Department of Mechanical Engineering, Aeronautics Advanced Manufacturing Center (CFAA), Faculty of Engineering of Bilbao, Plaza Ingeniero Torres Quevedo 1, 48013 Bilbao, Spain
[2]Aeronautics Advanced Manufacturing Center (CFAA), Parque tecnológico de Bizkaia, 202, 48170 Zamudio, Spain

soraya.plaza@ehu.eus

Abstract
Computerized tomography is nowadays a promising technology in industry. This technology has been used as qualitative tool for non-destructive analysis but today is used to carry out dimensional measurements with high accuracy. Recently, and thanks to the development of equipment and software, CT is also capable of measuring micro features such as roughness. However, results obtained from the CT are strongly influenced by high number of parameters. Physical filters usually are used with the aim of minimizing beam hardening. These filters also contribute to the change the way the X-rays are attenuated by the part contour. In this research work the influence of filter material on the roughness evaluation is analyzed. To do so, Inconel 718 and aluminium samples manufactured by SLM and turning respectively are used. Roughness value obtained from the CT scanner is compared with results obtained from focus variation microscope. For each sample, the suitable filter material (and thickness) is found. Results show that Ra can be accurately measured using CT technology.

Keywords: Computerized tomography, Beam Hardening, Roughness

1. Introduction

Technological evolution is providing faster and more advanced measurement techniques. This measurement technologies can be classified in contact and no-contact solutions. Non-contact technologies examine the surface of an object in a different way than tactile probing, resulting in additional influencing factors.

Within the non-contact technologies, computerized Tomography (CT) has become a useful tool for industrial applications such as material analysis, non-destructive analysis, and also for dimensional measurement, amongst roughness measurement can be found . [1]. However, the accuracy of CT-based measurements remains yet largely uncertain due to a number of influencing factors related to the technology [2] which, together with the lack of standards, imply a gap in the traceability of CT measurements.

Specifically, surface roughness has a strong influence on dimensional measurements causing a considerable increase of uncertainty especially for parts characterized by high surface roughness such as those manufactured by SLM.

Even so, it can be said that one of the most important artifacts that degrades the quality of CT images is the Beam Hardening [3]. Nowadays this negative effect can be minimized by placing plates of brass, copper, or tin in front of the X-ray source to filter out the lowest energy components of the beam before it reaches the detector [4]. Nevertheless, there is not found in the bibliography the relationship between the filter material and its thickness with the sample to be scanned.

Therefore, the contribucion of this work consists in the variation of different material/thicknesses of filters to achieve the best CT results from parts with different materials and roughness values.

1.1. The influence of surface roughness in dimensional metrology

ISO 14660-1 [5] defines a 'real surface' as the "set of features which physically exist and separate the entire workpiece from the surrounding medium". However, a precise definition of the spatial location of the 'real surface' is essential for measurements carried out by means of contact techniques since numerical result may differ from the 'real' surface contour due to convolution of the instrument and the surface[4], as shown in the **Error! Reference source not found.**(a).

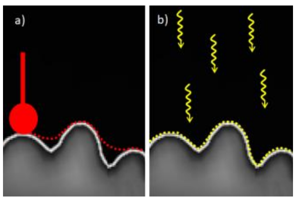

Figure 1 Hypothetical captured surfaces by a) contact and b) non-contact.

Due to the fact that the tactile probe cannot reach the valleys of the roughness profile, a false boundary is constructed, ignoring a major part of the surface roughness [6].Meanwhile, non-contact technologies take into account shorter wavelength components of the surface texture since the measurement is made by photons, which reach any region as they have no mass, assessing the real surface with higher detail (Figure 1 b)).

The measuring principle of CT is based on the attenuation of X-ray beam photons. A 3-D model is reconstructed based on voxels. In ths model, a grey value is attributed to each voxel depending on the density, atomic number and thickness of the material and the path followed by X-rays.

As previously mentioned, the highest difference between contact and non-contact tehcnologies is the 'threshold' selection for stablishing the surface (see Figure 2). Some research work report deviations up to 30µm [6].

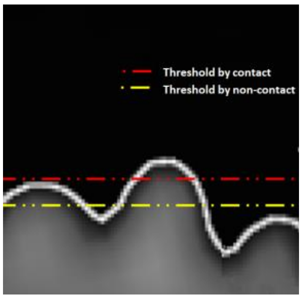

Figure 2 Threshold determination by different technologies

Therefore, the optimum surface determination is essential to achive accurate dimentional measurements being CT a technology from which good results can be expected.

1.2. Beam hardening artifact

Artifacts are innacuracies appeared during CT reconstructions that produce difficulties in their interpretation, and may simulate false defects [7].

There are different artifacts that impair the image fidelity to the object being scanned, one of the most important being the beam hardening. Beam hardening is a physical process that degrades the quality of CT images influencing dimensional measurements.

X-ray beam is composed of photons with a large energy spectrum. Photons with higher energies remain in the beam as they cross the matter being less prone to be attenuated than low-energy photons, so the polycromatic x-ray beam will receive different attenuations for the same conditions. Therefore, two different x-ray beams with the same set-up can cause different readings for the same sample. Due to the mismatch between the energy of photons that the X-ray detector expects to receive and the energy that it actually receives, the reconstruction cannot be correctly performed generating an oval-shaped form (see Figure 3).

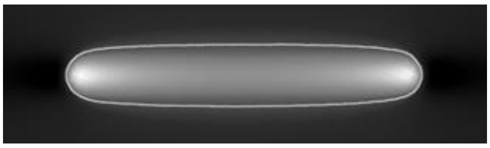

Figure 3 Section of a tomographied workpiece affected by beam hardening artifact

Many techniques based on both hardware and software solutions, such as linearization, iterative artifact reduction [8], and metallic filters are used to correct up to a point the beam hardening consequences.

Amongst these solutions, the correction by hardware filtering is the most simple method. Filters are placed between the X-ray source and the scanned object and usually have a thickness from 0.1 mm to several millimeters. The presence of the filter reduces the gap in intensity between the parts of the image formed by the X-rays penetrating large path lengths and the parts formed by X-rays not passing through the workpiece. Filter materials generally used are aluminum, copper, silver and tin [9]. Notice that spatial resolution is improved by the beam hardening correction.

2. Material and methods

Roughness is a critical parameter in most manufactured parts. In this work, samples manufactured by Selective Laser Melting (SLM) and turning were analysed (see Figure 4).

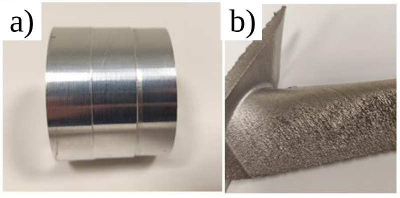

Figure 4 Roughness patterns b) turned sample made of aluminium b) SLMed sample made of Inconel 718

A General Electric X-Ray machine model X-Cube Compact with 5 axes was used for the scanning purpose. The maximum voltage and current of the CT system are 195kV and 8mA respectively and focus size little/big are 0.4/1mm. The orientation of the workpiece was selected attending to the reference [9]. It concludes that angles between 10°- 40° in relation to the vertical position lead to smaller measurement errors. A magnification of 0.913 was used so that all the samples could be entirely projected on the detector panel. VGStudio MAX2.2 software was used for analyzing the results. The material and thickness of filter´s used are shown in Table 1:

Table 1 Filter characteristics

Material	**Copper**	**Brass**	**Tin**
Thickness [mm]	0.3-0.5	0.3-0.5	0.5
Picture			

2.1. SLMed sample description

SLM is one of the most important and used techniques of the emerging AM. This process enables to build parts with complex external and internal geometries "layer by layer" [10]. At present is still under development as it has difficulties in providing end-use productions.

One of the major difficulties is ensuring the quality of the manufactured parts as many areas are inaccessible by traditional methods. Specifically, it can be said that there is a limitation in terms of surface quality due to the large number of factors that influence it, such as "overhanging surface"[11] "stair step", "balling", laser power, layer thickness, beam speed, hatch spacing, amongst others [10].

The material of the sample manufactured by SLM is Inconel 718. Parameters were chosen for obtaining a macro-roughness. The reference roughness values were carried out by focus variation microscope (ALICONA). Measurements were performed with a 10x magnification and 100nm resolution. λc of 2.5mm and Gaussin filter were used. The Ra and Rz values were measured and results are shown in Table 2.

Table 2 Reference roughness values of SLMed sample

	Ra [µm]	**Rz [µm]**
SLMed sample	63	358

2.2. Turned sample description

Turning is a machining process in which a tool remove material from the surface of a less resistant part, through the revolution movement against the tool force [12]

It is known that the surface finish in turning processes depends on many factors such as tool nose radius, cutting feed speed, stability of the machine, the use of cutting fluids, and othersthat are still being investigated to provide smoother surface finish [13].

In this work, an Aluminium sample was turned using 3 different turning conditions. The surface roughnes was measured using an infite focus variation microscope (ALICONA) with a 50x objective magnification and 20nm resolution. λc of 0.5mm and Gaussin filter were used.The Ra and Rz values were measured and results can be seen in Table 3.

Table 3 Reference roughness values of turned sample

	Ra [µm]	Rz [µm]
Turned sample	1.609	7.846

3. Methodology

To select the optimum scan parameters for the tomography, the following procedure was followed since it was necessary to provide a high quality tomography suitable for the measurements. Voltage and current of the X-ray source are the most critical parameters that provide greater or lesser penetration of the rays into the workpiece. Thus, they were firstly selected. To do it, the maximum voltage for the penetration assurance and, afterwards, the current was set so that the penetration was enough to performed further measurements. For the most dense materials such as Inconel 718, CT conditions were 175kV, 0,8mA, 33ms and 0,5° step whereas for aluminium sample 169kV was enough maintaining the rest of the parameters as they were for Inconel 718. In the bibliography consulted, it was found that a step between 0.9° and 0.45° results in good accuracy, and that an integration higher than 8 does not provide better results.

In a first approximation with the optimal scan parameters, the suitable threshold was determined attending to the metholodgy presented by the author of this work as an original contribution to the MESIC congress [14].

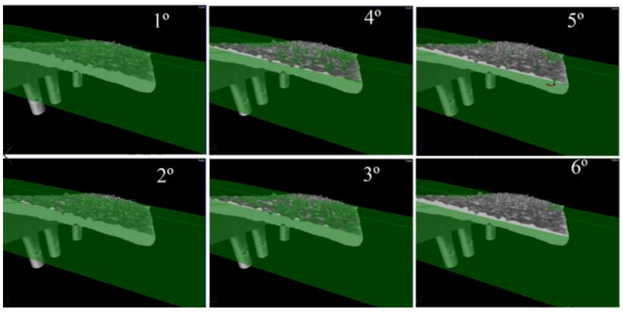

Figure 5 surface scan plans

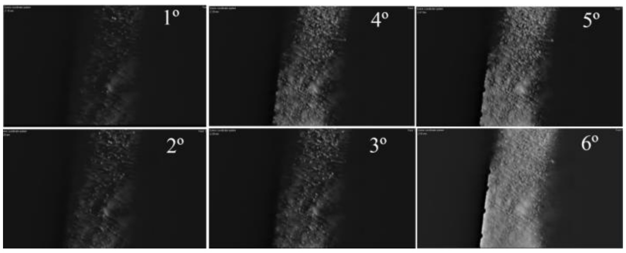

Figure 6 Images of the respective planes.

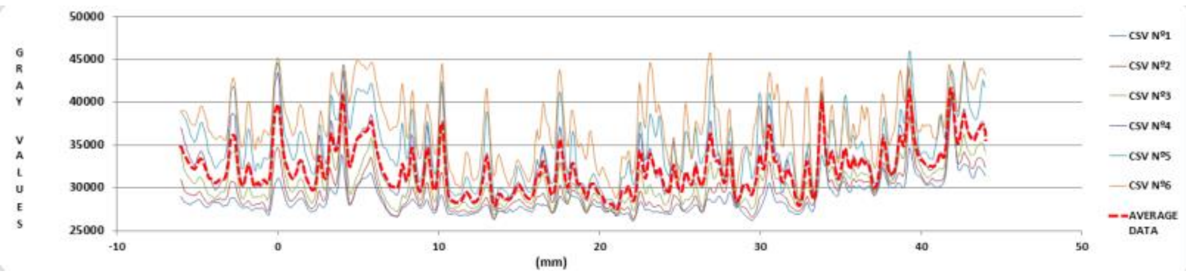

Figure 7 Extracted profiles from the different heights of surface reconstruction

4. Results

Figure shows the CT reconstruction of the SLMed sample. 6 different planes were used to cut the surface and compare results from topography. Obtained images are shown in Figure 6. The images that simulate topography are acquired in planes from the highest peak to the lowest valley of roughness, ensuring that all peaks were processed as shown in Figure 7.
Figure 7 shows all the profiles of the same line at the 6 different levels, as well as the average of all (in red) which represents the roughness in grey scale.

Once the average of grey values related to the surface roughness were acquired, the value of a pronounced peak was measured in a plane perpendicular to the one used for the profile extraction and in the direction of the roughness- line profile as shown in the Figure 8. Then, using the maximum value of grey (peak tip) and the minimum value (valley) of that particular peak in the CT topography described above the dimensions [mm] of the particular peak were acquired.Thought this methodology, the grey values were related to the height of the peaks. Same ratio was applied to all the profiles.

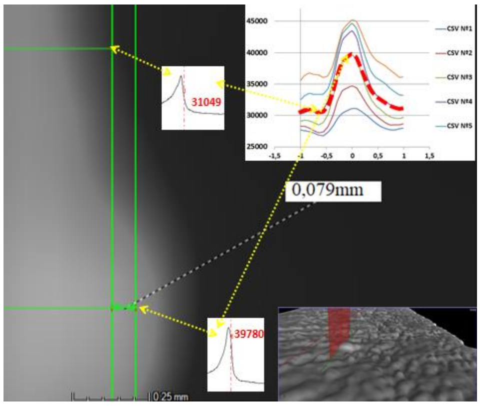

Figure 4 Scheme of the procedure for calculating the height of a particular peak.

Regarding the tests carried out for analyzing the influence of the filters on the roughness results, the variations of Ra and Rz depending on the filter used were studied. Table 4 shows the variations of Ra and Rz according to the filters used in case of the SLM sample.

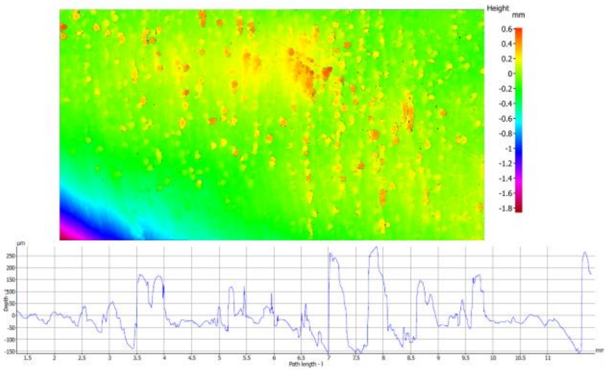

Figure 9 Topography of SLMed sample obtained by focus variation microscope.

Table 4 SLMed sample roughness values for each filter used in the CT.

	Ra [µm]	Rz [µm]
Reference values	63	358
No filter	41	126
0.5mm (CU)	63	152
0.5mm (LA)	29	96
0.5mm (SN)	49	173
0.3mm (CU)	61	152
0.3mm (LA)	46	134

Results show that Ra values were less influenced by the filter material than Rz values. The reason is that Rz values takes into count extrems features of the surface that CT cannot accurately reproduce using the equipment and parameters used. The best resut for Ra measurement was found for the copper filter with a 0.5mm thickness followed by the same filter with 0.3mm thickness having an error of 0% and 6.8% respectively.

On the other hand, Table 5 shows the results obtained in the case of the turned sample.

Table 5 Turned sample roughness values for each filter used in the CT.

	Ra [µm]	Rz [µm]
Reference values	1.609	7.846
No filter	1.594	4.023
0.5mm (CU)	2.274	4.328
0.5mm (LA)	2.081	5.401
0.5mm (SN)	2.487	5.611
0.3mm (CU)	2.101	4.366
0.3mm (LA)	2.199	4.527

Results show again that Ra values were less influenced by the filter material than Rz values. The best resut for Ra measurement was found for non-filtered case when an error of 0.9% is found. Results from other conditions are non acceptable.

5. Conclusions

From the research carried out the following conclusions can be drawn:

- A methodology for evaluating roughness on an Inconel 718 and aluminium samples manufactured by different processes (SLM and turning) by means of macro-CT was proposed.
- Although the size of the voxel is bigger than the largest peak (Rz) of the roughness to be examined, the wave created by the roughness peaks propagates at values higher than 91 µm (voxel size in the case of this work). Thus, using the copper filter with 0.5mm thickness provides good results for Ra.
- Rz values cannot be accurately obtained applying the proposed methodology and for the samples studied in this work.
-The influence of different filters on the roughness patterns was studied and it has been concluded that in all cases the 0.,5mm tin filter smooths out the "pumping" effect produced by beam hardening, which is the most harmful artifact for the wrong interpration of roughness.

References

[1] P. Reimers, J. Goebbels. New possibilities of non destructive evaluation by x-ray computed tomography. Materials evaluation, 41(1989) 732-737.

[2] F. Welkenhuyzen, K. Kiekens, M. Pierlet, W. Dewulf, P. Bleys, J-P. Kruth, A.Voet. Industrial Computer Tomography for Dimensional Metrology: Overview of Influence Factors and Improvement Strategies. OPTIMESS 2009, Belgium.

[3] P. Müller, J. Hiller, Y. Dai, JL. Andreasen, HN. Hansen, L. De Chiffre. Estimation of measurement uncertainties in X-ray computed tomography metrology using the substitution method. CIRP J Manuf Sci Technol, 7 (2016) 222–232.

[4] Villarraga-Gómez, H., Herazo, E. L., & Smith, S. T. (2019). Progression of X-ray computed tomography from medical imaging to current status in dimensional metrology. Precision Engineering.

[5] ISO 14660-1, Geometrical Product Specifications (GPS) — Geometrical features — Part 1: General terms and definitions, Geneva: ISO copyright office, 1999.

[6] Boeckmans, B., Tan, Y., Welkenhuyzen, F., Guo, Y., Dewulf, W., & Kruth, J. P. (2015). Roughness offset differences between contact and non-contact measurements. In Proceedings of the 15th international conference of the European society for precision engineering and nanotechnology (pp. 189-190).

[7] Boas, F. E., & Fleischmann, D. (2012). CT artifacts: causes and reduction techniques. Imaging in medicine, 4(2), 229-240.

[8] E. Van de Casteele, D. Van Dyck, J. Sijbers, E. Raman. The effect of beam hardening on resolution in X-ray microtomography. Medical Imaging 2004: Image Processing, 2004. San Diego, California. USA.

[9] H. Villarraga-Gomez, S.T. Smith. CT measurements and their estimated uncertainty: the significance of temperature and bias determination. Proceedings of 15th international conference on metrology and properties of engineering surfaces (2015) 509-515. Charlotte, USA.

[10] Strano, G., Hao, L., Everson, R. M., & Evans, K. E. (2013). Surface roughness analysis, modelling and prediction in selective laser melting. Journal of Materials Processing Technology, 213(4), 589-597.

[11] Wang, D., Yang, Y., Yi, Z., & Su, X. (2013). Research on the fabricating quality optimization of the overhanging surface in SLM

[12] Thamizhmanii, S., Saparudin, S., & Hasan, S. (2007). Analyses of surface roughness by turning process using Taguchi method. Journal of achievements in materials and manufacturing engineering, 20(1-2), 503-506.

[13] Mital, A., & Mehta, M. (1988). Surface finish prediction models for fine turning. The International Journal Of Production Research, 26(12), 1861-1876.

process. The International Journal of Advanced Manufacturing Technology, 65(9-12), 1471-1484.

[14] Plaza S, Ortega N, Minguez R, Barrenetxea L, Gonzalez A 2019 A proposal for the measurement of Inconel 718 components by means of computerized tomography 8th Manufacturing Engineering Society International Conference 14, Madrid, Spain 19-21 June.