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Impulse excitation technique for improved inspection in additive manufacturing

Juan Jose Bustos[1], Alex Van den Bossche[1]

[1]*GrindoSonic bvba*
Esperantolaan 4, Leuven 3001, Belgium
Juanjose.bustos@grindosonic.com

Abstract

The determination of mechanical properties is key when characterizing a material. In additive manufacturing, monitoring and validating printed materials is fundamental to confirm the adoption of this technology, aiming to improve the uniformity during a printing process. By using a non-destructive-testing method such as the Impulse Excitation Technique (IET), printed materials can be easily and accurately inspected to improve the printing process validation. Six lattice cubes, divided into two groups, were printed and tested using the Archimedes' method, gas pycnometry and impedance measurement by eddy current. These methods confirmed the identical values in volume, density and current resistance among the printed parts. Only by the use of IET we were able to detect differences among their elastic properties and internal friction. These results represent a highly valuable finding which indicates the possibility to improve the stability of the printing process by correlating these results with the printing parameters.

Additive Manufacturing, NDT, Impulse Excitation Technique, Material characterization, Quality Control, Quality assurance, LPBF

1. Introduction

Additive manufacturing (AM), also known as 3D printing, is an innovative technology that enables the construction of objects layer-by-layer starting from a 3D file that includes process parameters specifically dedicated to AM. Special attention from different branches of industry is dedicated to Laser Powder Bed Fusion (LPBF), which is an AM process consisting of a high-energy intensity laser beam that scans over the powder bed and fuses particles together according to the shape of that object [1], [2]. LPBF allows to manufacture complex geometries such as lattices and parts containing internal structures like cavities and channels, as well as mass-production of custom parts.

More and more manufacturers are using AM beyond prototyping and research. Nevertheless, there remain still some big challenges, particularly related to scalability, costs and materials, that need to be tackled in order to help for the acceptance of AM [3]. Therefore, quality assurance methods are necessary to bring bigger confidence in the adoption of this innovative technology as they, together with quality control methods, facilitate production of high-quality printed parts [4].

Material properties play an important role when characterizing a material. Moreover, the inspection of these properties, as well as the inspection of defects, could be performed by using different methods, either destructive or non-destructive.

The Impulse Excitation Technique (IET) is a known non-destructive testing method in industry, broadly known in refractory, cement and friction materials industry. This method is commonly used to determine mechanical properties such as Young's Modulus, Shear Modulus, Poisson's Ratio and internal friction.

The goal of this investigation is to apply the IET method into the inspection process of additive manufacturing to contribute for a more sustainable and accurate quality assurance and quality control.

2. Material and methods

The work involves the study of six Ti lattice cubes printed by LPBF. These cubes were divided into two groups of three cubes each, based on their cell sizes (77% and 79%). Figure 1 shows these components on a foam bed, ready to tested by IET.

In order to guarantee the integrity of the printed parts, it is necessary to investigate, evaluate and validate existing volume non-destructive testing methods with complex parts as well as utilizing these methods for routine control of printed parts [5].

Previous to this study, the six lattice cubes were tested on the following methods [5]:

- Archimedes' method and gas pycnometry (volume and density)
- Eddy-current testing (impedance)

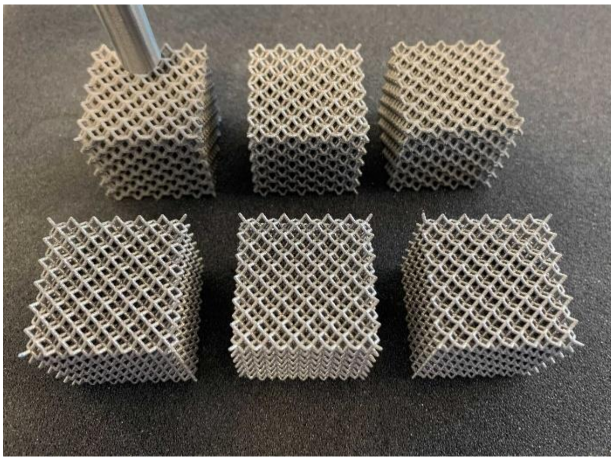

Figure 1. Six lattice cubes under study. Group 1 (in front) and group 2 (back).

The Archimedes' method and gas pycnometry allow the density measurement of the Ti cubes with different cell size structure. These methods were used due to the advantage on having independence on shape and size, surface condition and it is also an accredited method [6].

The Eddy-current testing enables to differentiate two specimens with different lattice sizes on the surface, with a certified and fast method [6].

2.1. Impulse Excitation Technique (IET)

The impulse Excitation Technique is based on the analysis of the resonance frequencies of a sample after it has been excited by a mechanical impulse. The vibration of the sample is detected by a piezoelectric accelerometer contact transducer or an acoustic vibration detector.

Three fundamental ground vibration modes are of interest when determining elastic properties: flexural, torsional and longitudinal modes. This method allows therefore to determine the dynamic elastic properties of elastic materials if the geometry, mass, and mechanical resonant frequencies of a suitable (rectangular or cylindrical geometry) test specimen of that material can be measured. Dynamic Young's modulus is calculated using the resonant frequency in either the flexural or longitudinal mode of vibration. The dynamic Shear modulus, is calculated by using the torsional mode. Dynamic Young's modulus and dynamic shear modulus are used to calculate Poisson's ratio [7].

For example, for the fundamental flexural frequency of a rectangular bar [7, eq. (2)]:

$$E = 0.9465 \times (m \times f_f^2 / b) \times (L^3/t^3) \times T_1$$

where:
E = Young's modulus, Pa,
m = mass of the bar, g,
b = width of the bar, mm,
L = length of the bar, mm,
t = thickness of the bar, mm,
f_f = fundamental resonant frequency of bar in flexure, Hz, and
T_1 = correction factor for fundamental flexural mode to account for finite thickness of bar, Poisson's ratio, and so forth.

Moreover, the measurement of damping results of great importance when characterizing a material. The damping, or attenuation value, is an indication of the amount of internal friction of a material, and it is independent of shape or size, for which a high damping value results on a clear indication of internal defects, such as microcracks [7], [8].

The frequency analysis for all six cubes was performed and analysed with GRINDOSONIC® MK7. All cubes were tapped twice to guarantee repeatability in the longitudinal mode. The set-up of the measurements can be seen in Figure 2.

The software GRINDOSONIC® Waterfall Spectrogram was then used for data visualization.

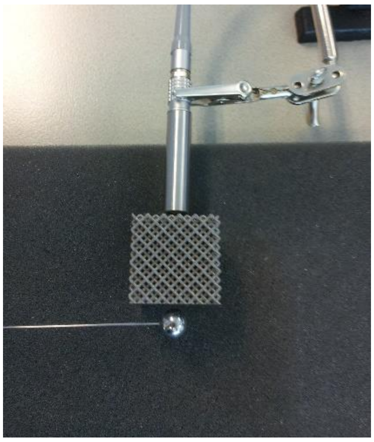

Figure 2. Set-up of lattice cube in order to perform IET.

3. Results and discussion

3.1. Volumetric testing

The results provided by the Laboratoire National de Métrologie et d'Essais (LNE) showed a consistency on volume and electrical conductivity for the 3 cubes in both groups as well as equal density among all six cubes. Gas pycnometry and Archimedes' methods give coherent density measurements. The repeatability in impedance shows a repeatability on surface for this AM process [5]. These results show no clear difference among the cubes on each group as seen in Figure 3, 4, 5.

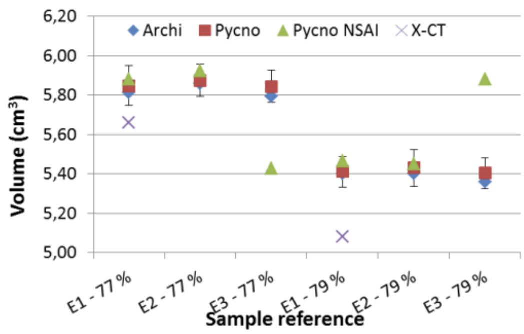

Figure 3. Volume of the six lattice cubes [5].

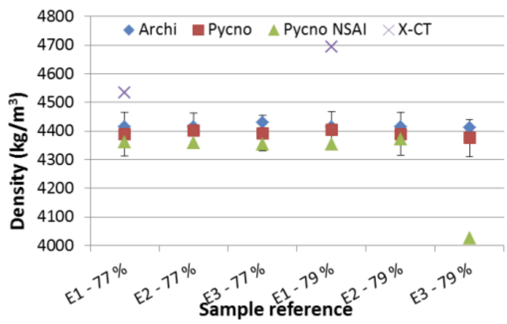

Figure 4. Density of the six lattice cubes [5].

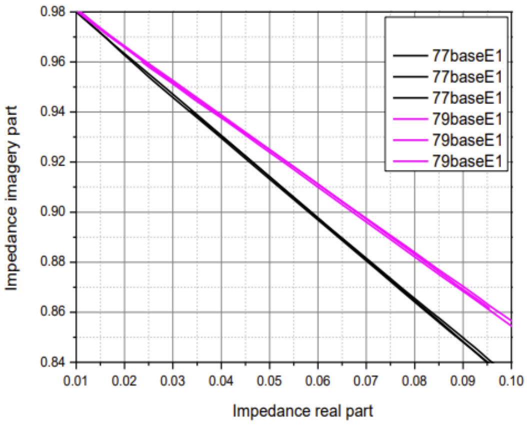

Figure 5. Impedance of the six lattice cubes [5].

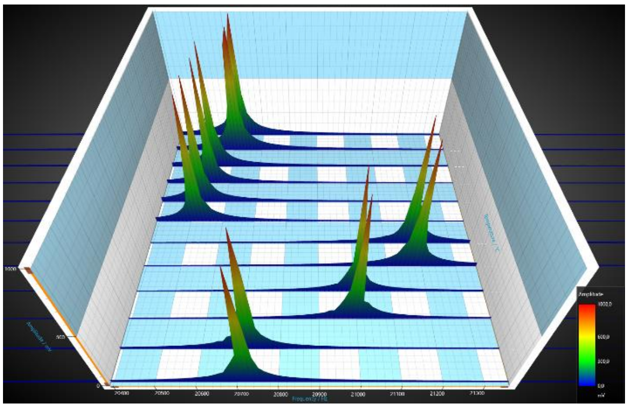

Figure 6. Waterfall Spectogram of the six Ti lattice cubes.

It results then challenging to find a significant difference between the printed parts by the use of these non-destructive methods, leading into an initial idea that the process is stable and consistent in terms of volume, density and electrical impedance.

3.2. Frequency analysis

Impulse Excitation technique showed, by the frequency of the cubes, on the contrary difference between both groups and among each component. These values are described in table 1. Frequency values show that the first group has a big spread among them but higher frequencies with respect to the second group, which are proportional to the Young's modulus and therefore are stronger parts. On the other hand, although the second group has lower frequency values, their spread is smaller, showing that the overall process of printing these cubes is more consistent, considering the mechanical behaviour.

Table 1 Frequency and damping values for six lattice cubes

	Component	**Frequency (Hz)**	**Damping (Hz)**
Group 1	Cube 1	20728	18.91
	Cube 1	20726	10.58
	Cube 2	20997	10.58
	Cube 2	21005	10.58
	Cube 3	21175	22.00
	Cube 3	21175	18.50
Group 2	Cube 1	20532	10.58
	Cube 1	20535	16.83
	Cube 2	20553	10.58
	Cube 2	20552	10.58
	Cube 3	20620	23.31
	Cube 3	20620	26.25

The frequencies were plotted into the Waterfall Spectogram Software for a clearer visualization of the results, as shown in Figure 6. In this plot, the first group is presented in the front and the second group in the back. Here, the difference on damping is more visible. Damping can be measured as the width at half height of the frequency peak [8]. By looking into the plot, the last cube of the second group is clearly the one with the highest value of damping, as also showed in table 1.

These results create special attention to the quality consistency of the printing process, revealing that there exists a difference on mechanical properties among parts printed on the same machine with the same process parameters. One possible explanation could be related to the position of the parts on the chamber, as well as the sinter quality that it's achieved during the build.

By testing only one part (e.g. in a tensile testing procedure), one could draw wrong conclusions if the part that was chosen is the one presenting the higher frequency, resulting in a higher Young's modulus. Ergo, it is evident the importance to guarantee first a stable process to achieve equal mechanical properties among all printed parts.

Special attention should be given to the energy deposition of the printing process among the whole build plate, which would explain better the sinter quality of the parts. Improving the distribution of energy during printing could lead to a higher quality consistency of the AM process, which becomes very important when printing high-end parts that need to meet specific standards as well as when printing a big part that occupies most of the build platform.

Furthermore, this certainly grows of higher importance when dealing with multi-optics machines, where other considerations come into place such as calibration and alignment.

Finally, the IET method is useful not only for quality control, where parts can be checked and classified based on their frequency response, but also on a quality assurance approach. By controlling every step of your AM process, IET can lead into easy detection of where the process is failing or improve the whole process itself.

4. Conclusion

Volumetric NDT methods were performed to prove the integrity of the Titanium lattice cubes. These tests showed no clear difference among the printed parts.

By utilizing the IET method it was possible to detect a difference on frequency and damping for all six cubes, which are strictly correlated to the elasticity and internal friction of the material. The first group (77%) showed a bigger spread in terms of frequency whilst the second (79%) showed a lower spread. The last cube of the second group showed though a higher value of damping with respect to the other five cubes, resulting on higher internal friction due to possible microcracks.

Although this method was used for a specific technology within the AM field, it can be applied to any material that vibrates. This means, that in the context of AM, the same approach could be followed in order to improve the inspection of printed parts, regardless of their process methodology.

In order to bring these results to a more conclusive interpretations, future work include the tomographic analysis of all 6 cubes in collaboration with the KU Leuven university.

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