Ultrasonic Monitoring of Part's Height and Layer Thickness in Powder Bed Fusion

Marc RAFFESTIN[1,2,a], Alexey DOMASHENKOV[1,b], Pierre FAVERJON[1,c], Philippe BERTRAND[2,d] and Cédric COURBON[2,e*]

[1]University of Lyon, Centrale Lyon-ENISE, CNRS, LTDS UMR 5513, F-42023, Saint-Etienne, France

[2]PCI SCEMM, Rue Copernic, 42030 Saint-Etienne Cedex 2, France

[a]marc.raffestin@pci.fr, [b]Alexey.DOMASHENKOV@pci.fr, [c]pierre.faverjon@pci.fr, [d]philippe.bertrand@enise.fr, [e]cedric.courbon@enise.fr

Abstract. This paper presents a preliminary study on an in-situ ultrasonic measurement technique applied to monitoring part's height and defect occurrence during the Laser Powder Bed Fusion process. Firstly the ultrasonic wave speed is determined for LPBF manufactured 100Cr6 samples with a pulse echo configuration and a 10Mhz ultrasonic wave. A measured propagation speed value, of 5660 ±100m/s in every direction confirms the isotropy of the obtained LPBF samples. Secondly, the ultrasonic pulse echo technique is used to monitor the part's height evolution during the process based on the measured propagation velocity. This new method provides in-situ measurements showing that the actual remelted layer thickness value oscillates in the range of ± 30% of the theoretical layer thickness.

Introduction

Additive manufacturing (AM), also known as 3D printing, is an expending manufacturing technique enabling the creation of lighter and stronger parts or systems. However, additive manufacturing processes, such as Laser Powder Bed Fusion (LPBF) in the present study, are known to induce typical defects within the processed material. Several studies tackled the process defects and especially their characterization and feasible monitoring options in metal LPBF [1, 2, 3, 4]. These works highlighted the importance of defects in situ monitoring developments to understand the physical phenomena and improve the performance of the LPBF process. Numerous detection technologies can be found in the literature [5, 6, 7, 8, 9, 10]. Particularly, Honarvar and Varvani-Farahani [11] presented a review on ultrasonic testing applications in additive manufacturing and concluded on the need to study the impact of key ultrasonic testing parameters to explore the potential of this technology. Turó et al. [12] characterized the pulse echo method as a suitable technology to monitor powder metallurgic processes and to ensure the part quality. Rieder et al. [13] developed an in-situ ultrasonic control system to monitor part's height evolution of simple parts. Rieder et al. [14] extended this work showing the ability of the technology to detect different sections with varying porosity rates, which were induced by a variation of the laser power. To date, the results reported in the literature confirm the interest of this monitoring solution. However, in-line monitoring capability of the melted layer thickness hasn't been yet investigated whereas it is a key parameter governing the printed part quality. The objective of this study is thus to develop a monitoring system not only providing the part's height but also the melted layer thickness and their evolution during the LPBF process.

Material and Methods

Machine and materials. An AMP-250 LPBF machine is used in the current study. It is equipped with an Ytterbium fiber laser with the following characteristics: maximum power 500W,

wavelength 1064nm and laser spot diameter around 50μm. The building zone dimensions are 250x250x250mm with a building plate made of 316L. The 100Cr6 bearing steel, provided by SANDVIK AB, has been used as a feedstock material for the current study. Powder characteristics are given as tap density of 4.76 g/cc, hall flow of 15.50 s/50g, chemical analysis presented by Table 1. Laser diffraction analysis, performed by the supplier with Malvern 2000 instrument, indicate measurements of D90 48.7μm, D50 33.3μm and D10 22.9μm.

Table 1 — 100Cr6 powder chemical analysis

Element	Cr	C	Mn	Si	Ni	Cu	P	S	Fe
% weight	1.50	1.10	0.45	0.27	0.04	0.01	0.01	0.004	Balance

Experimental configurations. A TriboDAQ ultrasonic pulser receiver unit made by Tribosonics Ltd is used in this study. It includes a square wave pulser, a low noise amplifier from 0 to 110 dB and a PC USB connection interface. The system enables measurements at a wave frequency of 10MHz with an acquisition rate of 100MHz.

Ex-situ controls are performed using Olympus ultrasonic testing probes (ref. U8401032). It is a contact transducer with a frequency of 10MHz and a nominal size of 13mm. In order to assess the effective sound wave propagation speed within the processed material, dedicated specimens were first manufactured for ex-situ tests. Two samples of X-Y-Z 12x14x15mm are built with a chessboard laser scanning strategy. After the LPBF process, samples were ground to ensure opposite surfaces parallelism, roughness and theoretical dimensions of 11x13x14mm before being controlled. The pulse-echo time of flight was measured five times for each dimension with replications on both opposite faces to improve the repeatability and reduce the impact of surface roughness. To analyse the sample porosity, the Archimedes' method was used. In the Table 2, the mean value of five identical measures is presented in order to reduce measurement uncertainties.

Table 2 — Propagation speed in function of the machine axis (chessboard laser fusion pattern)

Machine axis	Sample	Ref. dimension [mm]	TOF [μs]	Propagation speed [m/s]
X	X1	11,090	3,89	5696
	X2	11,090	3,90	5684
Y	X1	13,094	4,56	5738
	X2	13,09	4,57	5734
Z	X1	14,094	4,96	5678
	X2	14,086	4,99	5641

To implement the in-situ monitoring technique, piezoelectric wafers made of Lead Zirconate Titanate are employed. They are characterized by an outer diameter of 10mm and a thickness of 0.2mm leading to a natural excitation frequency of 10MHz. Wafers were bounded to the building plate with cyanoacrylate glue, wired to the TriboDAQ using standard wires and co-axial cables and installed in the TT AMP-250, as presented on the Figure 1. During the process, an A-scan is recorded each ten layers in order to monitor the evolution of the samples' construction. A full dense cylindrical sample of diameter of 20mm and 6.9mm of height is built with the embedded monitoring system. For this experimentation substrate thickness is 13.96mm.
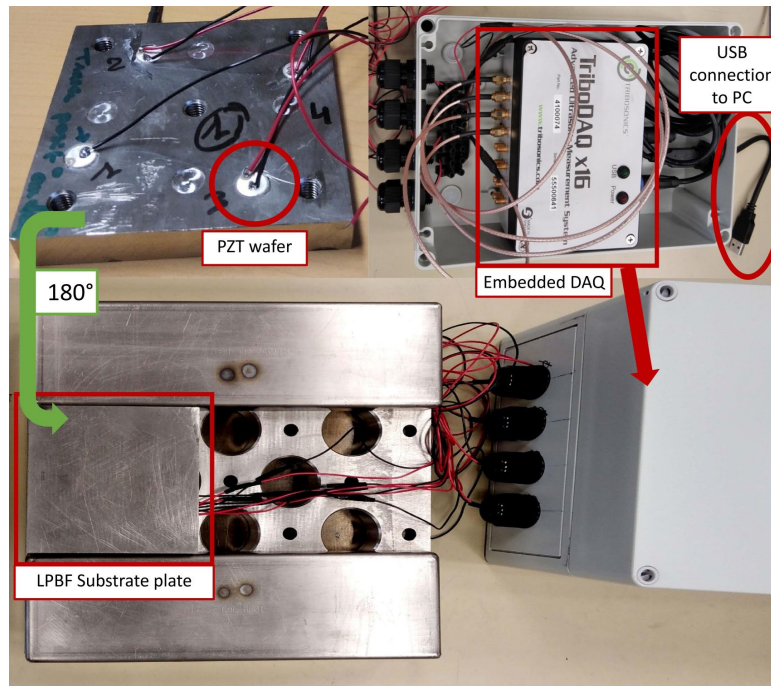
Fig. 1 — Experimental embedded system

Results

Ultrasonic wave speed determination - Ex-situ measurements. The ultrasonic wave emitted by a finite probe is not a plane wave. Thus a phenomenon of diffraction appears inducing different propagation speeds depending on the propagation direction: longitudinal (V_L) or transverse (V_T) relatively to the probe. Only longitudinal speed is considered here regarding to propagation direction and sample geometry. This choice is in agreement with the experimental results presented in this section. This speed could be defined by Equation 1 as a function of the material characteristics: E (Young modulus), v (Poisson's ratio) and ρ (density), according to Clezio et al. [15]. It was shown that Equation 1 leads to a theoretical value for 100Cr6 of 5945m/s for longitudinal propagation speed.

$$V_L(T) = \sqrt{\frac{E(T)}{\rho(T)} \cdot \frac{1-v(T)}{(1+v(T))(1-2v(T))}} \qquad (1)$$

At the time when an ultrasonic measurement is performed, typically after the fusion and next powder layer spreading, the temperature of the part and the building plate can be estimated between 20 and 100°C due to the laser beam and even between 150°C and 300°C if the heating stage is used to pre-heat the substrate [17]. As material properties might be affected by a temperature increase, the variation of the propagation speed over a temperature range between 20°C to 100°C was first checked. Theoretically estimated between 5518 m/s and 5577 m/s, it represents a relative error of only 1% that could therefore be considered as negligible in the present work. It confirms that the ultrasonic measurements could be reasonably performed assuming a constant propagation speed in between each layer-by-layer step of the building process for the estimated temperature range.

The Table 2 summarises the results only for a chessboard-type fusion pattern. These results show that the material is isotropic and the median value of propagation velocity regardless to the direction is about 5660 ±100 m/s. Porosity of the samples is determined with the Archimedes method and reveals the values of 0.8 % for sample X1 and 0.97 % for sample X2. Slotwinski and Garboczi [17] reported in their experiments that the ultrasonic wave propagation speed decreases while porosity rate increases. They concluded also that ultrasonic wave propagation speed could be affected by a 0.5% relative variation in density. Therefore, it can be assumed that porosity range induced within X1 and X2 samples by the additive manufacturing process could be responsible for the 2.4% difference between theoretical value of 5945m/s and experimental measurements of 5660 ±100m/s.

Process monitoring - Plain part's height monitoring. The Figure 2 presents the TOF evolution measured each 10 layers during the building process. One could notice that the initial and final backwall echoes, respectively noted Ei and Ef on the Figure 2, are well predicted by the measured propagation speed of 5660m/s despite the potential temperature variation impact.
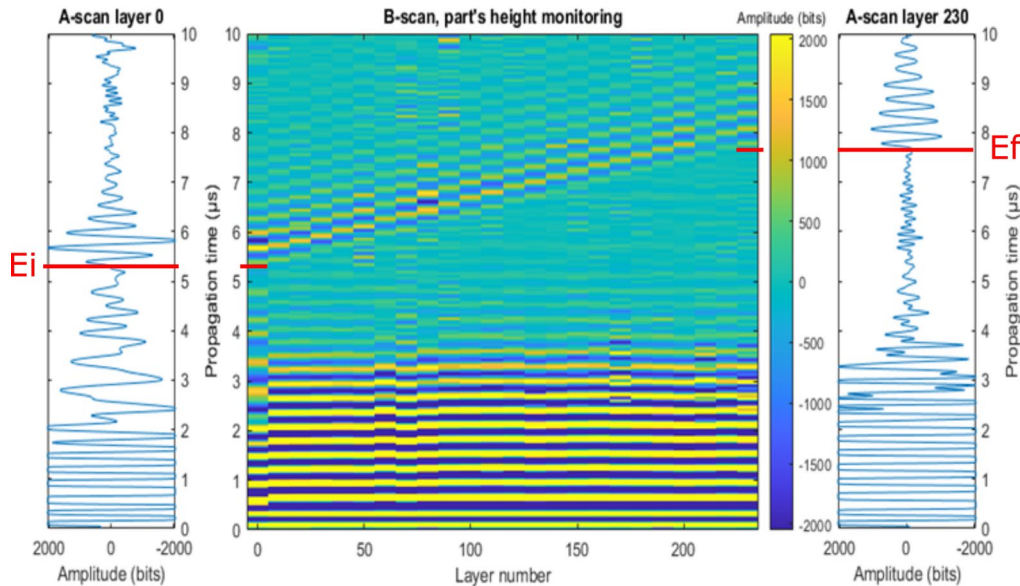

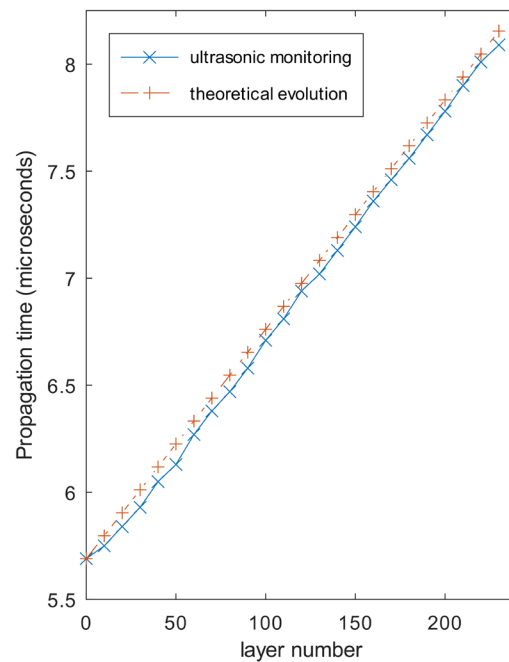Fig. 2 — Initial and final A-scans and B-scan of part's height monitoring

Fig. 3 — Part's height monitoring computed from the time-of-flight evolution compared to theoretical part's height

The evolution of the theoretical part's height and the measured one based on the TOF could thus be extracted and plotted versus the number of printed layers as shown in the Figure 3. As it can be seen on the Figure 3, after an initial transition, the experimental part's height presents a stable evolution in good agreement compared to the theoretical value. For the applied experimental conditions, the thickness of the remelted powder layer stabilizes after around 20 cycles.

Assuming a constant propagation speed, the ultrasonic-measured part's height could be decomposed to analyse the evolution of the layer height as shown in the Figure 4. Stability of propagation speed

is confirmed after this first transition zone probably due to the misalignment of the substrate. This initial variation is also seen in the Figure 3. The variation of the measured thickness in the range of 4.25 µm around the theoretical value of 30 µm can be related to the powder layering process. The powder levelling system is designed in such a way that two recoating polymer blades ensure bidirectional powder levelling for sequential layers. A constant amount of powder dropped once every two layers between two recoating blades. Thus, the effective amount of layered powder varies during the process between sequential layers. The ultrasonic measurement uncertainty was estimated in this case to approximately ±2% based on the sampling rate and propagation velocity assumption.
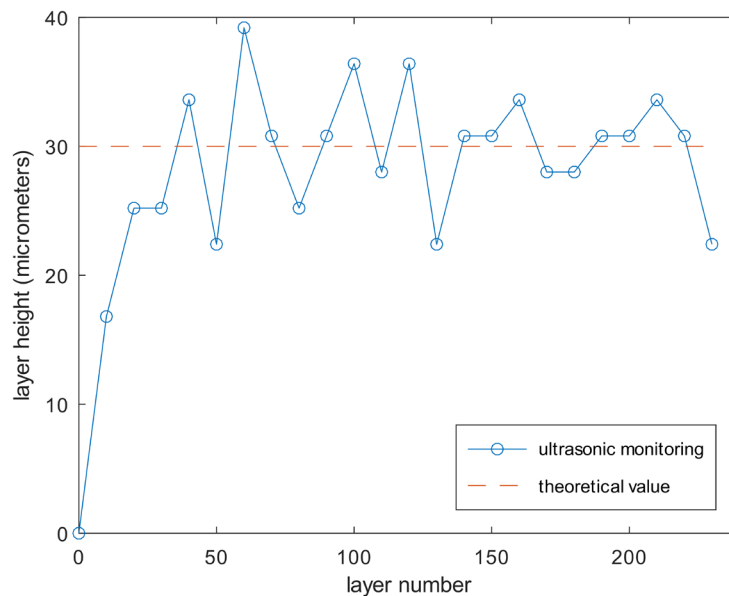

Fig. 4 — Evolution of the fused layer height assessed by the ultrasonic monitoring method compared to theoretical powder layer height ($30\mu m$)

Rieder et al. [13] presented the results of the ultrasonic speed evolution as a function of the part's height. They proposed that it could be the result of material properties variations induced by a thermal gradient in the part, which leads to changes of the wave velocity during the process. The Figure 3 and the Figure 4 highlight a stable evolution of the part's height. This trend confirms that the propagation speed is stable during all the process at a constant temperature, as shown in Figure 3, and thus the time of flight variation is directly related to the part's height evolution.

Conclusion

This work presented a preliminary study on the in-situ monitoring of part's height and melted layer thickness in LPBF process. Being a key parameter of the monitoring method, the ultrasonic wave propagation speed in LPBF samples was first investigated when using a 10MHz ultrasonic wave. A dedicated experimental campaign was conducted to assess this value, leading to a propagation velocity of 5660 ±100m/s in 100Cr6. Based on this measured wave velocity and the analysis of the time of flight, ultrasonic in-situ measurements were carried out with embedded sensors while building cylindrical samples in order to extract the part's height evolution during the whole printing process. The melted layer thickness was then computed from these recordings every ten layers and was found to be within ± 30% of the theoretical value of 30 µm. The present work confirmed the potential of this measuring technique not only for the monitoring of parts' height but also of the process stability regarding the evolution of the remelted layer thickness.

Acknowledgments

References

[1]   M. Grasso, B. M. Colosimo, Process defects and in situ monitoring methods in metal powder bed fusion: A review, Measurement Science and Technology 28 (2017).

[2]   S. K. Everton, M. Hirsch, P. I. Stavroulakis, R. K. Leac, A. T. Clare, Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing, Materials and Design 95 (2016) 431–445.

[3]   J.M. Waller, B.H. Parker, K.L. Hodges, E.R. Burke, J.L. Walker, Nondestructive Evaluation of Additive Manufacturing State-of-the-Discipline Report, Nasa/Tm-2014-218560 (2014) 1–36.

[4]   L. W. Koester, H. Taheri, T. A. Bigelow, P. C. Collins, L. J. Bond, Nondestructive testing for metal parts fabricated using powder-based additive manufacturing, Materials Evaluation 76 (2018) 514–524.

[5]   P. Nilsson, A. Appelgren, P. Henrikson, A. Runnemalm, Automatic Ultrasonic testing for Metal Deposition, 18th World Conference on Nondestructive Testing (2012) 16–20.

[6]   H. Krauss, T. Zeugner, M. F. Zaeh, Layerwise monitoring of the Selective Laser Melting process by thermography, Physics Procedia 56 (2014) 64–71.

[7]   J. Bamberg, Z. Günter, A. Ladewig, In-Process Control of Selective Laser Melting by Quantitative Optical Tomography, 19th World Conference on Non-Destructive Testing (2016) 1–8.

[8]   B. K. Foster, E. W. Reutzel, A. Nassar, B. T. Hall, S. Brown, C. Dickman, Optical, layerwise monitoring of powder bed fusion (2020) 295–307.

[9]   F. Honarvar, A. Varvani-Farahani, A review of ultrasonic testing applications in additive manufacturing: Defect evaluation, material characterization, and process control, Ultrasonics 108 (2020).

[10] Y. Song, X. Zi, Y. Fu, X. Li, C. Chen, K. Zhou, Nondestructive testing of additively manufactured material based on ultrasonic scattering measurement, Measurement 118 (2018) 105–112.

[11] A. Turó, J. A. Chávez, M. J. García-Hernández, A. Bulkai, P. Tomek, G. Tóth, A. Gironés, J. Salazar, Ultrasonic inspection system for powder metallurgy parts, Measurement 46 (2013) 1101–1108.

[12] D. Cerniglia, N. Montinaro, Defect detection in additively manufactured components: Laser ultrasound and laser thermography comparison, Procedia Structural Integrity 8 (2018) 154–162.

[13] H. Rieder, A. Dillhöfer, M. Spies, J. Bamberg, T. Hess, Online Monitoring of Additive Manufacturing Processes Using Ultrasound, Proceedings of the 11th European Conference on Non-Destructive Testing 1 (2014) 2194–2201.

[14] H. Rieder, M. Spies, J. Bamberg, B. Henkel, On- and offline ultrasonic characterization and inspection of additively manufactured components, 55th Annual Conference of the British Institute of Non-Destructive Testing, NDT 2016 (2016) 328–336.

[15] E. L. E. Clezio, G. Despaux, J. yves Ferrandis, E. Rosenkrantz, Caractérisation de solides ou liquides par méthode de pulse-écho, Les techniques de l'ingénieur 33 (2018).

[16] A. Domashenkov, Etude de la faisabilité de la fabrication de pièces fonctionnelles à partir d'alliages intermétalliques, matériaux métallo-céramiques et superalliages au moyen de la fusion sélective par laser, Ph.D. thesis, Ecole Nationale d'Ingénieurs de Saint-Etienne, 2016.

[17] J. A. Slotwinski, E. J. Garboczi, Porosity of additive manufacturing parts for process monitoring, in: AIP conference proceedings, volume 1581, American Institute of Physics, pp. 1197–1204.