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ASSESSMENT OF LOCAL MECHANICAL PROPERTIES OF LASER POWDER BED FUSED ALUMINIUM ALLOY BY NON-DESTRUCTIVE TESTING BASED ON FIMEC INDENTATION

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Abstract. Laser powder bed fusion process is a versatile metal additive manufacturing process. Although significant progress has been made so far, there is still limited large-scale adoption of this technique by the industry. The main problems are repeatability and lack of proper knowledge. In this work, an innovative and non-destructive testing methodology, based on flat-top cylinder indentation, was used to define the mechanical properties of laser powder bed fused aluminium alloy to highlight any variations induced by the combination of process parameters, for global characterization, and by the building direction, for local characterization. Results show similar or improved global mechanical properties of the laser powder bed fused specimens when compared to traditional die-casted ones. Indentation tests highlight a local dependence of properties along the building direction in favor of the upper part of the samples.

Keywords: Laser powder bed fusion, non-destructive testing, FIMEC.

1. Introduction

Additive Manufacturing (AM) technologies are of growing interest, thanks to their flexibility and ability to reduce time-to-manufacturing, allowing the speed-up of industrial process. The cost effectiveness of AM solutions depends on the particular application and it is generally proven that for the prototype stage or for smaller productions based on custom designs, AM components do have an economical advantage over traditional material processing strategies [1].

AM process is generally based on the addition, layer by layer, of thin sheets of materials to generate a physical object from a computer-aided design model, allowing the realization of complex structures [2]. This is recognized to be one of the main advantages in using AM, especially for metal additive manufacturing (MAM) techniques [3]. MAM parts can be realized producing very-little to no waste compared to traditional processes like forging, casting and extrusion [4].

Aluminum Alloys are known for their wide compatibility with industrial applications, thanks to easy processing, good corrosion resistance, and high specific strength. LPBF can solve some of the main problems found in traditional foundry technologies, generally related to low cooling rate in casting and limited flexibility of preparation and forming processes [5]. Main drawbacks of processing pure aluminium with LPBF are related to high reflectivity, high thermal conductivity, and poor flowability of the powders [6]. To overcome these problems, specific alloys are generally used as starting material, e.g., $AlSi_{10}Mg$, $AlSi_{12}$, A356, and A357 [7].

However, while significant progress has been made so far, the diffusion of this additive manufacturing technique by the industry is still limited given the lack of standardization of the process itself in terms of repeatability [8] and the high surface roughness of fabricated products [9]. Moreover, complexity in the geometry can induce local variations of the resulting properties due to the building direction [10]. Therefore, optimization of process parameters and consequently determination of effective final-part mechanical properties on both global and local scales need further investigation.

FIMEC (Flat-top cylinder Indenter for MEchanical Characterization) is a non-destructive and non-invasive testing methodology. Compared with other other indentation techniques, FIMEC uses a flat-top indenter tip, whose geometry is optimized to provide results that are not depended on local surface properties such as roughness [11], allowing local and global mechanical characterization of multiple materials [12]. Thanks to proven accuracy, ease of implementation, and great flexibility, FIMEC is of growing interest for several usage scenarios [13], including metal additive manufacturing, for which no known research works are available in the pertinent literature.

This study aims to evaluate the local and global mechanical properties of $AlSi_{10}Mg$ samples fabricated through LPBF by means of the FIMEC indentation test to highlight any variations induced by the combination of process parameters and building direction. The results are compared with the traditional tensile testing method to verify the suitability of the proposed solution to characterize the samples also for MAM processes.

Characteristic	Value				
Chemical composition [$wt\%$]	Al (78.38)	Si (18.93)	Mg (1.36)	C (0.94)	O (0.39)
Melting point [$°C$]	570				
Relative density [$g \cdot cm^{-3}$]	2.63				
Median diameter [μm]	37				

TABLE 1. Main characteristics of the metal powder as declared by the manufacturer.

2. MATERIALS AND METHODS

The starting material is a commercial powder of AlSi$_{10}$Mg from m4p Materials Solutions GmbH whose main characteristics are listed in Table 1.

FIMEC tests consisted of penetration of a tungsten carbide tip, 1 mm in diameter and 1.5 mm in height, to a certain depth (i.e., 0.8 mm) at a constant speed (i.e., 0.01 mm min^{-1}), according to the standard ASTM E2546. The tip was mounted on the MTS Insight electromechanical testing machine by MTS with 50 kN of nominal load that can appreciate a crosshead displacement with a resolution of 0.6 μmm (see Figure 1). The tests involved two steps, i.e., (i) loading phase and (ii) unloading to initial position. Penetration depth was taken from cross-head displacement. As suggested by the standards, three samples have been indented in five different positions (see Figure 2) to evaluate the eventual local variations of the final qualities.

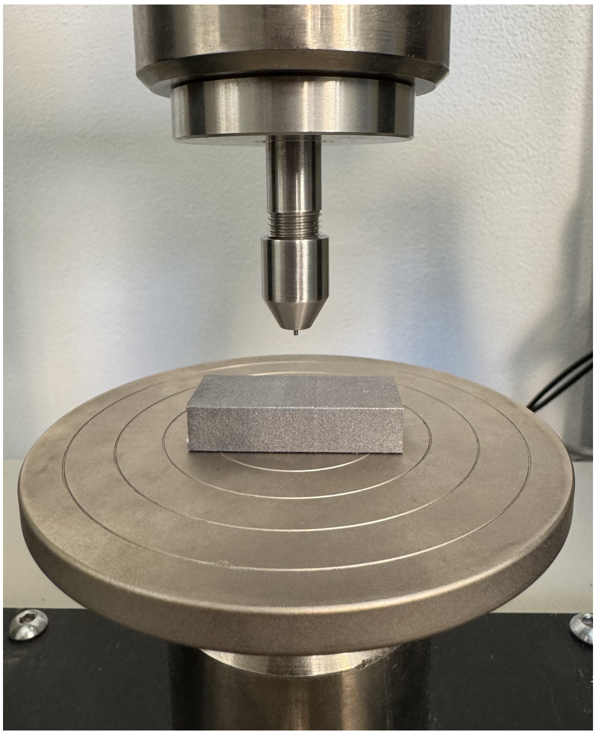

FIGURE 1. FIMEC setup.

The main mechanical properties that can be extrapolated from the pressure vs. depth curve obtained with the FIMEC test are the yield stress $\sigma_{\mathrm{Y,F}}$ and the elastic modulus E_{F}, using the inflection point P_{Y} of the loading part of the diagram and the slope S of the unloading portion, as shown in Figure 3, and according to the following equations [14]:

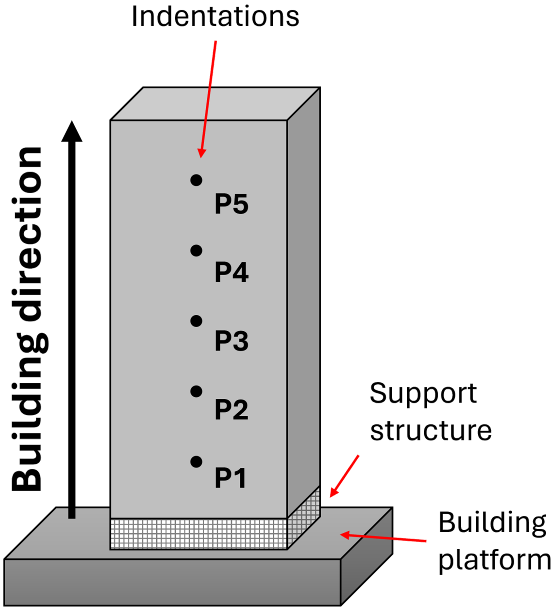

FIGURE 2. Schematization of the indentations along the building direction.

$$\sigma_{\mathrm{Y,F}} = \frac{P_{\mathrm{Y}}}{3}, \tag{1}$$

$$S = \frac{2}{\sqrt{\pi}} E_{\mathrm{a}} \sqrt{A}, \tag{2}$$

$$\frac{1}{E_{\mathrm{a}}} = \frac{(1-\nu_{\mathrm{F}}^2)}{E_{\mathrm{F}}} + \frac{(1-\nu_{\mathrm{i}}^2)}{E_{\mathrm{i}}}, \tag{3}$$

where E_{a} is the apparent elastic modulus calculated through the slope S, $A \approx 0.785\,\mathrm{mm}^2$, $E_{\mathrm{i}} = 668.35\,\mathrm{GPa}$, and $\nu_{\mathrm{i}} = 0.24$ are the section, the elastic modulus, and the Poisson ratio of the tip [15], while $\nu_{\mathrm{F}} = 0.36$ is the Poisson ratio of the material here investigated [16]. A total of three samples, each of one was tested in five different indentation position were tested during the experimental campaign, as shown in Figure 2.

Finally, the results were compared to traditional tensile tests of both LPBF-ed and die-casted samples carried out in a previous work [9].

3. RESULTS AND DISCUSSION

The characterization of the mechanical properties was carried out at a local level by means of indentation tests through a flat top cylinder tip. The aim was to highlight any dependence of mechanical performance in the direction of the building (see Figure 2), which

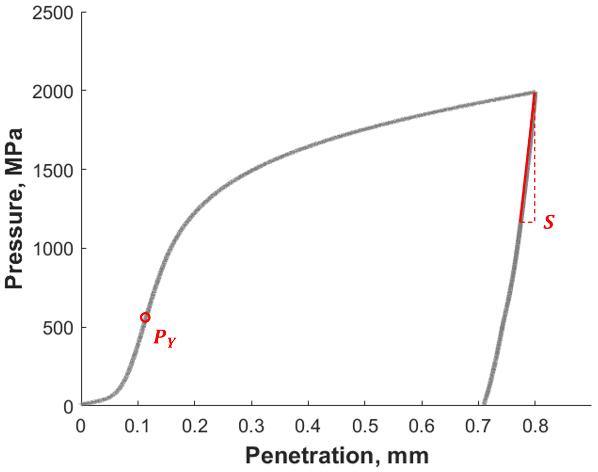

FIGURE 3. FIMEC test reference curve.

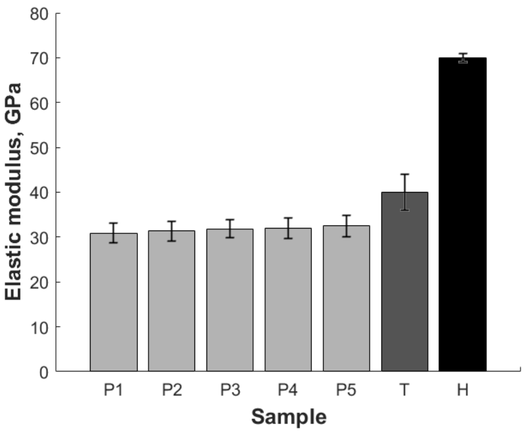

FIGURE 4. FIMEC test results: elastic modulus.

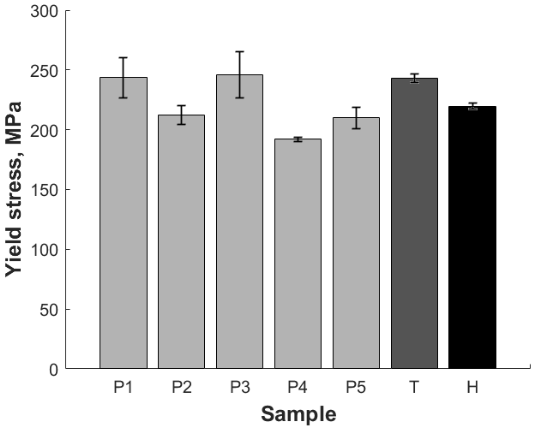

FIGURE 5. FIMEC test results: yield stress.

cannot be determined by traditional tensile testing methods.

The results of the FIMEC tests are shown in Figure 4 and 5. In the figures, “T” refers to the traditional tensile test carried out for LPBF samples. “H” refers to the traditional tensile test carried out for die-casted samples.

Figures 4 and 5 show a similar trend for both elastic modulus and yield strength between the two different approaches, when compared to LPBF samples, validating the newly proposed indentation test as a suitable alternative to the conventional method, also being non-destructive since it leaves only a very small imprint on the surface of the component [12]. Moreover, FIMEC diagrams provide additional information about the dependence of mechanical properties on the position in which they are evaluated [17]. This is very important for samples fabricated with LPBF because it is an additive manufacturing technique that involves the deposition of successive layers on top of the previous ones, thus potentially introducing anisotropy.

Figure 4 suggests that there is a change in the mechanical properties moving from the bottom to the top of the sample. Specifically, the bottom part of the specimen, named P1, appears to be characterized by the lowest value of elastic modulus, i.e., around 30.82 ± 2.16 GPa, up to 32.48 ± 2.47 GPa for P5 at the top. This finding can be attributed to the fact that the bottom part of the sample remains at high temperature longer than the upper part during the process, therefore experiencing a heat treatment able to partially relief the residual stresses [18].

A clear variation of the yield stress can be observed in Figure 5. Its distribution depends on the fabrication process, being the highest values in the bottom part of the samples (i.e., from P1 to P3), which is, as explained for the elastic modulus, the zone closer to the substrate where the cooling rate is higher, generating finer grains and therefore increasing the yield strength [19].

The measurement of the strength of the yield is probably influenced by microporosity, segregation, and microstructure, but the effect of the cooling rate on grain size can be considered the main influencing factor [13]. Comparing the results of the FIMEC test with “T” and “H” samples, it has to be reported that the elastic modulus of 3D printed samples is lower than die-casted samples due to difference in porosity, while the difference between traditional tensile test and FIMEC is related to lower speed test of the indentation methodology [11].

4. CONCLUSIONS

The FIMEC test recognizes the process history, allowing the quantification of the fabrication effect along the building direction of the sample geometry. Moreover, it can be considered as nondestructive since it leaves negligible indentation marks.

The comparison with traditional tensile test results demonstrates the suitability of the FIMEC indentation test to provide local and global information on the mechanical properties in terms of elastic modulus and yield strength.

Locally, the bottom part of the samples is characterized by the lowest values of the elastic modulus while ensuring high yield strength, because of the grain growth induced by the fact that the bottom part remains at high temperature longer.

Globally, the LPBF process allows to obtain similar characteristics in terms of yield stress, while the elastic modulus drops to half the value of traditional die-casted samples, probably due to the microporosity.

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