Effect of process parameters on the mechanical properties of a Titanium alloy fabricated by Electron Beam Melting (EBM)

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Abstract. Electron Beam Melting is a layer-by-layer additive manufacturing technique which proved to be very efficient and versatile in the fabrication of medical devices and automotive or aerospace components. Due to the highly innovative character of the technology, its potential is not yet fully exploited and a comprehensive understanding of how the different processing parameters may affect the mechanical performance of the resulting materials still deserves to be achieved. Tensile tests on a Titanium alloy (Ti-6Al-4V-ELI) are ran at static rates for investigating the effects of different fabrication parameters on the material response, namely the speed function, the line offset, the focus offset, the number of contours and the horizontal-vertical growing direction of the specimens. A combination of such parameters is identified as a “process setup” and different setups are adopted for producing corresponding series of specimens, machined after fabrication according to ASTM F2924 and ASTM E8 regulations. The experimental procedure relies on enhanced true stress-true strain data based on the optical measurement of the neck cross section of the specimen, as an alternative to the traditional elongation-based approach to the true stress-true strain evaluation. This approach allows to better highlight the effects of the different process setups on the material performance, by focusing on the most stressed/strained material points within the overall specimen volume. The true curves allow to relate the material performance in terms of both strength and ductility to each process setup, allowing to outline the influence of single/combined fabrication parameters on the two above performance indicators.

1. Introduction

Electron Beam Melting is a layer-by-layer additive manufacturing technique that proved to be very efficient and versatile in the fabrication of, among others, medical devices and automotive/aerospace components. According to the ASTM 52900, EBM is a powder bed fusion process. This means that “thermal energy selectively fuses regions of a powder bed” [1][2]. EBM builds parts in a high vacuum chamber providing an ideal contamination-free atmosphere for the printing of reactive materials, such as titanium alloys, that have a high affinity to nitrogen and oxygen [3]. Another advantage is that the deposition occurs at elevated temperatures (build temperature is higher than 700 °C), reducing residual stresses in the final part [4]. The EBM process consists of continuous repetition of four fundamental steps: 1) Spreading of a powder layer through the rake system. 2) Preheating of the powder layer to grow up the temperature close the melting temperature of the powder. 3) Melting the powder through the electron beam. 4) Lowering the production table by a certain quantity [5].
In very recent years, numerous alloys were processed by EBM. Among them, titanium alloys, with an emphasis on Ti-6Al-4V ELI, are commonly used in the aerospace and bioengineering industries because of their good mechanical properties [6][7], low density, and good corrosion resistance [8]. Furthermore, non-toxicity makes this class of materials a reference for a great variety of biomedical applications [9][10]. On the other hand, one of the major drawbacks is that the as-built components are characterized by a high surface roughness [11]. It is known that the processing of Ti6Al4V ELI is of great interest for several industrial applications but, despite some efforts in the literature [12][13][14], the link between processing conditions and properties of the parts is not fully understood. A lot of studies show results of parts fabricated by ARCAM EBM equipment used with automatic process parameter control. In these conditions, the printer, through a series of algorithms, continuously adjusts the beam parameters to optimize the deposition. The only way to obtain full control of the EBM process is to use the manual operation mode where it is allowed to change the value of each process parameter like the speed function, the focus offset, the line offset, and the number of contours (last two shown in Figure 1).

The speed function adjusts the scanning speed using a proprietary (ARCAM) automatic algorithm. It controls and maintains the thickness of the melting pool constant during the melting process keeping the ratio between current and speed constant. The line offset represents the distance between two successive beam lines, the standard default value is 0.1 mm [15].

![Figure 1. Line offset and number of contours.](image)

The focus offset controls the size of the spot generated by the beam of electrons incident the powder bed. The smaller the spot, the deeper the melting pool is between the layers of powder.

The main objective of this paper is to assess the influence of speed function, focus offset, line offset and number of contours on the mechanical properties of the Ti6Al4V ELI made by EBM. The influence of orientation of the parts in respect to the production plane will be evaluated through a specific experimental campaign. Experimental tensile test will be performed at static rates on a set of specimens made by EBM production under a set of specified combination of production parameters. Despite some efforts have been performed by the scientific community to obtain local material information from global tensile elongations [16], the used experimental procedure will be based on true stress-true strain data obtained by optical measurement of the neck cross section of the specimen [17][18][19][20], as an alternative to the traditional elongation-based approach. The results will be to understand the effects of the different process setups on the material performance.

2. Materials and Methods

The samples were fabricated with an ARCAM Q10 EBM machine (property of MT Ortho srl) using pre-alloyed Ti6Al4V ELI (Titanium grade 23) powder provided by Arcam. The size of the powder particles was within the range of 45 to 150 µm.

As widely recognized, “as-built” specimens do not necessarily need after-print CNC machining but, very often, they have geometric defects and high surface roughness not suitable for the repeatability of the mechanical tests. Therefore, for a large-scale comparative study, they are probably inadequate. On the other hand, CNC machined specimens present advantages in terms of repeatability of production processes, results and performance of the material, but they can be characterized by
possible modification of its response due to the mechanical processing. The choice fell on machined
specimens that were obtained from a block of solid material fused through EBM technology.

Regarding the geometry to be used, we referred to the ASTM E8 standard related to powder
metallurgy. The cylindrical samples were machined to obtain the ready-to-test samples shown in
Figure 2, with two ISO M8 threads at the specimens’ ends for appropriate coupling with the gripping
system. Moreover, a slight tapering is enforced by machining the diameter of the cross section varying
between 7 mm at the shoulders fillets and 6.9 mm at the mid length section.

Figure 2. Machined sample for mechanical test

Quasi-static tensile tests were carried out on a Zwick/Roell Z100 at a strain rate of 0.003 s\(^{-1}\). A
high-resolution video camera (1280x960) was used to record the evolution of the profile of the sample
during the test, especially in the post-necking phase, while a clip gage has been used in order to
evaluate more accurately the elastic properties of the material. The complete experimental setup is
shown in Figure 3.

The first experimental campaign concerned the study of the influence on the material
characteristics of the orientation of the specimens with respect to the production plane. Two
cylindrical samples were built perpendicularly to the production plane and two other samples were
built horizontally (Figure 4), using the default process parameters shown in Table 1. The thickness of
the powder layer was set to 50 \(\mu\)m and the building plate, following the default procedure, was
preheated to a temperature of about 730 °C before the printing process. The entire job was performed
under a controlled vacuum of 10\(^{-3}\) mbar in the chamber. In particular, the purpose of this first group of
tests was to evaluate which one of the two orientations allowed to obtain the best repeatability in terms
of the mechanical performance of the material.

Table 1. Default Process parameter used for EBM

| Speed Function | Focus offset (mA) | Line Offset (mm) | Number of contours |
|---------------|------------------|-----------------|-------------------|
| 46            | 32               | 0.2             | 3                 |

Figure 4. First Experimental campaign: Orientation
The second and third experimental campaigns were focused on the study of the influence on the material behaviour of the process parameters “speed function”, “focus offset”, “line offset”, and “number of contours”. For each configuration of process parameters, two identical specimens have been made to evaluate the repeatability of the results. The complete experimental campaign is shown in Table 2.

### Table 2. Experimental campaign

| Campaign | Specimen Code | Horizontal | Vertical | Speed Function | Focus Offset | Line Offset | N. of contours |
|----------|---------------|------------|----------|----------------|--------------|-------------|----------------|
| 1        | TESTORIZZ     | x          |          | 46             | 32           | 0.2         | 3              |
| 1        | TESTVERT      |            | x        | 46             | 32           | 0.2         | 3              |
| 2        | SF36          | x          |          | 36             | 32           | 0.2         | 3              |
| 2        | SF56          | x          |          | 56             | 32           | 0.2         | 3              |
| 2        | FO22          | x          |          | 46             | 22           | 0.2         | 3              |
| 2        | FO42          | x          |          | 46             | 42           | 0.2         | 3              |
| 2        | LO05          | x          |          | 46             | 32           | 0.5         | 3              |
| 2        | LO075         | x          |          | 46             | 32           | 0.75        | 3              |
| 2        | NC5           | x          |          | 46             | 32           | 0.2         | 5              |
| 2        | NC7           | x          |          | 46             | 32           | 0.2         | 7              |
| 3        | SF30          | x          |          | 30             | 32           | 0.2         | 3              |
| 3        | SF60          | x          |          | 60             | 32           | 0.2         | 3              |
| 3        | LO01          | x          |          | 46             | 32           | 0.1         | 3              |
| 3        | LO08          | x          |          | 46             | 32           | 0.8         | 3              |
| 3        | SF56_LO075    | x          |          | 56             | 32           | 0.75        | 3              |
| 3        | SF56_LO05     | x          |          | 56             | 32           | 0.5         | 3              |
| 3        | SF36_LO075    | x          |          | 36             | 32           | 0.75        | 3              |
| 3        | SF36_LO05     | x          |          | 36             | 32           | 0.5         | 3              |

For each test, the engineering and true stress-strain curves were obtained, together with the Young modulus, ultimate tensile strength, and elongation values.

To obtain the engineering curves, the well-known eqs. (1) and (2) have been used. Two nominal gage lengths are used: 10 mm for the mechanical extensometer and 30 mm for the optical extensometer; the mechanical measurement of the elongation was limited to the early plastic range, while the optical one was extended up to failure; optical elongation measurements were carried out by image scaling and pixel counting.

\[
\sigma_{eng} = \frac{F}{A_0} \quad (1)
\]

\[
\varepsilon_{eng} = \frac{\Delta L}{L} = \frac{L - L_0}{L_0} = \frac{L}{L_0} - 1 \quad (2)
\]

The true curves were obtained analysing optically the evolution of the diameter of the specimen, with the well-known eqs. (3) and (4).

\[
\sigma_{true} = \frac{F}{A} \quad (3)
\]

\[
\varepsilon_{true} = 2 \ln \frac{d_0}{d} \quad (4)
\]
3. Results

3.1. Horizontal and vertical specimens
The objective of the first experimental campaign was to understand how the different positioning of the specimens in respect to the production plane affects the mechanical characteristics of the material and their repeatability.

The engineering stress-strain curves obtained from the horizontal and vertical specimens are shown in Figure 5. All the curves show a similar maximum tensile strength. Moreover, all the first elastic phases are well-matched. On the other hand, the horizontal specimens have a greater elongation-based engineering strain at fracture than the vertical ones. Furthermore, there is much more dispersion in the post-necking phase between the vertical curves than between the horizontal ones.

![Figure 5. Horizontal Vs Vertical Engineering curves](image)

![Figure 6. Horizontal Vs Vertical True curves](image)

The diameter-based true stress-strain curves obtained from the horizontal and vertical specimens are shown in Figure 6. In this case, all curves are very similar to each other, with a maximum dispersion of 5%. The true deformations at fracture of the vertical specimens are greater than those of the horizontal specimens, which is exactly the opposite of what was found with the engineering curves. This fact confirms once again that the vertically printed specimens have greater variability of the quality of the printed material between the processing layers and, in turn, between the different single resistant sections. On the other hand, in the horizontal specimens, the differences between layers act uniformly on the whole length of the specimen and, therefore, do not determine single sections with different strengths affecting the overall specimen response. Another confirmation of this fact is that one of the vertical specimens did not show a centred necking (Figure 7), despite being all the specimens are slightly tapered with the minimum cross-section. Necking and failure stresses and strains of the horizontal and vertical specimens are shown in Table 3. Concluding the first experimental campaign, in order to have greater repeatability of the test results, only specimens printed with the horizontal orientation have been considered in the successive phases of the study.

| Table 3. Horizontal Vs Vertical specimens tests results |
|------------------------------------------------------|
| Campaign | Specimen Code | Necking σtrue [MPa] | Necking εtrue [ ] | Failure σtrue [MPa] | Failure εtrue [ ] |
|-----------|---------------|---------------------|------------------|---------------------|------------------|
| 1         | Horizontal test 1 | 1077 | 0.062 | 1296 | 0.498 |
| 1         | Horizontal test 2 | 1082 | 0.068 | 1282 | 0.544 |
| 1         | Vertical test 1 | 1080 | 0.077 | 1351 | 0.601 |
| 1         | Vertical test 2 | 1065 | 0.057 | 1302 | 0.648 |
3.2. Changing the process parameters

Figure 8 and Table 4 show the obtained results with specimens printed changing only the speed function value and keeping all the other parameters as standard. In Figure 8 and in all the following ones, the yellow line represents the true stress-strain curve obtained with standard parameters. Increasing the speed function delivers improvements in both material strength and ductility, until a peak optimum value of the speed function equal to 56. Indeed, for speed function values higher or lower than 56, the obtained true curves are lower and shorter.

Table 4. Tests results of the specimens with different Speed Functions

| Campaign | Specimen Code | UTS [MPa] | $\varepsilon_{\text{true}}$ necking | $\varepsilon_{\text{true}}$ failure |
|----------|---------------|-----------|-------------------|------------------|
| 2        | SF 30         | 947.83    | 0.069             | 0.413            |
| 2        | SF 36         | 1011.72   | 0.068             | 0.492            |
| 2        | SF 56         | 1060.87   | 0.066             | 0.569            |
| 2        | SF 60         | 1002.92   | 0.071             | 0.496            |

Figure 8. True curves of the specimens with different Speed Functions

Figure 9 and Table 5 show the obtained results with specimens printed only changing the line offset value and keeping all the other parameters as standard. Increasing the line offset delivers improvements of both material strength and ductility until a peak optimum value of the line offset equal to 0.75.
Table 5. Tests results of the specimens with different Line Offsets

| Campaign | Specimen Code | UTS [MPa] | $\varepsilon_{\text{true}}$ necking [\%] | $\varepsilon_{\text{true}}$ failure [\%] |
|----------|---------------|-----------|---------------------------------|---------------------------------|
| 2        | LO 0.1        | 970.80    | 0.070                           | 0.572                           |
| 2        | LO 0.5        | 1007.41   | 0.071                           | 0.587                           |
| 2        | LO 0.75       | 1055.60   | 0.060                           | 0.619                           |
| 2        | LO 0.8        | 997.38    | 0.069                           | 0.510                           |

Figure 9. True curves of the specimens with different Line Offsets

Figure 10 and Table 6 show the obtained results with specimens printed changing only the focus offset value and keeping all the other parameters as standard. Increasing the focus offset of nearly 100% does not affect both the strength and the ductility of the resulting material.

Table 6. Tests results of the specimens with different Focus Offset

| Campaign | Specimen Code | UTS [MPa] | $\varepsilon_{\text{true}}$ necking [\%] | $\varepsilon_{\text{true}}$ failure [\%] |
|----------|---------------|-----------|---------------------------------|---------------------------------|
| 2        | FO 22         | 1040.23   | 0.071                           | 0.476                           |
| 2        | FO 42         | 1032.40   | 0.065                           | 0.514                           |

Figure 10. True curves of the specimens with different Focus offset

Figure 11 and Table 7 show the obtained results with specimens printed changing only the number of contours value and keeping all the other parameters as standard. Increasing the number of contours of nearly 50% does not affect both the strength and the ductility of the resulting material. This was highly expectable because specimens are machined.
Table 7. Tests results of the specimens with different Number of contours

| Campaign | Specimen Code | UTS [MPa] | $\varepsilon_{\text{true necking}}$ | $\varepsilon_{\text{true failure}}$ |
|----------|---------------|-----------|-------------------------------------|-------------------------------------|
| 2        | NOC 5         | 1046.21   | 0.044                              | 0.588                              |
| 2        | NOC 7         | 1058.27   | 0.055                              | 0.581                              |

Figure 11. True curves of the specimens with different Nr. of contours

Figure 12 shows the obtained true curves with specimens printed changing both the speed function and line offset values and keeping all the other parameters as standard. With the same value of SF, the variation of line offset does not affect both the strength and the ductility of the resulting material. For different values of SF (with LO fixed) the graph shows an improvement of the material features at higher SF values.

Figure 12. True curves of the specimens with different combined values of Speed Function and Line Offset

4. Conclusion
The results of the experimental campaigns can be summarized in the following points:

- The specimens printed perpendicularly and parallelly to the building plane give slightly different true stress-strain curves; moreover, perpendicular specimens present a higher dispersion in the test results, reasonably caused by the differences between the mechanical properties of different cross sections which, for the vertical specimen orientation, belong to different layers that are printed in different phases of the fabrication process under possibly slightly different printing
conditions. Therefore, horizontally printed specimens are more suitable for a consistent analysis of the influence of the process parameters on the mechanical characteristics of the material.

- The speed function largely affects the mechanical properties of the material: starting from the default setting, greater values deliver better material strength and ductility until an optimum peak value of 56.
- The line offset affects the mechanical properties of the material: starting from the default one, greater values deliver better material strength and ductility until an optimum peak value of 0.75 mm.
- To change the focus offset and number of contours values in respect to the default ones shows no influence on the mechanical behaviour of the material.
- The curves obtained with the specimens printed changing simultaneously the line offset and speed function values shown that the speed function is the most decisive parameter among the studied ones regarding the mechanical performance of the resulting printed material.

References
[1] Frazier W J 2014, Metal additive manufacturing: a review. J. Mater. Eng. Perform. 23(6), 1917–1928.
[2] Herzog D, Seyda V, Wycisk E and Emmelmann C 2016, Additive manufacturing of metals. Acta Mater. 117, 371–392.
[3] Liu S and Shin Y C 2019, Additive manufacturing of Ti6Al4V alloy: A review. Mater. Des. 164, 107552.
[4] Silvestri A T, Foglia S, Borrelli R, Franchitti S, Pirozzi C and Astarita A 2020, Electron beam melting of Ti6Al4V: Role of the process parameters under the same energy density. J. Manuf. Process., 60, 162-179.
[5] Körner C 2016, Additive manufacturing of metallic components by selective electron beam melting—a review. Int. Mater. Rev. 61(5), 361-377.
[6] Mirone G, Barbagallo R, Corallo D and Di Bella S 2016, Static and dynamic response of titanium alloy produced by electron beam melting. Procedia Struct. Integr. 2, 2355-2366.
[7] Mirone G, Barbagallo R, Giudice F and Di Bella S 2020, Analysis and modelling of tensile and torsional behaviour at different strain rates of Ti6Al4V alloy additive manufactured by electron beam melting (EBM). Mater. Sci. Eng. A, 793, 139916.
[8] Chastand V, Quaegebeur P, Maia W and Charkaluk E 2018, Comparative study of fatigue properties of Ti-6Al-4V specimens built by electron beam melting (EBM) and selective laser melting (SLM), Mater Charact, 143, 76-81.
[9] Elias C N, Lima J H C, Valiev R and Meyers M A 2008, Biomedical applications of titanium and its alloys. JOM, 60(3), 46-49.
[10] Hao Y L, Li S J and Yang R 2016 Biomedical titanium alloys and their additive manufacturing. Rare Met., 35(9), 661-671.
[11] Galati M, Minetola P and Rizza G 2019, Surface roughness characterisation and analysis of the Electron Beam Melting (EBM) process, Materials, 12(13), 2211.
[12] Prisco U, Astarita A, El Hassanin A and Franchitti S 2019, Influence of processing parameters on microstructure and roughness of electron beam melted Ti-6Al-4V titanium alloy, Mater. Manuf. Process., 34(15), 1753-1760.
[13] Wang X, Gong X and Chou K 2015, Scanning speed effect on mechanical properties of Ti-6Al-4V alloy processed by electron beam additive manufacturing, Procedia Manuf., 1, 287-295.
[14] Ge W, Guo C and Lin F 2014, Effect of process parameters on microstructure of TiAl alloy produced by electron beam selective melting, Procedia Eng., 81, 1192-1197.
[15] Shao M, Vijayan S, Nandwana P and Jinschek J R 2020, The effect of beam scan strategies on microstructural variations in Ti-6Al-4V fabricated by electron beam powder bed fusion.
[16] Mirone G, Verleysen P and Barbagallo R 2019, Tensile testing of metals: Relationship between macroscopic engineering data and hardening variables at the semi-local scale, *Int. J. Mech. Sci.*, **150**, 154-167.

[17] Zhang L, Gour G, Petrinic N and Pellegrino A 2020, Rate dependent behaviour and dynamic strain localisation of three novel impact resilient titanium alloys: Experiments and modelling, *Mater. Sci. Eng. A*, **771**, 138552.

[18] Mirone G, Barbagallo R and Giudice F 2019 Locking of the strain rate effect in Hopkinson bar testing of a mild steel. *Int. J. Impact Eng.* **130**, 97-112.

[19] Mirone G, Corallo D and Barbagallo R 2016 Interaction of strain rate and necking on the stress-strain response of uniaxial tension tests by Hopkinson bar. *Procedia Struct. Integr.*, **2**, 974-985.

[20] Mirone G and Barbagallo R 2021 How sensitivity of metals to strain, strain rate and temperature affects necking onset and hardening in dynamic tests. *Int. J. Mech. Sci.*, **195**, 106249.