# Structure and machinability of thin-walled parts made of titanium alloy powder using electron beam melting technology

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**Abstract**
The present paper aims to study the structure and properties of raw and thermal treated titanium-based powder material that is used to produce thin-walled components by electron beam melting technology. Producing the end product means also studying the finishing cutting process. Examining the quality of end product in terms of geometric tolerance and thin walls thickness stability as well as control the surface roughness is also included in this study.

Keywords. Electron beam melting, microstructure, machinability, titanium alloy powder, additive manufacturing.

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## 1. Introduction

Nowadays, the additive manufacturing (AM) processes are extensively used to produce various kinds of machine components, including metal ones. One of the most widespread AM technologies is electron beam melting (EBM) which produces parts by melting metal powder layer by layer with an electron beam in high vacuum. Unlike other techniques, e. g. direct metal laser sintering (DMLS), selective laser sintering (SLS) etc., parts made by the EBM are fully dense, void-free, and very strong.

Thin-walled parts are widely used in various products of aerospace, power engineering, fine mechanics and others, where lightweight, high usability and ergonomics are required. In some cases, thin-walled components having complex geometry have to be produced using the AM technologies and further be machined either by traditional methods (turning, milling, grinding etc.), or by non-traditional ones, like electrical discharge machining or water jet cutting.

Milling is one of the most common machining method used in thin-walled part processing. Cutting and clamping forces acting during removal of chip produce the deflections of walls that are comparable with the machining stock thickness [1]. The specific microstructure of the parts made using the AM technologies causes additional instability of the machining process. Those deflections and process instability result in machining error that depends on wear of cutting tool, cutting conditions, parameters of the machine-workpiece-tool system, and other factors [2]. In practice, the type of milling (conventional or climb) dramatically influences the processing accuracy and machined surface roughness. Therefore, it is important to figure out how the machining errors vary with the change of operation conditions and material characteristics.

## 2. Material characterization

The raw (as-built) sample parts made of VT-6 titanium alloy powder (equivalent to Ti 6Al-4V) with the average powder grain size ~70 µm using the Arcam A2 EBM system (Sweden) have the specific microstructure caused by the non-uniform thermal conditions of crystallizing and cooling of titanium alloy in vacuum chamber [3]. The X-ray diffraction phase analysis showed that the sample parts consist of A2 type structure (β-Ti, up to 10% by volume) and A3 type structure (α-Ti, up to 90% by volume). The typical microstructure of the raw parts in different cross-sections is shown in *Fig. 1*. This microstructure is characterized with specific stroke pattern. When melting the powdered metal, grains of β-Ti stretch along the direction of the metal flow. During cooling the parts in the vacuum chamber, when temperature goes down to the α-Ti precipitation, rate of β-Ti growth slows down. Regardless the cooling rate, α-Ti phase precipitates on β-Ti defects and along the metal flow. In *Fig. 1.a* the microstructure of the layer parallel to the horizontal XY plane (base plane) where the melting is performed, is shown. In *Fig. 1.b,* long horizontal lines correspond the layers of the part, while vertical lines in *Fig. 1.c* coincide with the tracks columns.

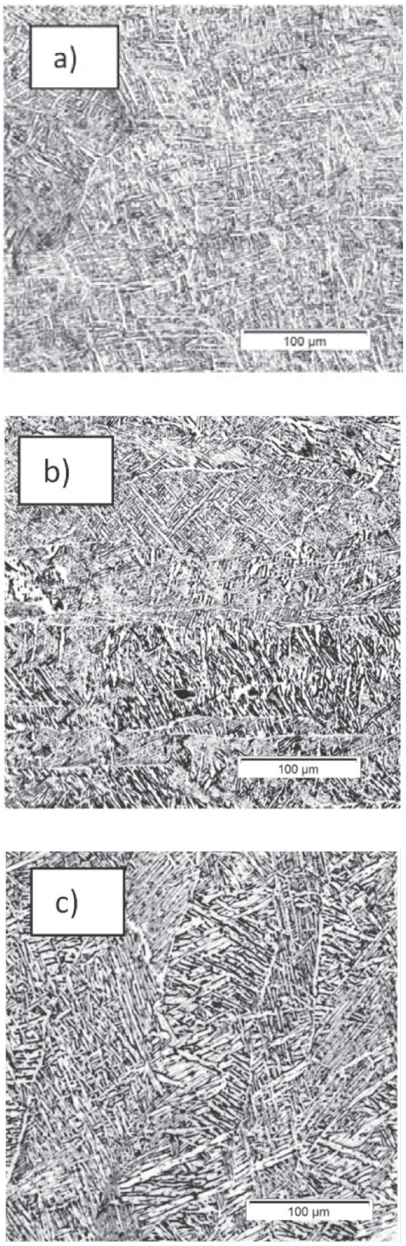

*Fig. 1. Microstructure of parts produced by the Arcam A2 EBM system in cross-section planes: a) XY; b) YZ; c) XZ*
*1. ábra Arcam A2 EBM technológiával gyártott alkatrészek mikroszerkezete az a) XY; b) YZ; c) XZ keresztmetszetekben*

The raw material characterization in different cross-section planes is shown in *Table 1*. As it is shown there, the content of α-Ti and β-Ti depends on the cross-section plane orientation.

At the same time, regardless the cross-section plane orientation, the same structure can be seen in the microsection. On the former β-Ti grain boundaries spherical α-Ti grains start to grow (*Fig. 2.a*). With the cooling rate increasing (possibly when the electron beam moves away from the melting region), new α-Ti grains becomes platy (Widmanstätten patterns). Between the plates of α-Ti some retained β-Ti grains can be observed, whilst the α-Ti grains contain a few number of micro-inclusions, that could be either needle-like precipitates of α-Ti oriented normally to the surface of microsection, or some unknown third phase.

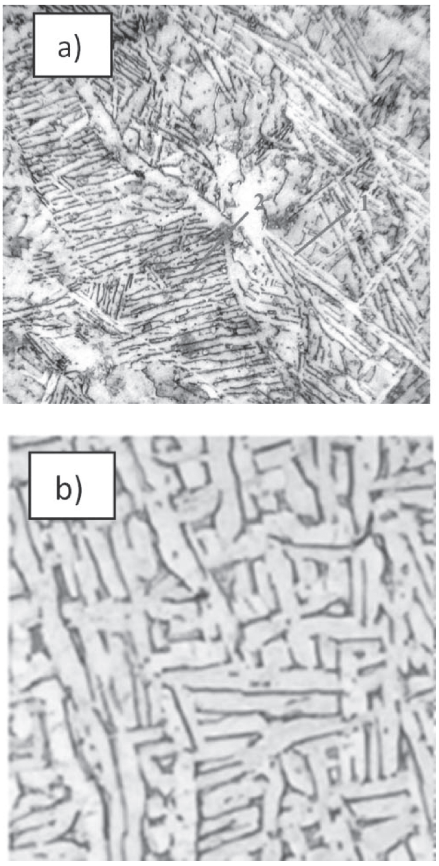

*Fig. 2. Comparison of the raw (a, 200×) and heat treated (b, 500×) microstructures*
*2. ábra A nyers (a, 200x) és hőkezelt (b, 500x) próbatestek mikroszerkezetének összehasonlítása*

The precipitating α-phase has larger grain size. This is the reason of residual tensile stresses in the end product. Thus, recrystallization annealing is recommended to lower these stresses. In the present work, the hot isostatic pressing (HIP) was applied to the sample part (hot isostatic press AIP8-30H (USA), 920 °C, 1000 Bar, 120 min). The microstructure after the HIP is shown in Fig. 2.b. It is obvious that the structure became much more homogenous in all cross-section planes. Consequently, the mechanical properties of the part are more isotropic than in the raw material. On the other side, the effect of HIP is just about 3-4%. Actually, this small difference in properties between HIP and raw is an indication of a defect-free product.

| Phase | Lattice parameter | Volume ratio in XY plane | Weight content in XY plane | Volume ratio in ZY plane | Weight content in ZY plane | Volume ratio in ZX plane | Weight content in ZX plane |
|---|---|---|---|---|---|---|---|
| **β-Ti** | a=2.92 Å,<br>c=4.683 Å | 7.0 ± 0.2 | 7.3 ± 0.2 | 4.9 ± 0.1 | 5.1 ± 0.1 | 10.0 ± 0.1 | 10.4 ± 0.1 |
| **α-Ti** | a=2.912 Å | 93.0 ± 0.2 | 92.7 ± 0.2 | 95.1 ± 0.1 | 94.9 ± 0.1 | 90.0 ± 0.1 | 89.6 ± 0.1 |

*Table 1. VT-6 titanium alloy characterization*
*1. táblázat VT-6 titánötvözet jellegzetességei*

## 3. Experimental procedure

The geometric parameters of the EBM-parts do not match the initial 3D model. In addition, the side faces of the EBM-parts have stochastic irregular surface. Thus, to provide the end product quality, it is necessary to machine the parts using some traditional methods like milling or grinding [4].

A sample part to be machined during the experiment is shown in *Fig 3.a*. Four series of experiments were conducted with the wall thickness *t* of 1.5 mm, 1.0 mm, 0.5 mm and 0.3 mm. Finishing cutting speed: 188 m/min; feed rate: 0.03 mm/tooth; depth of cut: 0.5 mm; width of cut: 3.6 mm. The part was machined downwards in 5 passes. Walls thickness measurement scheme is shown in *Fig. 3.b*. To measure vibrations generated during the machining process, a measuring information system has been used [5].

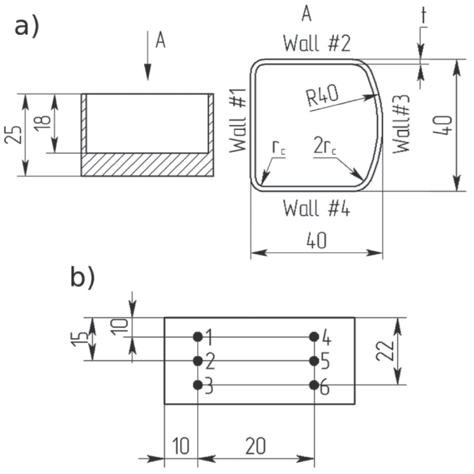

*Fig. 3. Sample part (a) and walls thickness measurement scheme (b)*
*3. ábra A minta alakja (a) és a falak vastagság mérésének elve (b)*

Fig. 4 indicates the line graph of walls thickness measured in corresponding points from the top of the workpiece. Fig. 4.a shows that relatively thick walls (t = 1.5 mm) gets thicker towards the bottom of the workpiece, especially for conventional milling, because in this type of milling a normal component of cutting force acts towards the axis of the cutter making the body of the cutter to slightly increase its radial runout and to deviate from the relatively stiff wall being machined. While the point of contact between the cutting edge and the surfaceof the part moves downwards during the machining process, the stiffness of the wall increases and the deviations of the cutter and runout become smaller, that leads to increasing wall thickness towards the bottom. In addition, the chips disposed before the cutter can also affect the milling cutter and increase the thickness of the walls. In climb milling, the width of the cut starts at the maximum producing less friction forces [6]. The normal component of the cutting force acts in a direction of the relatively stiff wall. The chips are disposed behind the cutter. This provides less deviations of the cutter and hence less walls thickness variation.

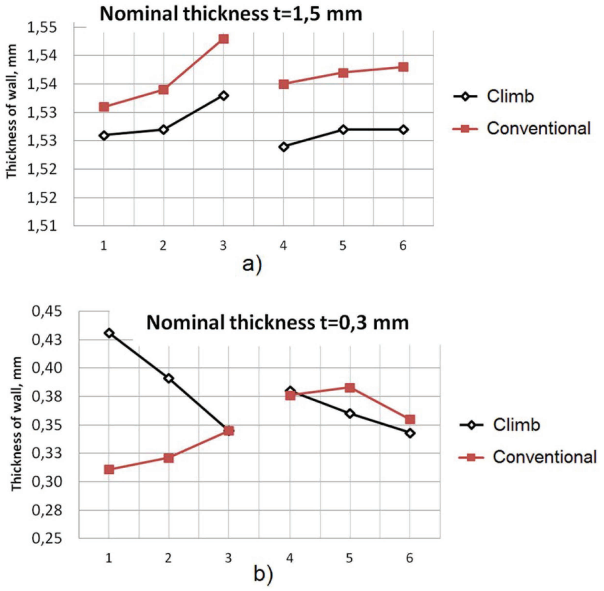

*Fig. 4. Walls thickness variations depending on the measuring point and milling type*
*4. ábra A falvastagság változása a mérési hely és a koptatási mód függvényében*

This situation changes as the walls are getting thinner and their stiffness decreases (Fig. 4.b). In this case, the walls deform more than the cutter does. In climb milling, the top part of the walls deviates from the body of the cutter and gets thicker than their lower part. Conversely, in conventional milling the walls become thicker to the bottom part of the workpiece, and the mean thickness of the wall is closer to its nominal value.

The roughnesses of the wall #1 and the smaller inner corner surface was performed using the contact profilometer. The climb milling provides slightly better roughness (Ra = 0.2-0.4 μm) than the conventional one (Ra = 0.3-0.7 μm) when machining relatively thin walls (0.5 mm or thinner). Both conventional and climb milling produces very rough surface in the corners of small radii in comparison with the rest of surfaces being machined (Ra = 2.0-7.8 μm). Though the roughness of the curved surface of relatively large radius (the wall #3) could not be measured directly with a contact profilometer, it has obviously a better roughness than other surfaces of the sample part. It can be explained by the higher stiffness on the curved wall that produces less chattering of the elastic system of machine-tool-workpiece.

Surfaces of the walls with t = 0.3 mm machined under different cutting conditions are shown in Fig. 5. In Fig. 5.a, the periodic milling marks left after climb milling are visible. In

Fig. 5.b, the wall machined by conventional milling where there is a lot of spots left by chip, is shown. Fig. 5.c represents the curved wall #3 which has visibly lower roughness than other surfaces. Fig. 5.d shows a very rough surface in the corner of small radius which is equal to the radius of the milling cutter.

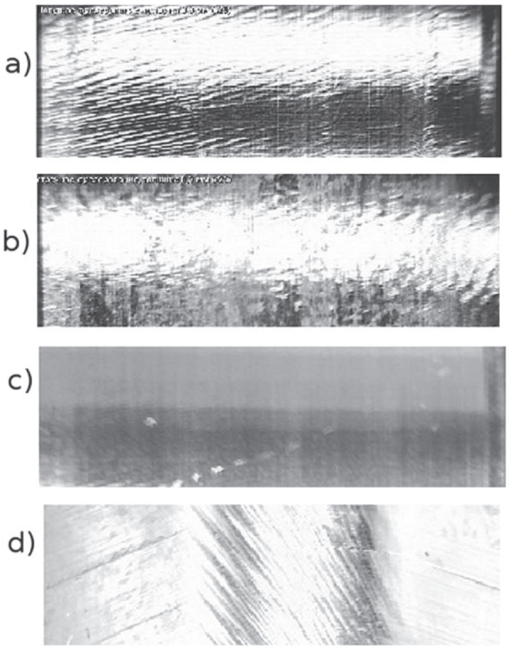

*Fig. 5. Surfaces of the walls with t = 0.3 mm: a) climb milling; b) conventional milling; c) climb milling of the curved wall; d) climb milling of the corner with a small radius*

*5. ábra A t=0,3 mm falvastagságú alkatrész felületének minősége a) egyenirányú és b) hagyományos koptatásnál illetve c) íves felületeken illetve d) kis rádiuszú sarokban*

## 4. Vibroacoustic signal analysis

During the milling process a vibroacoustic signal was recorded using the accelerometer installed on the table of the machine [7]. The samples of the vibroacoustic signal for conventional and climb milling are shown in Fig. 6. In conventional milling, non-repetitive accidental peaks of up to 0.3 ms width have been observed. These peaks are caused by chips disposed before the milling cutter, as it was shown above, and result in a poor appearance of the surface of the walls (spots and strokes), although a roughness parameter Ra has not been significantly changed on these parts of surface. The appearance of the waveform both for raw and heat treated materials is very similar.

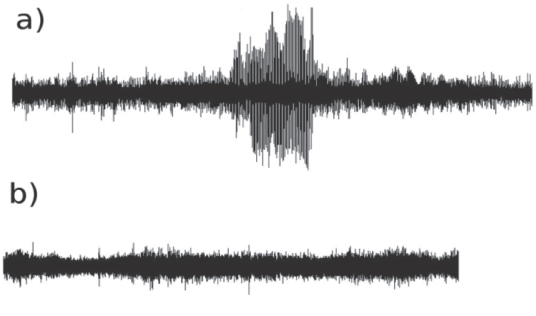

*Fig. 6. Vibroacoustic signal for conventional (a) and climb (b) milling processes*

*6. ábra Vibroakusztikus jel hagyományos (a) és lüktető (b) felület-megmunkáláshoz*

The vibration acceleration spectra for climb and conventional milling are represented in Figs. 7.a and 7.b, respectively. These waveforms were obtained for the last pass of the cutter that have been moved along the bottom surface of the workpiece, where a large amount of chip affects the machining process.

The spectra presented in Fig. 7 have their maximum amplitudes at double tooth frequency (2×$f_{tooth}$) and the local maximum amplitudes at frequencies multiple to the rotation of the cutter ($f_{rot}$). However, for the conventional milling the amplitude of vibroacoustic signal at high frequencies is significantly lower than the maximum at 2×$f_{tooth}$. It means decrease of impacts when the teeth enter and exit the workpiece which is caused by the chip-disposal effect described above.

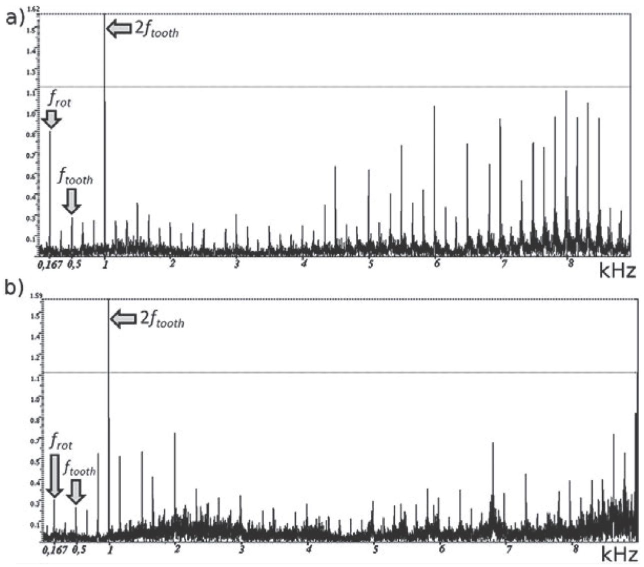

*Fig. 7. Vibration acceleration spectra of climb (a) and conventional (b) milling*

*7. ábra A vibrációs gyorsulási spektrumok lüktető (a) és hagyományos (b) felületmegmunkálás esetén*

## 5. Summary

According to the results of the present study, the microstructure and material properties of EBM parts in the base horizontal plane and in vertical ones are different, i. e. the raw EBM samples structure and properties are anisotropic. Annealing of the parts produced by EBM has no significant affect on the machining process and the resulted surface properties.

When milling EBM thin-walled parts, the form accuracy and the surface roughness are the functions of variable wall stiffness, which is estimated in a local cutting zone. This fact must be taken into account when selecting the cutting conditions.

Milling of surfaces with low stiffness is a dynamically unstable process which produces vibrations (chattering) and relatively large displacements of the cutter and the workpiece. These vibrations are lower when conventional milling is used, but the surface roughness is significantly higher due to the chip disposed at the cutting zone.

When designing thin-walled parts, it is desirable to replace flat surfaces with curved ones, if possible, as the curved surface provides a higher stiffness and hence a better surface roughness and less deviations of the form.

Use of vibroacoustic analysis seems to be feasible when technological process of thin-walled parts machining is developed, since it helps to efficiently detect and estimate the undesirable effects.

## 6. Acknowledgement

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### Titán ötvözetporból elektronsugaras olvasztással gyártott vékonyfalú alkatrészek anyagszerkezete és megmunkálhatósága

Jelen tanulmány célja a titán ötvözetporból elektronsugaras olvasztási technológiával gyártott vékonyfalú alkatrészek anyagszerkezetének és felület-megmunkálási módszereinek vizsgálata és összehasonlítása. A szerzők külön vizsgálják és tanulmányozzák a titán ötvözetporok előzetes hőkezelésének hatását a gyártott termék anyagszerkezetére és megmunkálhatóságára - különös tekintettel a vékonyfalú alkatrészek gyártásakor.

Kulcsszavak: elektronsugaras olvasztás, mikroszerkezet, megmunkálhatóság, titán ötvözetpor, adalékanyag, gyártás