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Helical milling of bore holes in Ti6Al4V parts produced by selective laser melting with simultaneous support structure removal

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Abstract

Selective Laser Melting (SLM) is a powder bed based Additive Manufacturing (AM) process that is currently being established in the series production of Ti6Al4V components in the aviation industry. One advantage is the significantly lower Buy-to-Fly ratio. However, subsequent machining is necessary in order to remove support structures of the SLM process and to fulfill quality requirements.

Experimental results on support structure removal and simultaneous finishing of holes by helical milling are presented.

Engagement conditions in helical milling are strongly influenced by the support structure. Material removal rates in both peripheral and axial direction are calculated and agree well with the variation of measured forces in these directions. In addition, the surface roughness of the machined holes is affected by the support structure design and may change along the hole perimeter.

The findings indicate how support structures should be designed in order to obtain high quality bore holes in one machining step.

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Keywords: helical milling, SLM, support structure removal, force, surface roughness, modeling, titanium

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1. Introduction

With its high specific strength, high corrosion resistance and low density, titanium is an established lightweight material in the aviation industry. Usually, parts of high diversity are produced by high-performance volume metal cutting of sheet metal or forged plates. The machining process leads to significant chipping volumes of up to 95 % Buy-to-Fly ratio (volumetric fraction of chips to semi-finished product). This leads to a great demand for alternative production processes such as Additive Manufacturing (AM) [1-5].

AM offers several advantages, including low material use compared to conventional subtractive processes. The design process of AM parts is not limited by the constraints of conventional processes, so bionic designs are more easily achieved.

Selective Laser Melting (SLM) is an important AM process used to generate metallic parts. Here, layers of powdered material are consecutively added and melted to form the part. Before each new layer of powder is applied, the intersection of the current layer and the final part is exposed to a high-power laser, binding the current layer to the layer below by melting. However, the SLM-process requires temporary support structures for slim or overhanging part geometries, cavities or heat dissipation which have to be removed subsequently [6]. An example for developing cavities are bore holes with an axis not aligned vertically in the build chamber. Independent of the necessity for support structures, functional surfaces, e.g. for fits or seals, cannot be produced directly by SLM but require precision machining to fulfill surface roughness and quality requirements [7].

Ti6Al4V is difficult to machine due to its high yield strength and ultimate strength, its low Young's modulus of elasticity and its low thermal conductivity, which result in high static and dynamic cutting forces. Therefore, productivity is limited by occurrence of chatter vibrations and high tool wear [1,4,5,8].

For the combined removal of support structures and precision machining of bore holes, helical milling may be used. Helical milling is able to produce variable bore hole diameters without the need of changing the tool. In addition, chip formation compared to conventional drilling is better, as chips are formed discontinuously and are removed without forced contact to the bore hole surface [9-10].

Helical milling is characterized by complex engagement conditions which have to be distinguished for axial and peripheral direction. Material removal rates can be modelled mathematically, which allows drawing conclusions on cutting forces and resulting tool deflections in helical milling [11-12]. Existing models apply for helical milling of solid materials, whereas in case of parts generated by SLM, the material volume to be removed is given by the support structure design.

In this paper, kinematic modelling of axial and peripheral material removal rates as well as measured forces and surface roughnesses in combined removal of various support structures and hole finishing by helical milling are presented.

2. Kinematic Modelling of Helical Milling of Support Structures

Kinematic modelling of the engagement conditions is necessary to understand measured process dynamics. Fig. 1 shows these conditions for the helical path used in the presented experiments. The generated material removal rates for axial and peripheral direction are analyzed separately. In addition, the axial and peripheral material removal rates are respectively subdivided into precision machining at the bore wall and support structure removal.

Material removal rates for precision machining are constant within a full helical revolution for both axial and peripheral direction. These constant material removal rates are comparable to the rate for helical milling of solid material. However, material removal rates for support structure removal fluctuate periodically, as the contact areas of workpiece and tool vary. The derivation of axial and peripheral material removal rates of the support structure $Q_{ss,ax}$ and $Q_{ss,pe}$ is therefore necessary and is exemplarily carried out in Fig. 2 for the given situation and the depicted helix angle ranges. Multiplication of the marked areas, $A_{ss,ax}$ and $A_{ss,pe}$, with the respective velocities, $v_{f,ax}$ and $v_{f,pe}$, yields $Q_{ss,ax}$ and $Q_{ss,pe}$. A tool diameter of $D_t < b_{ss}$ enables a complete engagement of the tool in axial direction and implies a height of the cropped circle segment of $h = 0$.

In the given formula for $A_{ss,ax}$, a simplification was made. A subtraction of the axial precision machining area from $A_{ss,ax}$ was not carried out due to its small size. The conclusions which are extracted from the model still apply after this simplification. On the other hand, the modelling of $A_{ss,pe}$ accounts for the situationally different engagement conditions by introducing limits for the engagement angle φ and integrating a_p within these limits to obtain the peripheral area. The kinematic model extends Dege's approach of modeling the cutting depth a_p in helical milling depending on the tool to bore diameter ratio [9].

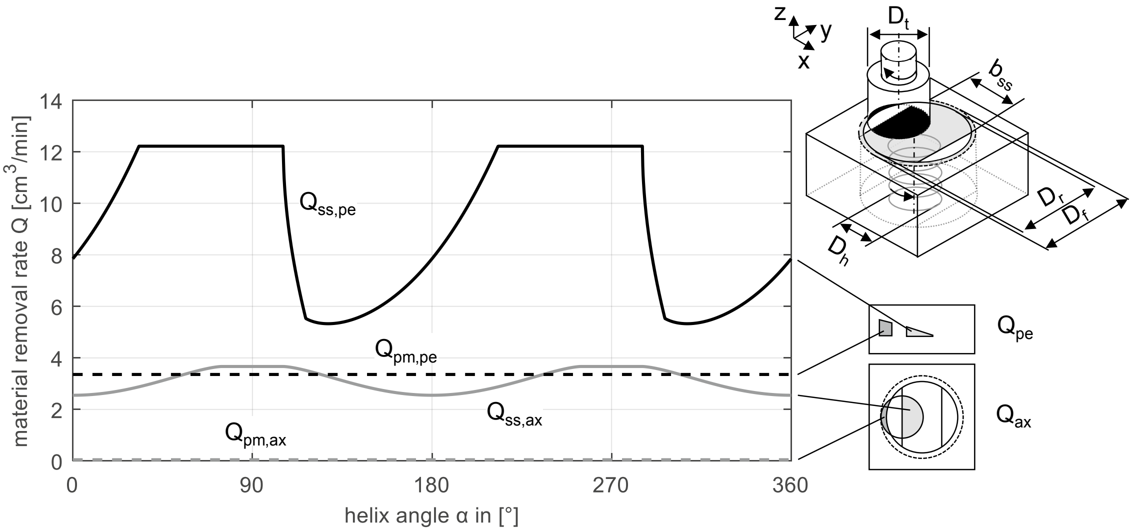
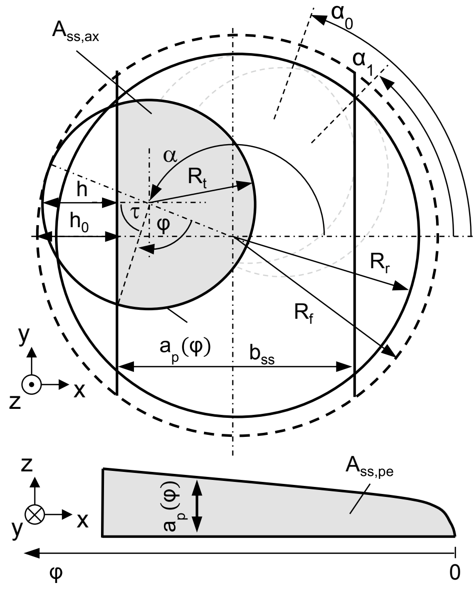


Fig. 1 Engagement situation and material removal rate of combined precision machining and removal of support structures by helical milling



$$\alpha_0 = \arccos\left(1 - \frac{h_0}{R_f - R_t}\right) \qquad \alpha_1 = \arccos\left(\frac{b_{ss}}{2\,R_r}\right)$$

Axial:

$Q_{ss,ax}$: $(n \cdot 180° - \alpha_0) < \alpha < (n \cdot 180° + \alpha_0)$, n = 0,1,2, …

$$h = h_0 - (R_f - R_t)\,(1 - \cos(\alpha - 180°)) \qquad h_0 = R_f - b/2$$

$$A_{ss,ax} = R_t^2\pi - R_t^2 \arccos\left(1 - \frac{h}{R_t}\right) + (R_t - h)\sqrt{2R_t h - h^2}$$

$$Q_{ss,ax} = A_{ss,ax} \cdot v_{f,ax}$$

Peripheral:

$Q_{ss,pe}$: $(n \cdot 180° - \alpha_1) < \alpha < (n \cdot 180° + \alpha_1)$, n = 0,1,2, …

$$\varphi = \alpha - \tau \qquad \tau = \arccos\left(1 - \frac{h}{R_t}\right)$$

$$A_{ss,pe} = \int_0^{\varphi} a_p(\varphi)\, d\varphi\, \frac{\pi R_t}{180°}$$

$$Q_{ss,pe} = A_{ss,pe} \cdot v_{f,pe}$$

Fig. 2 Calculation of the support structures' material removal rates in axial and peripheral direction as an extension to the model in [9]

3. Experimental Setup

Experiments were conducted in a machining center of type Heller MC12 with emulsion cooling. Process forces were measured using a force plate of type Kistler 9257B using the workpiece coordinate system (F_x, F_y, F_z). Because of variable engagement conditions, the measured forces were transformed into the tool coordinate system (F_{ax}, F_{pe}). Surface roughness of the precision machined inner bore wall was measured using a surface measuring device of type Mahr Surf XR 20. The TiAlZrN-coated cemented carbide milling tool had a diameter of D_t = 16 mm, number of teeth z = 5, length of cutting edge l_2 = 36 mm, angle of twist γ_p = 38° and angle of rake γ_f = 6°. Helical milling was used as the machining strategy. Precision machining of the inner bore wall was conducted in down-milling.

The inner diameter of the semi-finished, raw SLM-workpieces was D_r = 30 mm, and the inner diameter of the finished part was determined to be D_f = 31 mm to ensure combined precision machining and removal of support structures. Considering the tool diameter of D_t = 16 mm, the tool's programmed helical path diameter was calculated as D_h = 15 mm. The milling tools were examined after each process and exchanged upon the slightest appearance of wear. The additively manufactured workpieces were produced using SLM of Ti6Al4V powder. Support structures were introduced into the SLM-workpieces with the bore holes' axes being oriented horizontally. Altogether, three types of support structures (weak, medium and strong) with varying material volume fractions were manufactured. The dimensional accuracy of the SLM-workpieces in the peripheral areas without support structures with regard to cylindricity was ±0,118 mm. After helical milling, the cylindricity of the bore holes amounted to ±0,012 mm.

In addition to the SLM-workpieces with support structures, the same experiments were conducted on two solid workpieces without a previously introduced bore which were produced by SLM as well as conventional forging ($\alpha+\beta$ structure).

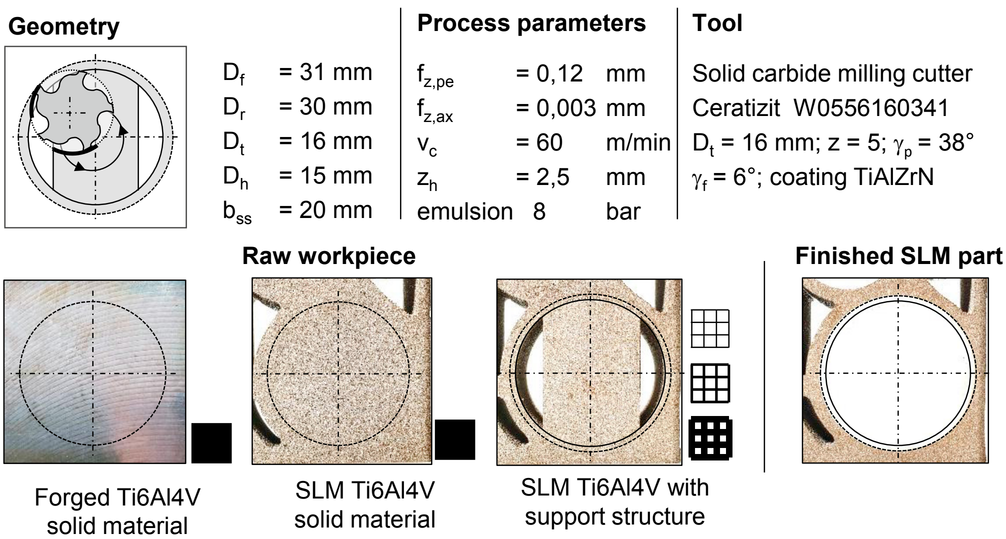
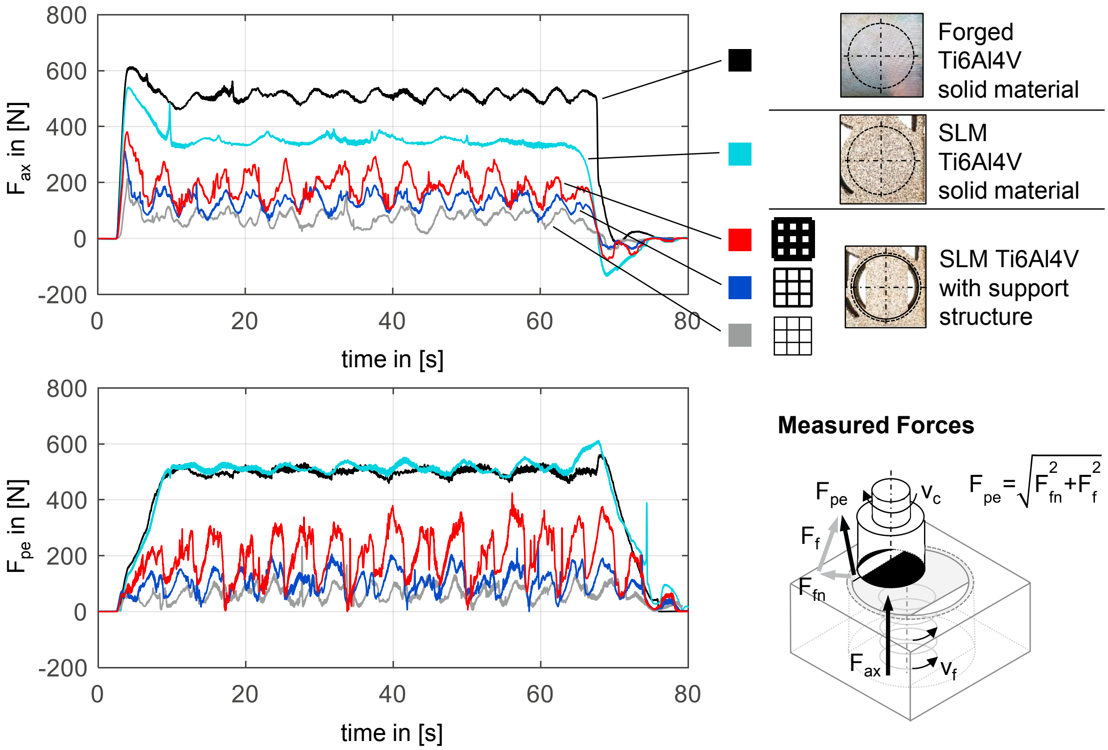


Fig. 3 Experimental conditions of the helical milling processes

4. Impact of Tool Position on Forces and Surface Roughness

Fig. 4 shows components of the resultant forces during helical milling of the described workpieces both in peripheral (F_{pe}) and in axial direction (F_{ax}). The solid workpieces (without previously existing bore hole) demonstrate a constant level of forces in both axial and peripheral direction along the helical tool path on a high level which is a consequence of constant material removal rate and stationary machining characteristics. F_{ax} is higher for the solid and conventionally forged produced workpiece than for the solid SLM workpiece. This deviation results from different material properties and ultimately from the different production processes of the semi-finished workpieces.

Forces during helical milling of the SLM-workpieces with support structures are lower than for the solid workpieces which is a consequence of significantly lower material removal rates, see Fig. 1. A comparison of the forces for



Process parameters: $f_{z,pe}$ = 0,12 mm; $f_{z,ax}$ = 0,003 mm; v_c = 60 m/min; z_h = 2,5 mm; emulsion 8 bar

Tool: Solid carbide milling cutter; D_t = 16 mm; z = 5; γ_p = 38°; γ_f = 6°; coating TiAlZrN

Fig. 4 Axial and peripheral forces for combined precision machining and support structure removal

different support structures reveals differences between them, stemming from different material volume fractions of the support structures. A higher material volume fraction equals higher axial and peripheral forces.

Another obvious difference between the axial and peripheral forces of solid workpieces and those with support structures is the process dynamics. Solid material axial and peripheral forces vary only slightly during milling while support structure forces vary significantly due to periodically changing material removal rates. The support structure with the highest material volume fraction corresponds to the highest force amplitude of the periodic variations due to the highest differences between minimum and maximum material removal rates.

Fig. 5 shows the surface roughness of the bore walls after the workpieces were machined by helical milling. The roughness (Rz, Rt) was measured at two positions: at helix angle α = 0° (Position 1) and at the center of the previously existing support structures at helix angle α = 90° (Position 2). Position 1 is at the center of the area without support structures for the SLM-workpieces with support structures. Measurement of roughness at position 2 showed lower values for all workpieces after helical milling. At position 1, on the other hand, roughness was influenced by the type of support structure. Increasing the support structure's material volume fraction corresponds to higher roughness values.

Similar levels of roughness are observed at both measuring positions of the forged workpiece when comparing both workpieces made from solid material. In contrast to this the roughness of the SLM workpiece observed at position 1 is higher than the one at position 2. This might result from the build direction of the SLM-component.

The different roughness levels of the SLM-workpieces with support structures for position 1 and 2 can be explained by the engagement conditions of the tool. In position 2, the complete arc length of the tool front is in engagement, with one part of the arc being in contact with support structures and the other in contact with solid material. However, in position 1, part of the tool front is not engaged, and the teeth return to engagement on their trajectory at a high cutting depth. These unsteady engagement conditions induce tool vibrations and lead to surface damages of the inner bore wall. A higher material volume fraction leads to higher tool vibration and deflection.

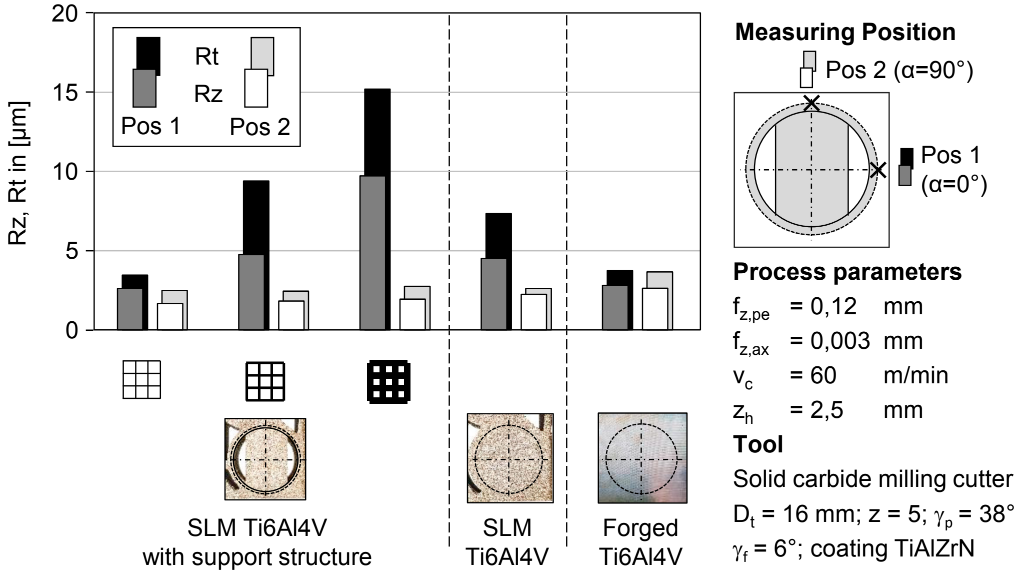


Fig. 5 Impact of material type and measuring position on surface roughness

5. Comparison of Kinematic Model and Experimental Results

The previously assumed relationship between surface roughness of the inner bore wall of the SLM-workpieces with support structures on the one hand, and varying material removal rates Q_{ax} and Q_{pe} on the other hand, is further substantiated by comparing the material removal rates with the measured process forces. Here, Q_{ax} and Q_{pe} denominate the sum of material removal rates for precision machining and support structure removal in the respective directions, as seen in Fig. 1.

In Fig. 6, periodic process forces and material removal rate variations are shown for the SLM-workpiece with strong support structures, where the impact of material removal rate variation is greater than for weak and medium support structures. It becomes obvious that in the axial direction, forces correlate strongly with material removal rate. At positions $\alpha = 0°$ and $\alpha = 180°$, Q_{ax} reaches its minimum. Therefore, F_{ax} becomes minimal. At positions $\alpha = 90°$ and $\alpha = 270°$, the axial tool area is in complete engagement which is why F_{ax} reaches its maximum.

In addition, a correlation of forces and material removal rates in peripheral direction can be identified. The plateaus of maximum material removal rate Q_{pe} between $\alpha = 33°\ldots105°$ and $\alpha = 213°\ldots285°$ are reflected by the plateaus of the forces in peripheral direction, F_{pe}. Between these areas, a sharp drop followed by a steady increase is seen in both measured forces and material removal rates.

The dependence of the forces on the material removal rate as well as the teeth's irregular engagement conditions are the reason for the varying surface qualities as shown in section 4.

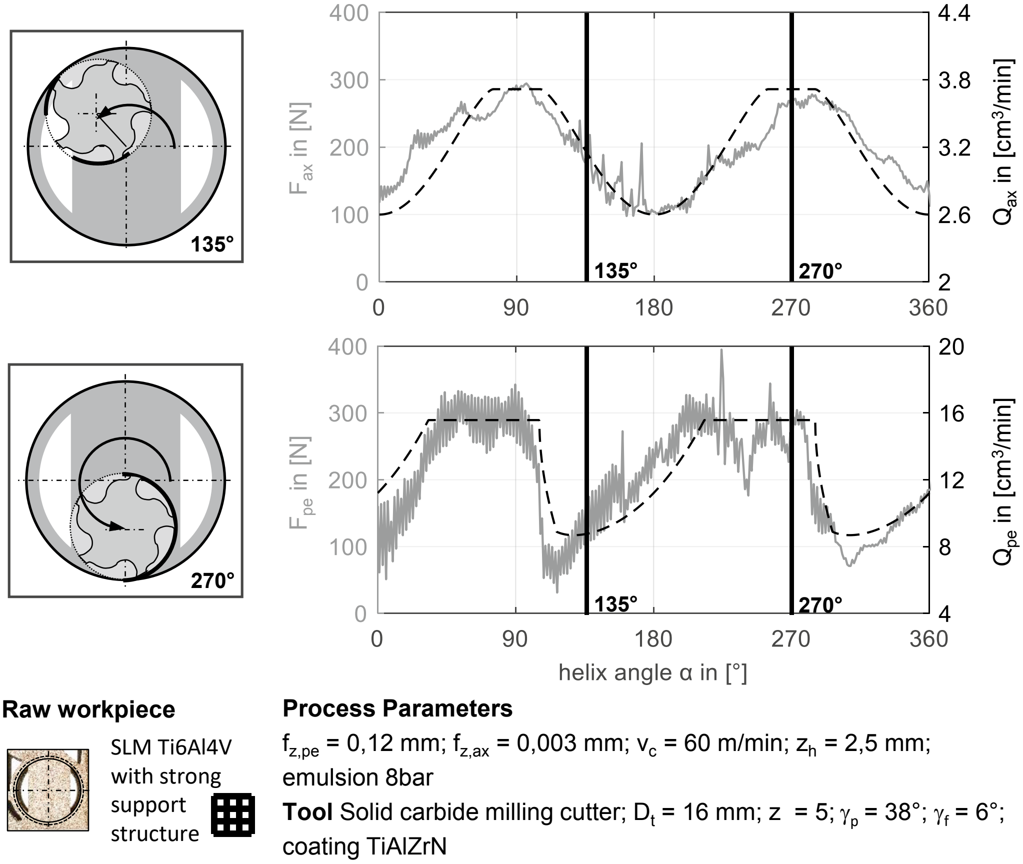


Fig. 6 Comparison of material removal rate with axial and peripheral forces in a complete revolution of the helical path

6. Conclusion and Outlook

Experimental results on combined support structure removal and finishing of precision holes by helical milling are presented and compared to the results for helical milling of solid material. The process kinematics were modeled and the model's correlation to axial and peripheral forces was experimentally verified.

The most important conclusions of this paper are:

- Compared to helical milling of bores into solid material, helical milling of those into SLM material with support structures results in very different forces. The former shows a constant force on a high level, whereas in the latter case, forces are lower but also strongly fluctuate along the helical tool path. The intensity of fluctuation depends on the support structure's material volume fraction.
- The developed model enables the calculation of material removal rates in helical milling of bores with support structure as a function of tool path. A complete revolution of the tool in the helix shows sections with constant as well as fluctuating material removal rates which lead to varying surface roughness.
- Weak support structures with low material volume fraction allow for combined precision machining and support structure removal. Strong support structures lead to low surface roughness of the bore wall. Thus, surface roughness can then only be achieved in a two-stage process.

- Since the surface roughness of bores made into forged solid material is constant along the hole periphery, the different bore hole roughness in SLM material can be traced back to the build-up direction.

The results can be used to optimize support structures with regard to efficient machining processes and to high precision of holes in SLM parts.

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