

EVALUATION OF THE CUTTING FORCE COMPONENTS AND THE SURFACE ROUGHNESS IN THE MILLING PROCESS OF MICRO- AND NANOCRYSTALLINE TITANIUM

Abstract: Nanocrystalline pure titanium in comparison to microcrystalline titanium is characterized by better mechanical properties which influence its wider usability. The aim of the research was to evaluate whether the grain size of pure titanium (micro- and nanocrystalline) has influence on the cutting force components and the surface roughness in the milling process. Models of cutting force components for both materials were prepared and differences between the results were examined. The feed rate effect on selected parameters of surface roughness after milling of micro- and nanocrystalline pure titanium was determined.

Keywords: nanocrystalline titanium, hydrostatic extrusion, cutting force, surface roughness, milling

1. Introduction

Development of severe plastic deformation (SPD) methods allows to obtain the titanium with nanocrystalline grains. Grain refinement in pure titanium results in improvement of its mechanical properties [1]. Nanocrystalline pure titanium have three times higher strength than the microcrystalline one. Its mechanical properties are comparable to widely used Ti-6Al-4V alloy [2]. Due to the unique properties of titanium and its alloys like thermal conductivity and elastic modulus, high hardness at elevated temperature and high chemical reactivity at low density, these materials are difficult to machine [3]. These factors may cause rapid tool wear, low material removal rate and degradation of surface integrity of machined parts [4-5]. The cutting force components and surface roughness are the main parameters providing information on machinability of materials [6-9]. It is expected that machinability of nanocrystalline titanium is changed mainly due to work hardening caused by grain refinement. In titanium alloys work hardening during machining eliminates formation of built-up edge in front of the cutting tool and increase of the shearing angle. As a consequence the thin chips contact a relatively small area in the cutting face, resulting in high bearing loads per unit area. For this case the friction between the chip and bearing area causes significant heat increase in a very small area of the cutting tool and formation of cratering close to the cutting edge leading to rapid tool breakdown [10-12].

The specific properties of nanocrystalline titanium allows its use in medicine. Nanocrystalline titanium could be used for the production of e.g. dental implants. Some titanium alloys used in medicine contain toxic elements, such as vanadium. Therefore, from a biological point of view it is preferable to use implants made of pure titanium [13]. Obtaining information

on process quality indicators is a way of supporting decisions in the design stage: tool life, surface roughness, state of technological surface layer [14], chip control and cutting force components [15].

Extensive research work has been done on machining of titanium and its alloys [16,17] taking into account modelling and simulation of this process [18,19]. However only a few papers are related to ultrafine-grained titanium [20]. Therefore, it is necessary to acquire knowledge in the field of machining of nanocrystalline titanium. The comparison of test results on micro- and nanocrystalline titanium allows to check whether the grain size of pure titanium has influence on the cutting force components and the surface roughness in the milling process.

2. Experimental procedure

2.1. Characteristics of examined materials

The experimental research was carried out based on two types of materials: microcrystalline CP titanium Grade 2 and high purity nanocrystalline titanium (Table 1).

TABLE. 1
The characterization of examined materials

| Material | Short name | Ti content, wt. % |
|--------------------------------------|------------|-------------------|
| Microcrystalline CP titanium | micro-Ti | ~98.9 |
| Nanocrystalline high purity titanium | nano-Ti | 99.99 |

Nanocrystalline titanium (nano-Ti) was produced by hydrostatic extrusion method (HE). HE experiments

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The characteristic of cutting tool

| Tool designation | Tool material | Mill diameter | Corner radius | Helix angle | Number of flutes |
|------------------|---------------|---------------|---------------|-------------|------------------|
| UGDE0600A5ARA | KC643M | 6 mm | 0,2 mm | 43° | 5 |

were realized at the Institute of High Pressure Physics, Polish Academy of Sciences, within the framework of a project coordinated by the Faculty of Materials Science and Engineering, Warsaw University of Technology.

Initially high purity titanium was in the form of the rod with the diameter of Ø50 mm. This material was subjected to the multi-pass hydrostatic extrusion process. 10 passes of the hydrostatic extrusion process at the room temperature were conducted during which the rod diameter was gradually reduced. The final rod diameter was Ø7 mm.

The material before extrusion was characterized by irregular, fine-crystalline grains. No inclusions were observed <Fig. 1a>. The transmission electron microscopy observations of the Ø7 mm rod have revealed the grain refinement of the initial microstructure <Fig. 1b>. On the transverse section, based on the image analysis methods, the average grain size in the extruded material was found to be about 110 nm.

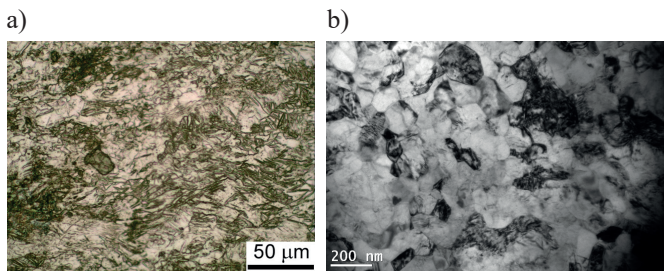


Fig.1. Microstructure of high purity titanium rod: a) before and b) after hydrostatic extrusion

2.2. Test stand and cutting condition

The tests was carried out on test stand prepared with a use of high precision, 5-axis milling machine Ultrasonic 20 Linear <Fig. 2>. This machine tool allows micro machining with high dimensional accuracy. The sample was mounted directly on Kistler 9256C2 dynamometer, which was screwed to the rotary table in the milling machine.



Fig. 2. Sample fixed to dynamometer on the Ultrasonic 20 Linear milling machine

A proper cutting tool material and coating selection also plays an important role in titanium alloys machining [15]. For the process end mill UGDE0600A5ARA made of KC643M carbide was used. Characteristic dimensions of end milling cutter <Fig. 3><Tabl. 2>: D1=6 mm; D=6 mm; Ap1 max=18 mm; L=63 mm; Re=0,2 mm.

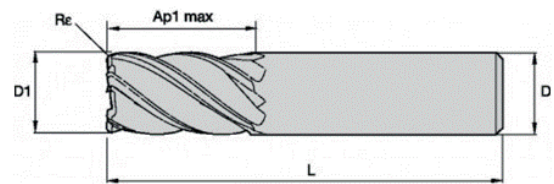


Fig. 3. The geometry of end mills UGDE

The analysis of cutting forces and surface roughness for the shoulder face milling process of pure micro- and nanocrystalline titanium required selection of the specific research area. The range of machining parameters which was applied during the research of cutting force components was determined on the basis of initial investigations and the recommendations of tool manufacturer <Tab. 3>.

TABLE 3

The range of machining parameters

| Parameter | Unit | Range |
|---------------------|----------|-------------|
| Cutting speed v_c | m/min | 40-60 |
| Feed f | mm/tooth | 0.009-0.029 |
| Depth of cut a_p | mm | 1-2 |
| Width of cut a_c | mm | 1.2 |

Analysis of surface roughness was realized only for feed changes in the adopted range.

2.3. Design of experiment

The response surface methodology (RSM) is a procedure able to determine a relationship between independent input process parameters and output data (process response). The data required to develop the computation were collected by designing the experiments based on Central Composite Design <Tab. 4>. This procedure creates designs with desirable statistical properties. The analysis of results was performed using the Design Expert 8.0.7 software.

3. Results and discussion

In the first step the components of cutting force for specified process conditions were determined. The cutting

TABLE 4

Cutting parameters for Central Composite Design

| Levels | -Alpha | Low | Central | High | +Alpha |
|--------------------------------|--------|-------|---------|-------|--------|
| Coded value | -1.68 | -1 | 0 | +1 | +1.68 |
| Cutting speed v_c [m/min] | 33.18 | 40 | 50 | 60 | 66.82 |
| Depth of cut a_p [mm] | 0.66 | 1 | 1.5 | 2 | 2.34 |
| Feed rate f [mm/tooth] | 0.002 | 0.009 | 0.019 | 0.029 | 0.036 |

TABLE 5

The results of cutting force components for the each tests during milling of micro- and nanocrystalline titanium

| Std | Factor 1: Cutting speed v_c , m/min | Factor 2: Depth of cut a_p , mm | Factor 3: Feed rate f , mm | Micro-Ti Force F_t , N | Micro-Ti Force F_r , N | Nano-Ti Force F_t , N | Nano-Ti Force F_r , N |
|-----|---|---|------------------------------------|--------------------------------|--------------------------------|-------------------------------|-------------------------------|
| 1 | 40 | 1 | 0.009 | 28 | 22 | 18 | 27 |
| 2 | 60 | 1 | 0.009 | 25 | 24 | 19 | 26 |
| 3 | 40 | 2 | 0.009 | 35 | 41 | 31 | 42 |
| 4 | 60 | 2 | 0.009 | 37 | 48 | 35 | 45 |
| 5 | 40 | 1 | 0.029 | 53 | 36 | 38 | 40 |
| 6 | 60 | 1 | 0.029 | 50 | 36 | 38 | 39 |
| 7 | 40 | 2 | 0.029 | 66 | 81 | 57 | 79 |
| 8 | 60 | 2 | 0.029 | 72 | 77 | 60 | 78 |
| 9 | 33.18 | 1.5 | 0.019 | 50 | 49 | 44 | 49 |
| 10 | 66.82 | 1.5 | 0.019 | 47 | 48 | 38 | 48 |
| 11 | 50 | 0.66 | 0.019 | 31 | 19 | 29 | 26 |
| 12 | 50 | 2.34 | 0.019 | 58 | 73 | 52 | 74 |
| 13 | 50 | 1.5 | 0.002 | 18 | 22 | 13 | 23 |
| 14 | 50 | 1.5 | 0.036 | 77 | 75 | 61 | 62 |
| 15 | 50 | 1.5 | 0.019 | 51 | 51 | 40 | 48 |
| 16 | 50 | 1.5 | 0.019 | 47 | 48 | 36 | 48 |
| 17 | 50 | 1.5 | 0.019 | 52 | 46 | 37 | 49 |
| 18 | 50 | 1.5 | 0.019 | 49 | 52 | 39 | 51 |
| 19 | 50 | 1.5 | 0.019 | 41 | 48 | 40 | 54 |
| 20 | 50 | 1.5 | 0.019 | 51 | 49 | 39 | 48 |

force components measure the resistance of machined material, which has to be overcome during the machining process. In this case, the research aimed at examining to what extent the cutting force components, during machining of microcrystalline and nanocrystalline titanium, differ. The total cutting force F can be decomposed into tangent F_t , radial F_r and axial component F_a . Based on the obtained results, the components F_t and F_r were selected for the comparison. The tangent and axial component of cutting force were calculated on the basis of measurement results obtained from dynamometer (F_x , F_y , F_z) and geometric relations presented in Figure 4.

Table 5 shows the values of the cutting force components obtained during the milling of micro- and nanocrystalline titanium.

For adopted modified linear model the analysis of variance ANOVA was performed. The analysis showed that significant effect on the obtained value of the cutting force F_t has feed rate f and depth of cut a_p for both examined materials.

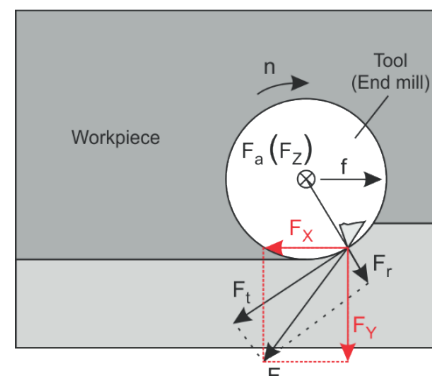


Fig. 4. The relationships between the components of the cutting forces

The result is the mathematical models of tangential component of cutting force F_t for milling process of microcrystalline titanium:

$$F_t = -4,675 + 13,094 \cdot a_p + 1649,177 \cdot f \quad (1)$$

and nanocrystalline:

$$F_t = -9,426 + 15,916 \cdot a_p + 1250,113 \cdot f \quad (2)$$

In Figures 5 and 6 the graphical representation of the above models as a dependence of cutting force Ft on the depth of cut ap and feed rate f consecutively for micro- and nanocrystalline titanium were showed.

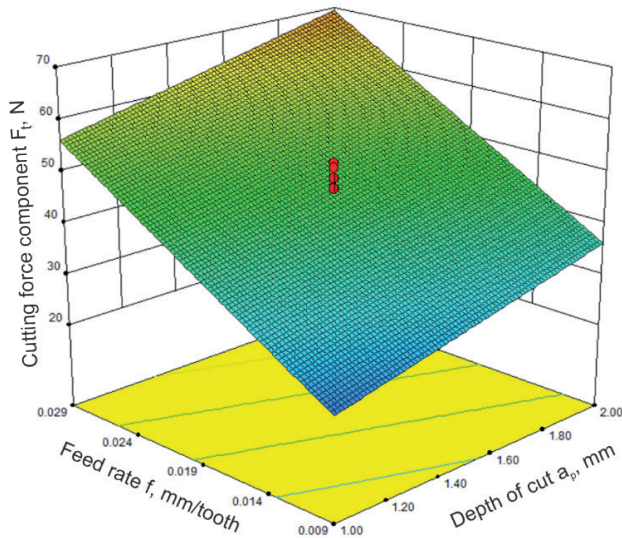


Fig. 5. Effect of feed rate and depth of cut on the tangential force during the milling of microcrystalline titanium (Eq. 1)

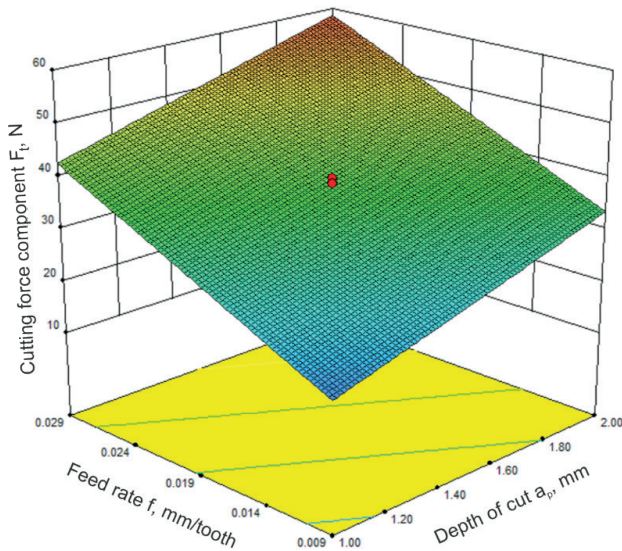


Fig. 6. Effect of feed rate and depth of cut on the tangential force during the milling of nanocrystalline titanium (Eq. 2)

The tangent force was obtained in the range of 18-77 N for microcrystalline titanium and in range of 13-61 for nanocrystalline titanium. The values of tangent component of cutting force Ft during the milling process of nanocrystalline titanium are lower (in the range to 40%) than in the case of its microcrystalline form.

Analysis of the radial component of cutting force was carried out as for tangential force. For adopted modified 2FI model the analysis of variance ANOVA was performed. The analysis showed that significant effect on the obtained value of the radial force Fr has feed rate f, depth of cut ap and interaction between these parameters for both examined materials.

The result is the mathematical models of radial component of cutting force Fr for milling process of microcrystalline titanium:

$$F_r = 3,983 + 11,766 \cdot a_p - 264,203 \cdot f + 1075 \cdot a_p \cdot f \quad (3)$$

and nanocrystalline:

$$F_o = 14,333 + 7,324 \cdot a_p - 466,785 \cdot f_z + 1100 \cdot a_p \cdot f_z \quad (4)$$

In Figures 7 and 8 the graphical representation of the above models as a dependence of cutting force Fr on the depth of cut ap and feed rate f consecutively for micro- and nanocrystalline titanium were showed.

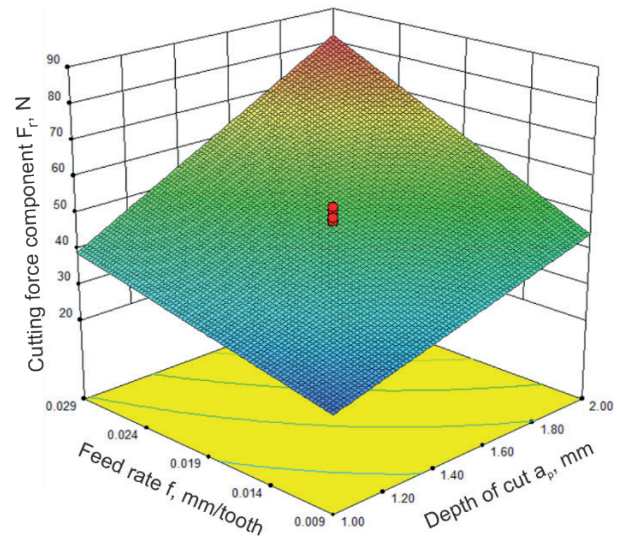


Fig. 7. Effect of feed rate and depth of cut on the radial force during the milling of microcrystalline titanium (Eq. 3)

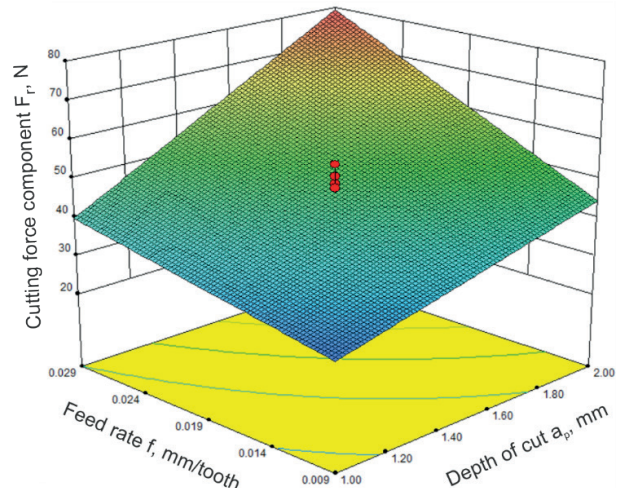


Fig. 8. Effect of feed rate and depth of cut on the radial force during the milling of nanocrystalline titanium (Eq. 4)

The radial force was obtained in the range of 19-81 N for microcrystalline titanium and in range of 23-79 for nanocrystalline titanium. The values of radial component of cutting force showed no significant differences in the adopted range of cutting parameters.

Fig. 9 presents images of the surface topography after face milling. In the case of microcrystalline titanium surface images show a dependence on feed rate. For nanocrystalline titanium the machining traces are more similar.

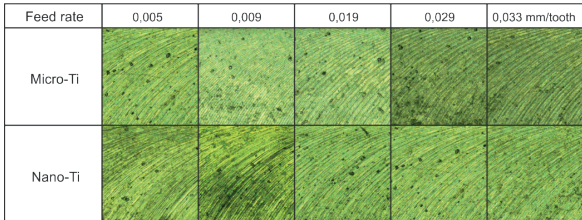


Fig. 9. Surface topography after face milling for different feed rate

For face milling, the results of surface roughness show that parameters Sa and Sz obtained during the milling of nanocrystalline titanium are greater than for microcrystalline titanium surface machined with the same cutting conditions <Fig 10,11>.

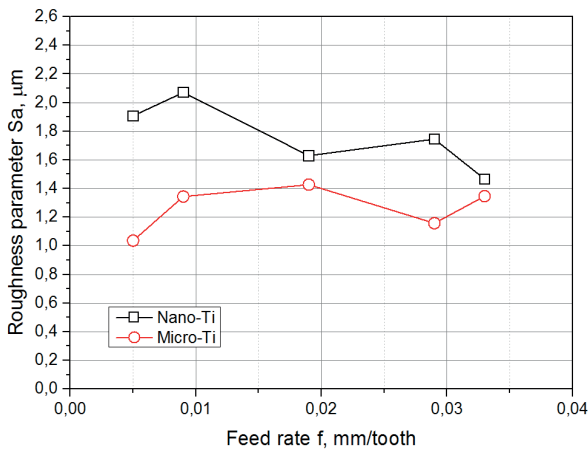


Fig. 10. The impact of feed on the roughness parameter Sa for face milling

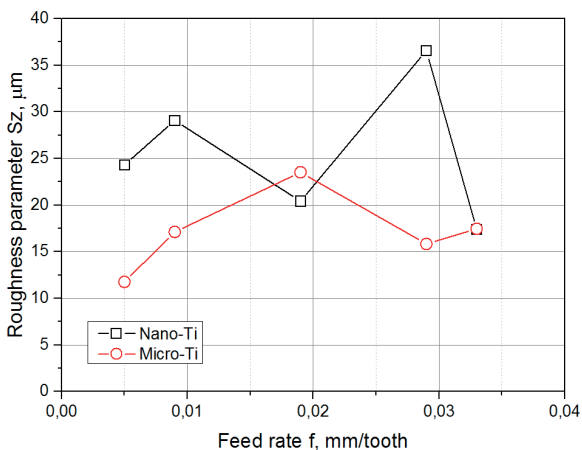


Fig. 11. The impact of feed on the roughness parameter Sz for face milling

The obtained value of surface roughness parameters present a rather complex nature of the forming of surface roughness during the milling of nanocrystalline titanium. The inverted trend of the parameter Sa for face milling of nanocrystalline titanium was observed. With the increase of feed rate the value of Sa parameter was decreased.

The images of surface topography after the side milling are presented on Fig. 12. The machining traces for nanocrystalline titanium depend on feed rate.

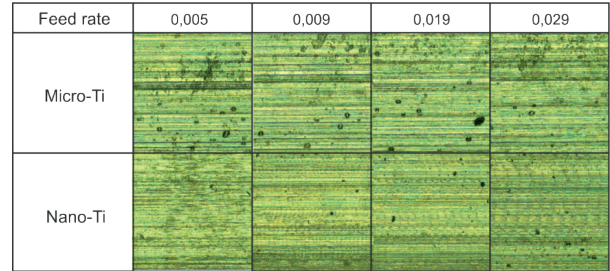


Fig. 12. Surface topography after side milling for different feed rate

As for face milling, the results of surface roughness for side milling presents the same trend. The obtained roughness parameters Sa and Sz during the milling of nanocrystalline titanium are greater than for microcrystalline <Fig. 12, 13>. The significant impact of feed rate on the roughness parameters for side milling was not determined.

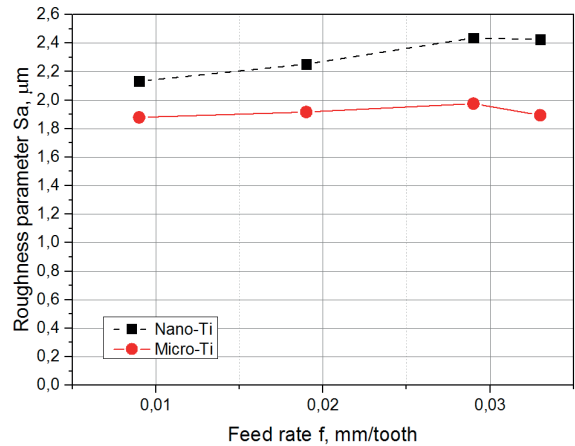


Fig. 13. The impact of feed rate on the roughness parameter Sa for side milling

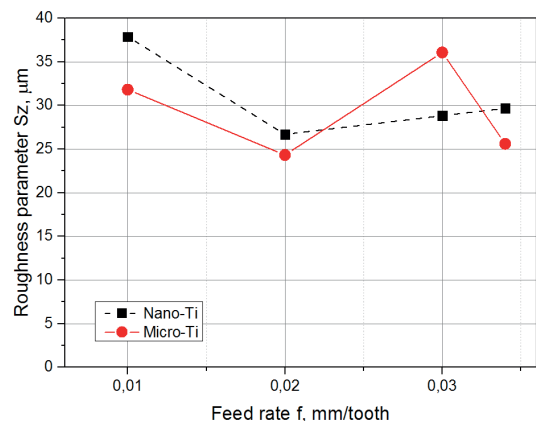


Fig. 14. The impact of feed rate on the roughness parameter Sz for side milling

4. Conclusions

The values of tangential component of cutting force F_t during the milling process of nanocrystalline titanium are lower to 40% than for its microcrystalline form. The comparison of value of radial component F_r does not show significant differences between obtained results.

The research enabled to elaborate models of tangential and radial components of cutting force for milling process of micro- and nanocrystalline titanium. The models of the components of cutting forces show a significant impact of depth of cut and feed rate in the analysed range of cutting parameters.

In the case of machining of nanocrystalline titanium, the determined values of roughness parameter S_a are higher than 15 to 24% than for microcrystalline titanium. The inverted trend of the parameter S_a for face milling of nanocrystalline titanium was observed (in the adopted range of machining parameters). Analysis presents a rather complex nature of the forming of surface roughness during the milling of nanocrystalline titanium.

The subject of further investigations should be determination if the change in forming process of surface topography occurred for lower feed parameters, also a comparison with the results of surface topography measurements obtained by a contact method (only optical method could be used for the geometry of applied sample, which could influence the accuracy of measurement).

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