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Evaluation of the Surface Topography of Ti6Al4V Alloy after the Finish Turning Process under Ecological Conditions

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ABSTRACT

This paper describes findings in the surface topography of Ti6Al4V alloy after finish turning process under dry and MQL (minimum quantity lubrication) machining. The research was fulfilled in the range of variable feeds per revolution of 0.005–0.25 mm/rev and cutting speeds of 40–100 m/min using the depth of cut of 0.25 mm that fits finish processing conditions. The test plan was developed on the way to use the Parameter Space Investigation (PSI) method. The topography features were measured by a Sensofar S Neox optical profilometer using the Imaging Confocal Microscopy technique. *Ra* parameters and surface roughness profiles as well as 2D images and contour maps were analyzed. Under the studied machining conditions, lower *Ra* roughness parameters are obtained in the feed rate of 0.005–0.1 mm/rev and cutting speeds of 40–60 m/min. In comparison with dry machining, up to 17% reduction in *Ra* parameter values was obtained using the MQL method and v_c = 70 m/min and f = 0.127 mm/rev as well as v_c = 47.5 m/min and f = 0.22 mm/rev. Depending on the machining conditions, peaks and pits as well as feed marks typical for the turning process are observed on the machined surfaces.

Keywords: dry machining, MQL method, finish turning, surface topography, Ti6Al4V titanium alloy.

INTRODUCTION

One of the most serious challenges in machining difficult-to-cut alloys is to ameliorate the surface topography of parts made, as it affects fatigue strength responsible for almost 90% of failures [1]. Titanium alloys are widely used in different industry brunches including aerospace, automotive, medicine [2]. Despite their wide application, they are defined as difficult for machining due to, among other: low elastic modulus, high chemical reactivity and low thermal conductivity. When cutting, almost 80% of the generated heat penetrates to the cutting tool providing its accelerated wear, which contributes to deterioration of the machined surface roughness of machine parts [3]. Hence, the selection of suitable cooling conditions for surface shaping is crucial to obtain favorable results [4].

Among titanium alloys, Ti6Al4V alloy is one of the best known in industry. On the other hand, due to the difficulties occurring during machining, this alloy is of great scientific interest. Obtaining the required surface roughness is one of the significant problems, and for this aim different cooling methods are compared using different cutting parameters. For this purpose Leksycki and Feldshtein [5] conventional flood and dry machining used. A constant depth of cut of 0.5 mm and cutting speeds in the range of 40–120 m/min, feed rate in the range of 0.05–0.4 mm/rev were applied. Compared to the results obtained for a wet machining, a reduction in *Ra* parameter up to 50% was obtained during dry turning. Relatively low surface roughness was found with a feed rate of 0.2 mm/rev and a cutting speed of 80 m/min for dry machining. Hardt et al. [6] used conventional flood and cryogenic cooling. The experiments were conducted at a constant depth of cut of 0.2 and a cutting speed in the range of 75–150 m/min and a feed rate in the range of 0.05–0.125 mm/rev. Regardless of cooling conditions, a surface roughness of lower than *Ra* = 1 μm was obtained. Under cryogenic machining conditions, using a feed rate of 0.05 mm/rev and a cutting speed of 75 m/min, the smallest surface roughness was registered, namely *Ra* = 0.27 μm. Ploughing marks are visible on the surface machined under cryogenic conditions. During conventional machining a valleys and periodic peaks are found on the machined surface. Peng et al. [7] analyzed ultrasonic vibration and conventional machining. They used a wide range of cutting speeds, namely 100–400 m/min. Machining under HUVC conditions enables the obtainment a lower surface roughness and uniform surface texture. Liang et al. [8] used high-pressure jet assisted machining (HPJAM). Variable cooling pressure (10–20 MPa) and injection positions were tested. Conventional flooding (0.5 MPa) and dry machining were used as reference. HPJAM machining provides a reduction in the *Sa* parameter of surface roughness, and the greatest differences were observed with an increase in pressure and double injection position. Regardless of the machining conditions, many defects including plowing grooves were observed on the tested surfaces. Agrawal et al [9] evaluated the effects of wet and cryogenic machining. A constant depth of cut of 0.5 mm and feed rate of 0.3 mm/rev were used, along with cutting speeds in the range of 70–110 mm/m. Regardless of cutting speed, compared to wet machining with cryogenic cooling, the surface roughness decreased ~22%. Leksycki et al [10] evaluated the effect of machining conditions on selected 2D surface roughness parameters. For samples with *Ra* = 0.25–0.37 μm after dry machining, a 165% reduction in surface roughness was found compared to MQL. However, for samples with *Ra* = 1.62–2.22 μm machined with MQL, a reduction up to 27% was obtained. Luan et al. [11] analyzed dry machining, laser-assisted machining (LAM), MQL, and a combination of LAM and MQL (LAM-MQL). Compared with results reached for a dry machining, the surface roughness was decreased by 33.7% in case of LAM, by 19.9% for MQL and by 12.7% for LAM-MQL. Qi et al. [12] evaluated the surface roughness with high cutting speeds under dry, cold air, MQL, cryogenic-MQL and ionized air machining conditions. The lowest surface roughness was achieved under ionized air conditions. Khan et al. [13] analyzed cutting parameters and machining conditions. Feed rate and machining conditions have the greatest effect on surface roughness, and moreover the surface finish improves under wet and cryogenic cooling conditions.

Summarizing, it can be concluded that recent research studies analyze the effects of processing and machining conditions on the roughness, topography and integrity of Ti6Al4V titanium alloy commonly used in the manufacturing industry. This confirms that the research topic is important and requires further research. The scope of this paper was to analyze the effect of dry machining and using MQL conditions on the surface formation of high-grade Ti6Al4V alloy (Grade 5) after the finish turning process.

MATERIALS AND METHODS

Materials

Ti6Al4V titanium alloy has high strength with low weight, favorable fatigue properties and very good corrosion resistance. This alloy is nonmagnetic, has low density and relatively low thermal conductivity. Due to its aluminum content, the material has high strength, including tensile strength relative to commercially pure materials [14]. Its summary of chemical element content is presented in Table 1, which is consistent with ISO 5832-3 [15].

Machining conditions

The machine tool used for this study was a lathe type CKE6136i from DMTG manufacturer. The tests were carried out using the SDJCR 2020K 11 tool holder and DCMX 11 T3 04-WM 1115 index able inserts. Some features of cutting tools are introduced in Table 2.

The turning process was carried out at variable feed per revolution (*f*) of 0.005–0.25 mm/rev

Table 1. Summary of chemical element content of Ti6Al4V alloy, based on the ISO 5832-3 standard

Chemical composition, %							
Ti	Al	V	O	Fe	C	N	H
The rest	5.5–6.75	3.5–4.5	<0.2	<0.3	<0.08	<0.05	<0.015

Table 2. Some details of cutting tools, according to manufacturers

Tool holder SDJCR 2020K 11		Insert DCMX 11 T3 04-WM 1115	
Description	Value	Description	Value
Edge angle κ_r	93°	Wedge angle β	55°
Rake angle γ	18°	Major flank angle α	7°
Tool lead angle χ	-3°	Nose radius r_ε	0.397 mm

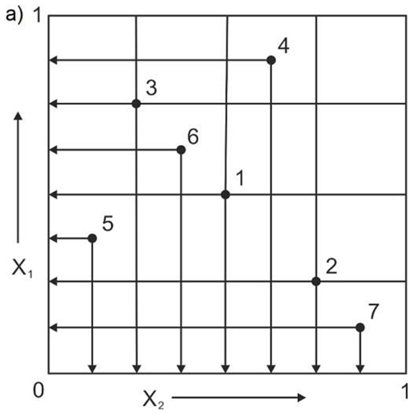
and cutting speeds (v_c) 40–100 m/min, with a stable depth of cut (a_p) 0.25 mm.

Turning was fulfilled under dry machining and using the MQL method, because these machining conditions are considered to be environmentally friendly. For MQL , ECOCUT MIKRO 20 E oil was applied. The oil-air mist conditions were constant and were described in Leksycki et al. [16]. According to Haron et al. [17], dry cutting is highly preferable because it provides environmental benefits and also reduces production costs. On the other hand, according to Egea et al. [18] dry machining causes increasing temperature in the cutting zone, which significantly accelerates the tool wear and adversely affects the quality of manufactured products. According to Singh [19], MQL method is an environmentally friendly cooling strategy. The oil mist droplets that penetrate into the cutting zone at high speed form a thin lubricating film and provide beneficial heat dissipation. Machining with MQL leads increasing chip affinity and forming build-up-edge (BUE) on the cutting edge.

Research method

The Parameter Space Investigation (PSI) method was applied to design experiments. The PSI method has been described by Statnikov and Statnikov [20]. It allows DoE planning with minimizing the number of test points. The test points were arranged in multidimensional space so that their projections on the X1 and X2 axes were at equal distances from each other. The projections of the points on the axes and the coordinates for their placement are shown in Figure 1. The application of the PSI method made it possible to identify 7 experimental test points that successfully allow statistical analysis. To perform it, the Statistica version 13 software was used. The PSI method was successfully applied to the turning process by Leksycki et al [21].

The machined surface of the Ti6Al4V titanium alloy was tested with a Sensofar S Neox optical 3D microscope. The surfaces were scanned using the Imaging Confocal Microscopy technique. A λc filter according to ISO 16610-21 standard [22]



b)

Variables	Test points coordinates						
	1	2	3	4	5	6	7
X_1	0.500	0.250	0.750	0.875	0.375	0.625	0.125
X_2	0.500	0.750	0.250	0.625	0.125	0.375	0.875

Fig. 1. Projections of points on the X1 and X2 axes (a) and coordinates of their placement (b) in the PSI method

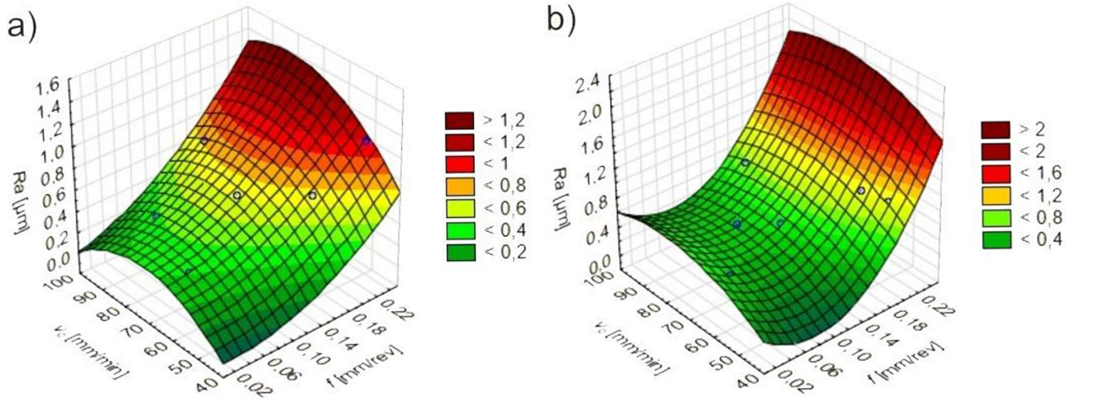


Fig. 2. Changes in *Ra* parameter as a function of *f* and v_c under dry machining (a) and MQL conditions (b)

was used during the measurements. According to this standard the cut-off λc is the limit wavelength between waviness and roughness.

Contour maps, 2D images and machined surface roughness profiles, as well as the roughness parameter *Ra* were evaluated. As it is stated in ISO 4287 [23], the *Ra* parameter is a deviation of the arithmetic mean of the roughness profile. In production, it is a basic parameter describing geometric features of manufactured parts of machines and devices.

RESULTS AND DISCUSSION

The statistical analysis allowed creating regression models for the *Ra* parameter as a function of the feed per revolution and cutting speed:

- for dry machining

$$Ra = -1.63 - 1.78f + 0.05v_c + 13.66f^2 + 0.03fv_c - 0.001v_c^2 \tag{1}$$

- for MQL conditions

$$Ra = -1.27 - 8.51f + 0.05v_c + 57.53f^2 - 0.003fv_c - 0.001v_c^2 \tag{2}$$

where: f – feed per revolution and
v_c – cutting speed.

Based on these, graphs were generated that characterize the changes of the *Ra* parameter in dependence with machining conditions (Fig. 2).

After dry and MQL conditions, the feed per revolution has the greatest effect on the *Ra* parameter, while the cutting speed has a negligible effect. In both cases, as the feed increases, the *Ra* parameter increases too. After dry turning, lower *Ra* values are achieved in the feed per revolution of 0.005–0.1 mm/rev and the cutting speeds of 40–50 m/min. After MQL turning, the lowest *Ra* values have been obtained for feed per revolution of 0.04–0.1 mm/rev and a cutting speeds of 40–60 m/min.

The comparison of average percentage changes of *Ra* parameter between the MQL turning and dry turning, acquired at 7 test points in PSI method, depended on the cutting parameters tested (v_c, f) is shown in Figure 3.

Compared to results reached for a dry machining, the *Ra* parameter, which obtained during processing with MQL, decreases ~(13–17)% with v_c = 70 m/min and f = 0.127 mm/rev as well as v_c = 47.5 m/min and f = 0.22 mm/rev, that is indicated by the red dotted line. On the other hand, *Ra* increases ~(5–52)% over the whole studied range of feeds and cutting speeds of 50-65 m/min. Of especial note are the test points that indicate trends

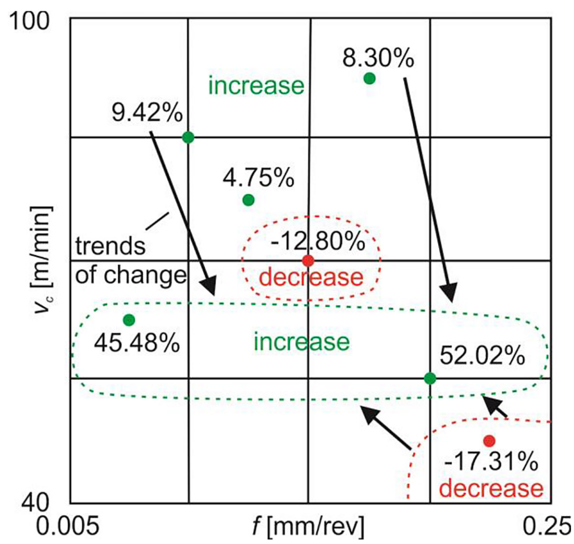


Fig. 3. Percentage changes in the averaged values of *Ra* parameters of Ti6Al4V alloy after MQL conditions compared to dry machining

of change (arrows in Fig. 3). At these points, the largest percentage changes in *Ra* values were obtained between MQL and dry cutting. They are 45% (point 5 of PSI) and 52% (point 2 of PSI).

Figure 4 shows contour maps, 2D images and surface profiles of the samples after machining with v_c = 62.5 m/min and f = 0.036 mm/rev (point 5 of PSI) under the tested conditions.

After dry machining, irregularly distributed small areas of peaks and pits are observed on the surface, and for MQL only a larger area of peaks (visible on contour maps) was observed. This

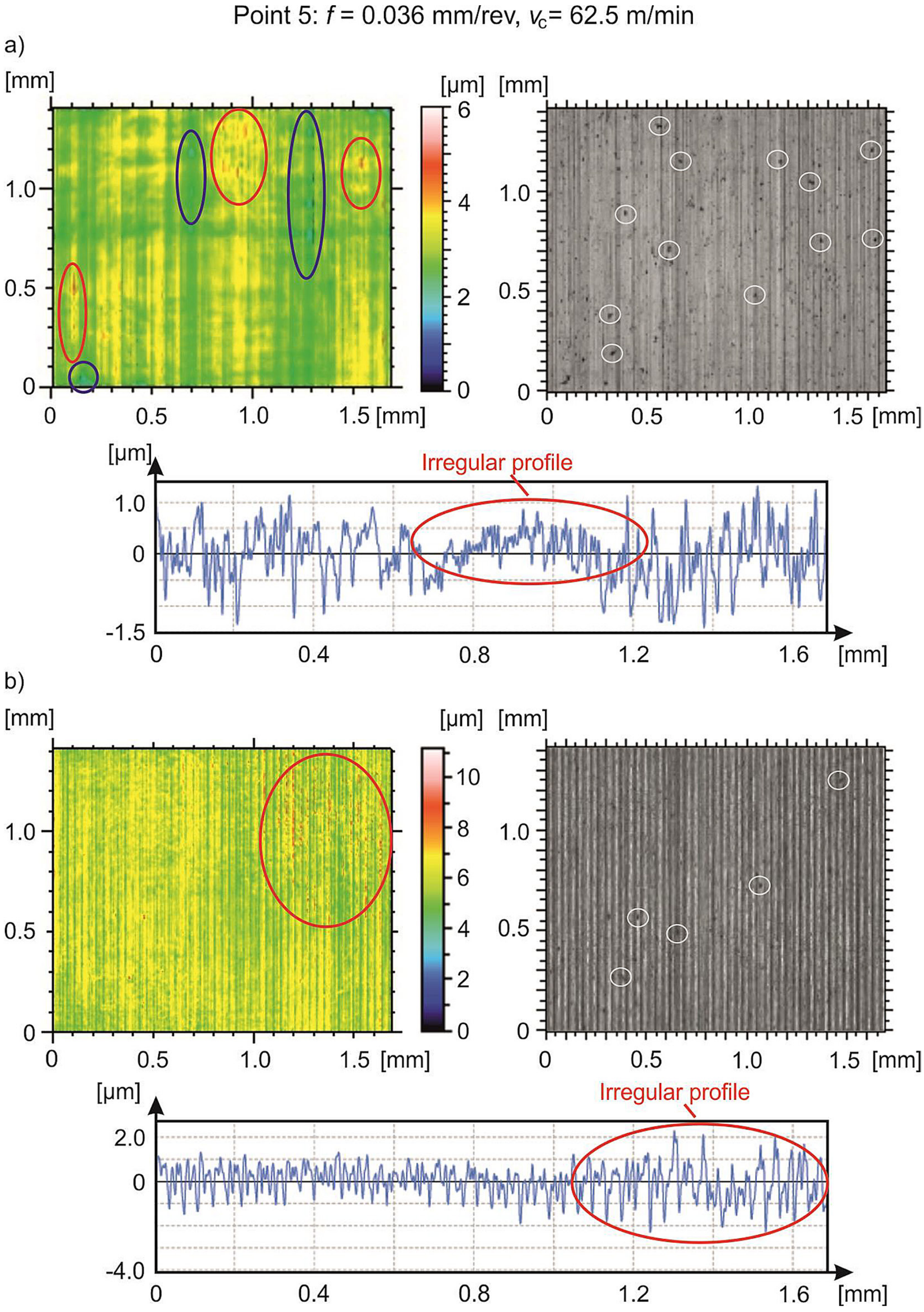


Fig. 4. Contour maps, 2D images and surface profiles after (a) dry and (b) MQL turning with v_c = 62.5 m/min and f = 0.036 mm/rev

indicates plastic deformation of the machined material (as confirmed by irregular surface roughness profiles) induced by high cutting temperature, which is typical for titanium alloys machining due to their low thermal conductivity [24]. The changes in the height of surface roughness under dry conditions are 6 μm and under MQL conditions they are 11 μm. On the other hand, for the studied machining conditions, adhesion bonds of small chip particles with the machined surface are visible in 2D images, which was also observed by Leksycki and Feldshtein [5] and Liang

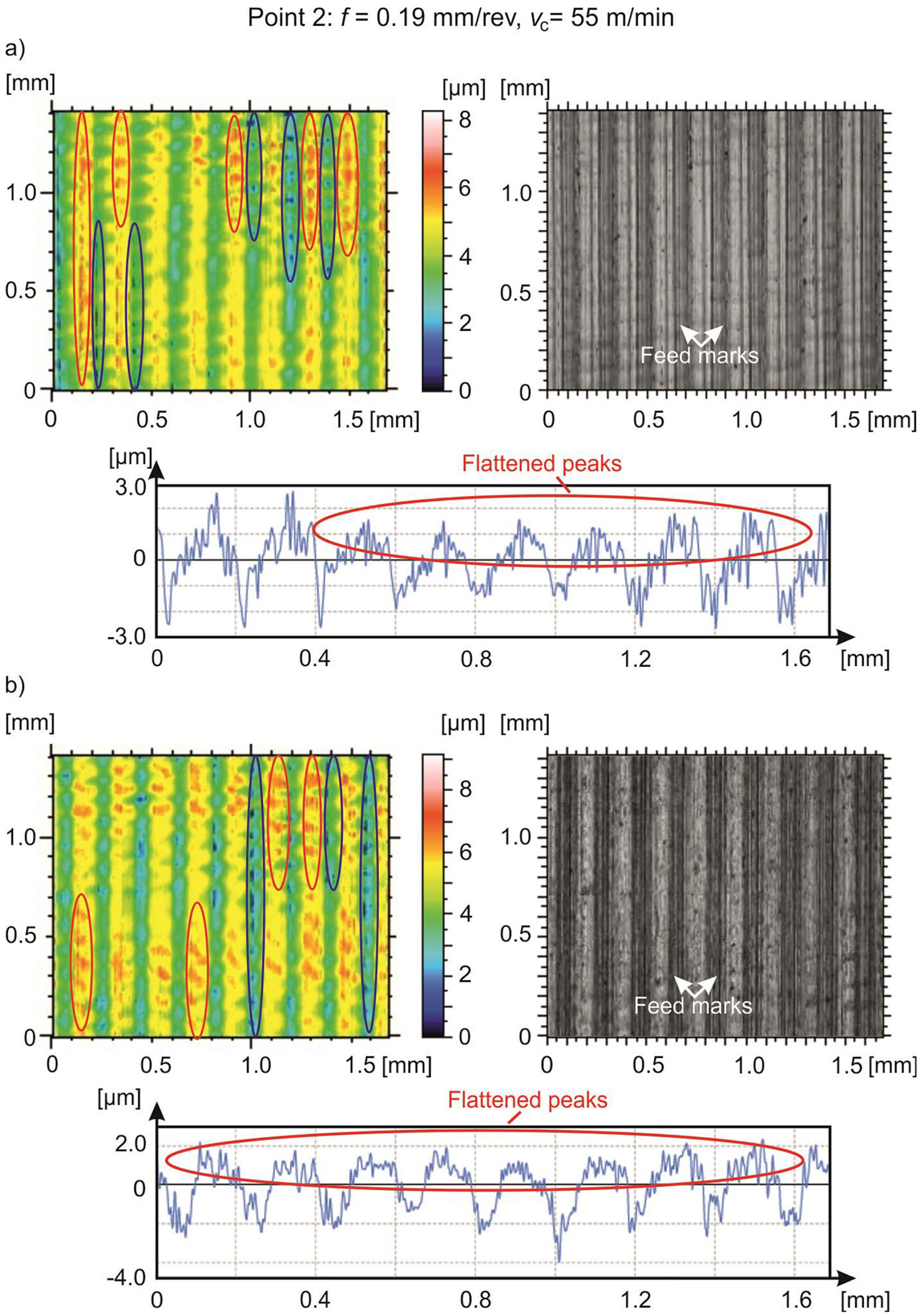


Fig. 5. Contour maps, 2D images and surface profiles after (a) dry and (b) MQL turning with v_c = 55 m/min and f = 0.19 mm/rev

et al. [25]. A larger number of connections are observed on the dry machined surface, since under MQL conditions some of them were washed away by the oil mist.

Figure 5 shows contour maps, 2D images and surface profiles of the samples after machining with v_c = 55 m/min and f = 0.19 mm/rev (point 2 of PSI) under the tested conditions.

After turning under the studied machining conditions, feed marks characteristic for turning (2D images) are visible on the machined surfaces as irregular valleys and peaks, which can be observed on the contour maps. On the other hand, flattened peaks, indicating the appearance of a plastic deformation can be seen on the surface roughness profiles. The changes in the height of surface roughness under dry conditions are 8 µm and under MQL conditions they are 9 µm.

CONCLUSIONS

The surface topography of Ti6Al4V alloy after the finish turning process was evaluated. Ecological machining conditions were compared, namely dry machining and using the MQL method. Variable feed per revolution of 0.005–0.25 mm/rev, cutting speeds of 40–100 m/min and a constant depth of cut of 0.25 mm were employed, corresponding to the finish machining conditions. The machined surface was analyzed using a Sensofar S Neox 3D microscope and optical point scanning by Imaging Confocal Microscopy technique. The *Ra* parameters and surface roughness profiles, as well as 2D images and contour maps were analyzed. It was found basing on the research results, that:

- In dry turning, smaller *Ra* values are obtained with cutting speeds of 40–50 m/min and feed per revolution of 0.005–0.1 mm/rev. When MQL turning, the lowest *Ra* values are achieved for cutting speeds of 40–60 m/min and feed per revolution of 0.04–0.1 mm/rev,
- In comparison with dry machining, decreasing *Ra* parameters up to 17% was observed under MQL conditions with v_c = 70 m/min and f = 0.127 mm/rev as well as v_c = 47.5 m/min and f = 0.22 mm/rev,
- Small areas of peaks and pits are observed on surfaces machined with f = 0.036 and v_c = 62.5 m/min under dry cutting conditions, and only larger areas of peaks are observed when cutting under MQL. The height of these changes is 6 µm and 11 µm, respectively,
- Feed marks with irregular peaks and valleys are observed on surfaces machined with f = 0.19 and v_c = 55 m/min under the conditions studied. During dry machining, the value of these changes is 8 µm, and under MQL conditions it is 9 µm.

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