ANALIZA VIBRACIJA I KVALITETA OBRAĐENE POVRŠINE PRI STRUGANJU LEGURE Ti-6Al-4V

ANALYSIS OF VIBRATIONS AND MACHINED SURFACE QUALITY DURING TURNING OF Ti-6Al-4V ALLOY

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REZIME
Ovaj rad analizira uticaj osnovnih parametara struganja na vibracije i kvalitet površine legure titanijuma Ti-6Al-4V. Zbog specifičnih mehaničkih svojstava, obrada titanijuma često izaziva pojavu rezonancije, nestabilnosti i povećane hrapavosti. Eksperiment je izveden na univerzalnom strugu, uz variranje brzine rezanja, posmaka i dubine rezanja, kako bi se ispitali različiti režimi obrade. Mjerenjem vibracija i hrapavosti potvrđeno je da se najbolji rezultati postižu izbjegavanjem režima rada koji uzrokuju rezonanciju, čime se smanjuju vibracije i poboljšava kvalitet površine. Dobijeni rezultati pokazuju da je za stabilan i precizan proces obrade važno pažljivo odabrati parametre i pratiti vibracije u realnom vremenu. Na taj način se može produžiti vijek trajanja alata i postići bolji kvalitet gotovog proizvoda.

Professional paper

SUMMARY
This paper analyzes the influence of basic turning parameters on vibrations and surface quality of titanium alloy Ti-6Al-4V. Due to specific mechanical properties, titanium processing often causes resonance, instability and increased roughness. The experiment was performed on a universal lathe, with varying cutting speed, feed and depth of cut, in order to test different machining regimes. Vibration and roughness measurements confirmed that the best results are achieved by avoiding operating modes that cause resonance, thus reducing vibrations and improving surface quality. The obtained findings show that for a stable and precise machining process it is important to carefully select parameters and monitor vibrations in real time. In this way, the service life of the tool can be extended and a better quality of the finished product can be achieved.

1. INTRODUCTION

Titanium and its alloys, particularly Ti-6Al-4V, have found widespread application in high-performance and safety-critical industries such as aerospace, space technology, biomedicine, and automotive engineering. This growing interest is attributed to their exceptional mechanical properties, including high strength-to-weight ratio, excellent corrosion resistance, and biocompatibility, as well as their relatively low density. These characteristics make titanium alloys ideal for components that must withstand extreme conditions while maintaining high reliability.

One of the most critical issues during the machining of titanium alloys is the occurrence of vibrations, particularly self-excited vibrations (chatter), which can significantly compromise process stability. In extreme cases, resonance occurs when the excitation frequency of vibrations approaches the natural frequency of the workpiece or the machine–tool–workpiece system. Under such resonance conditions, even minor disturbances are amplified, resulting in unstable cutting, increased tool wear, loss of dimensional control, and poor surface integrity.

In this context, it becomes essential to understand how key cutting parameters, such as cutting speed, feed rate, and depth of cut, influence the onset and intensity of vibrations, as well as their effect on surface roughness. Therefore, the aim of this study is to perform a systematic analysis of the influence of selected cutting parameters on vibration behavior and surface quality during the turning of Ti-6Al-4V alloy. Special emphasis is placed on identifying optimal machining conditions that ensure process stability, minimize surface roughness, and improve overall machining efficiency.

2. EXPERIMENTAL DESIGN

The experiment was conducted using a full factorial design with three factors at two levels and three repetitions at the center point, resulting in a total of eleven trials. This design enabled simultaneous analysis of main effects, factor interactions, and assessment of nonlinearity in the system response. An additional advantage of this approach is the potential to expand the design into a Central Composite Design (CCD) if the initial model does not sufficiently describe the process behavior.

The selected input factors, cutting speed, depth of cut, and feed rate, were chosen based on a review of relevant literature and the specific characteristics of machining Ti-6Al-4V alloy. These parameters are known to significantly influence process stability, the occurrence of vibrations, and surface quality. The experiment was performed under dry cutting conditions, without the use of cooling or lubrication, in order to isolate the mechanical effects of the cutting process.

Factor levels were carefully defined to cover a broad spectrum of machining conditions, ranging from roughing to finishing operations. Special attention was given to aligning parameter values with the technical limitations and capabilities of the machine tool used. In particular, cutting speed values were calculated based on the selected spindle speed and workpiece diameter using the standard machining formula:

$$v = \frac{\pi \cdot D \cdot n}{1000} \tag{1}$$

This formula enabled precise control over cutting speed in accordance with the selected machine spindle settings and workpiece geometry.

The full factorial design resulted in eight unique parameter combinations, complemented by three center points to enhance the reliability of the data and enable detection of nonlinear trends. This provided a solid foundation for statistical analysis and the development of an accurate process model.

Table 1 presents the selected factor levels used in the experimental investigation of Ti-6Al-4V alloy machining.

Table 1 Factor levels for the matchining experiment of Ti-6Al-4V titanum alloy

FACTORS	Low level	Central point	High level
Cutting speed m /min	49,76	75,39	111,58
Feed rate mm	0,107	0,196	0,285
Depth of cut mm/o	1	1,5	2

3. EXPERIMENTAL SETUP

In this study, the entire experiment was carried out at the Laboratory for Machining and Machine Tools of the Faculty of Mechanical Engineering in Zenica, which is equipped with modern machine tools and diagnostic equipment necessary for detailed analysis of machining processes.

The experimental setup consisted of several key components: a workpiece made from a hard-to-machine titanium alloy, a lathe machine used for the turning operation, an appropriate cutting tool, and independent measuring units for recording vibrations and surface roughness. All elements of the experiment were carefully selected and mutually aligned to ensure the validity of results and enable clear interpretation of the collected data.

3.1. Workpiece

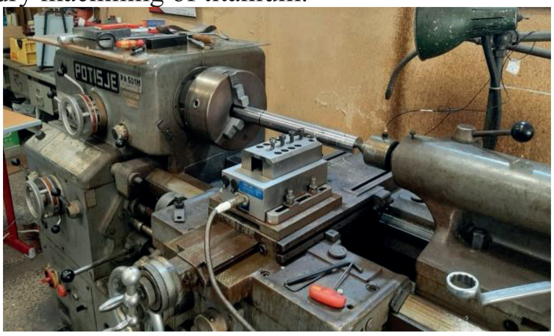
For the purposes of the experimental investigation, a cylindrical workpiece with a diameter of Ø48 mm (Figure 1) was used, made from Ti-6Al-4V (Grade 5) alloy, which is the most widely used titanium alloy in modern industrial applications. This alloy consists of approximately 6% aluminum, 4% vanadium, and the balance titanium. The workpiece was prepared in the form of a standard cylindrical blank in its raw state, without any prior machining, allowing the application of various turning regimes under different experimental conditions.

Figure 1 *Workpiece*

3.2. Machine tool

The turning experiment of the Ti-6Al-4V titanium alloy was performed on a universal lathe PA 501-M. The cutting process was carried out using a tool with an indexable insert, type R245-12 T3 M-PM 1030, manufactured by Sandvik Coromant. The insert is made of cemented carbide with a PVD coating, specifically designed for machining difficult-to-cut materials such as titanium.

The medium positive geometry (PM) offers a balance between efficient material removal and surface quality control, while the coating enhances wear resistance and reduces the risk of built-up edge formation, a common issue in dry machining of titanium.



.***Figure 2*** *Mounted workpiece position on PA 501-M Lathe*

3.3. Equipment and methods for vibration measurement

To ensure accurate vibration measurement during the turning of Ti-6Al-4V alloy, two methods were employed: non-contact laser-based and contact piezoelectric.

The non-contact method utilized an Ometron VQ-400-A laser vibrometer (Figure 3), which uses the Doppler effect to precisely measure vibrations without interfering with the workpiece or tool. The laser beam was directed at the machining zone, and the data were recorded and analyzed using dedicated software.

In parallel, a piezoelectric sensor was mounted directly on the lathe near the cutting area (Figure 4) to capture mechanical oscillations transmitted through the machine structure. Signals from both systems were analyzed using a computer-based data acquisition and processing unit.

The parallel use of laser and contact methods enabled more reliable vibration analysis and result validation under real machining conditions.

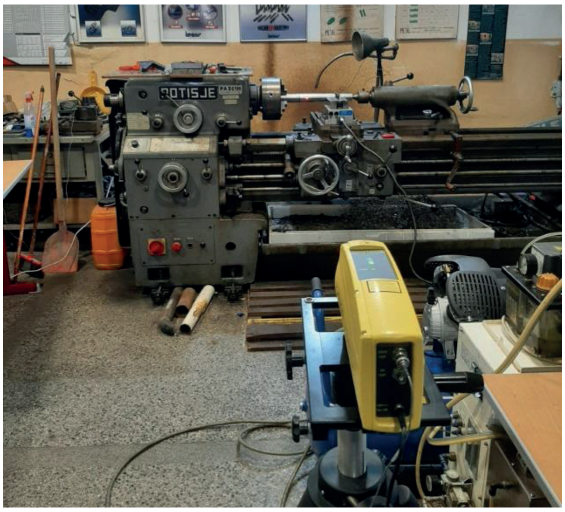


Figure 3 *Ometron VQ-400-A Setup ready for vibration measurement*

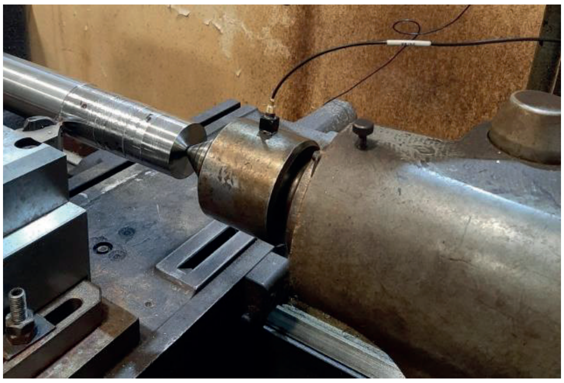


Figure 4 *Positioning of the contact sensor during experimental machining*

3.4. Equipment and methods for surface roughness measurement

The surface quality was assessed using the high-precision Mahr MarSurf TS 50 device, capable of measuring roughness parameters according to ISO 4287, including the widely used Ra parameter. Samples were cleaned prior to measurement and the device was calibrated according to manufacturer guidelines. Figure 6 shows the experimental setup for roughness measurement, while Figure 5 presents the longitudinal surface profile after machining.

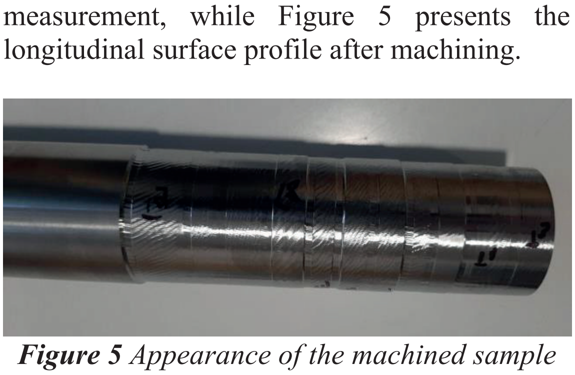


Figure 5 *Appearance of the machined sample surface after the experiment*

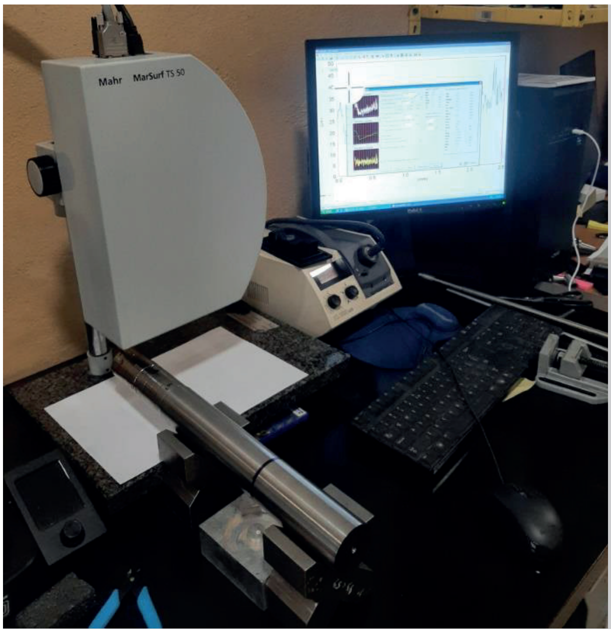


Figure 6 Mahr MarSurf TS 50 device during roughness measurement of the machined sample

4. RESULTS OF EXPERIMENTS

For each machining condition, the following variables were measured: vibration amplitude (A), dominant vibration frequency (F), arithmetic mean roughness Ra [µm], and surface roughness Sa [µm]. In addition to quantitative data, visual analysis of the surface microstructure was conducted using microscopic images to further evaluate the surface quality.

4.1. Vibrations during machining

As part of the vibration analysis, the natural frequency of the Ti-6Al-4V workpiece was measured prior to machining to determine its dynamic characteristics. Three fundamental vibration modes were identified:
- first mode: 325 Hz,
- second mode: 932 Hz,
- third mode: 2700 Hz.

Subsequently, during all 11 machining experiments, vibration levels were monitored for various combinations of spindle speed and feed rate.
The measured vibration results for each experiment are presented in the table 2.

4.2. Machined surface roughness

Measurements were conducted on the samples after each experiment and included the following:
- line roughness (Ra) – arithmetic mean deviation of the profile
- surface roughness (Sa) – three-dimensional surface roughness parameter.

The measured surface roughness results for each experiment are presented in the table 2.
The following images show the microstructure of the machined surface after each individual experiment. These images provide a visual assessment of the influence of different machining regimes on the final surface quality.

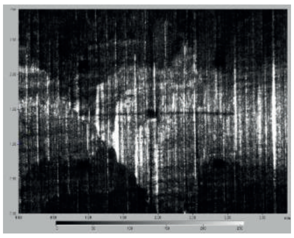


Figure 7 *Surface microstructure - Experiment 1*

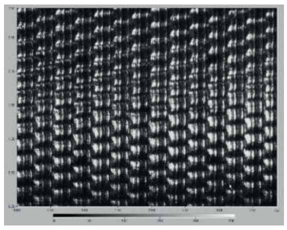


Figure 8 *Surface microstructure - Experiment 2*

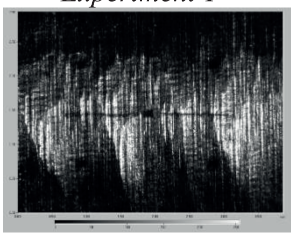


Figure 9 *Surface microstructure - Experiment 3*

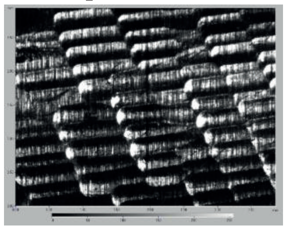


Figure 10 *Surface microstructure - Experiment 4*

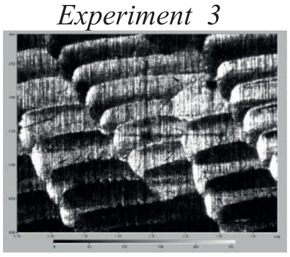


Figure 11 *Surface microstructure - Experiment 5*

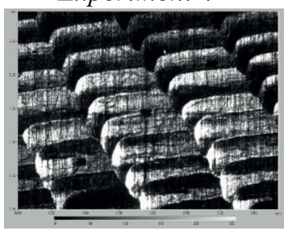


Figure 12 *Surface microstructure - Experiment 6*

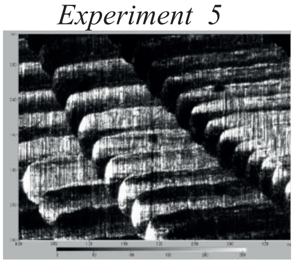


Figure 13 *Surface microstructure - Experiment 7*

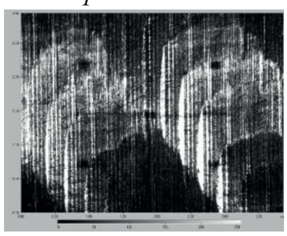


Figure 14 *Surface microstructure - Experiment 8*

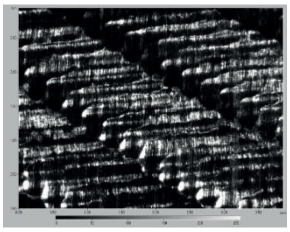


***Figure 15** Surface microstructure - Experiment 9*

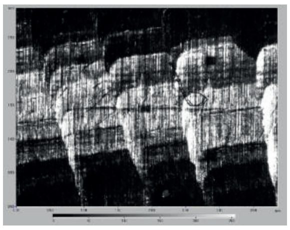


***Figure 16** Surface microstructure - Experiment 10*

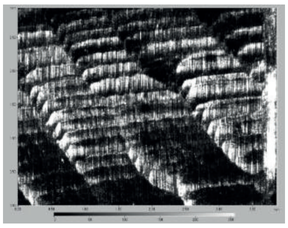


***Figure 17** Surface microstructure - Experiment 11*

4.3. Processing of experimental test results

Data processing was conducted using a methodology that combines classical experimental design and the Taguchi method. The first step in the analysis of the presented results is the determination of effects, specifically the influence of individual factors on the observed process. This is shown in table 3.

The factor effect represents the difference between the mean output value corresponding to the observed factor at the high level and the mean value at the low level, where n is the number of repetitions of individual trials, and k_1, k_2, …, k_{11} are the results obtained from the experiment. The effect is calculated as follows:

$$A = \overline{y_{A+}} - \overline{y_{A-}},$$
$$A = \frac{1}{4n}[k1 - k2 + k3 - k4 + k5 - k6 + k7 - k8 + k9 - k10 + k11]. \quad (2)$$

Table 2 Experimental matrix and results for the sample

Exp. Nº	v	f	d	A	B	C	Ra [μm]	Sa [μm]	F [Hz]	A [dB/1m/s^2]
1	111,58	0,285	2	1	1	1	3	3.1	584	222
2	49,76	0,285	2	-1	1	1	6.4	6.5	584	186
3	111,58	0,107	2	1	-1	1	3.6	4.1	1.161k	218
4	49,76	0,107	2	-1	-1	1	3.4	4.9	584	214
5	75,39	0,196	1,5	0	0	0	3.2	4.5	584	203
6	75,39	0,196	1,5	0	0	0	4.1	5.0	281	206
7	75,39	0,196	1,5	0	0	0	3.1	4.8	281	192
8	111,58	0,285	1	1	1	-1	4.1	5.0	565	212
9	49,76	0,285	1	-1	1	-1	3.6	5.2	565	228
10	111,58	0,107	1	1	-1	-1	4.2	4.6	286	199
11	49,76	0,107	1	-1	-1	-1	3.5	5.1	565	218

Table 3 Factor effect determination table for experimental design

Exp. Nº	I	A	B	AB	C	AC	BC	ABC
1	1	1	1	1	1	1	1	1
2	1	-1	1	-1	1	-1	1	-1
3	1	1	-1	-1	1	1	-1	-1
4	1	-1	-1	1	1	-1	-1	1
5	1	0	0	0	0	0	0	0
6	1	0	0	0	0	0	0	0
7	1	0	0	0	0	0	0	0
8	1	1	1	1	-1	-1	-1	-1
9	1	-1	1	-1	-1	1	-1	1
10	1	1	-1	-1	-1	-1	1	1
11	1	-1	-1	1	-1	1	1	-1

Table 4 Factor effect determination table for experimental design

COMBINATION	A	B	AB	C	AC	BC	ABC
Ra	0,5	0,6	-0,95	0,25	-1,1	0,6	-0,85
Sa	-1,225	0,275	-0,575	-0,325	-0,875	0,025	-0,725
A	1,25	-0,25	8,75	-4,25	18,75	-11,75	7,25
F	-71,5	71,5	71,5	87	68	-68	-68

By summing the obtained results, the order of factors according to the magnitude of their effects becomes evident. For both surface (Sa) and line roughness (Ra), the feed rate has the greatest influence; for vibration amplitude, it is the combination of cutting speed and depth of cut; while for dominant frequencies, the depth of cut has the most significant impact. These findings are presented in table 4 above.

4. CONCLUSION

The conducted experimental analysis clearly demonstrated that machining parameters significantly affect the occurrence of vibrations and the quality of the machined surface during the turning of Ti-6Al-4V alloy. The obtained results indicate that feed rate has the greatest influence on surface roughness, while the combination of cutting speed and depth of cut has the most significant effect on vibration amplitude. Additionally, depth of cut was identified as the key factor influencing the dominant vibration frequency.

A closer inspection of individual experiments revealed the best and worst machining conditions. Experiment 7 produced the most favorable results, with low surface roughness values (Ra = 3.1 µm, Sa = 4.8 µm) and low vibration amplitude (A = 192 dB/1m/s²), achieved at medium levels of all input parameters (cutting speed = 75.39 m/min, feed rate = 0.196 mm/rev, depth of cut = 1.5 mm). This confirms that moderate machining regimes often provide the best balance between process efficiency and surface quality.

In contrast, Experiment 2 showed the most unfavorable conditions, resulting in the highest surface roughness values (Ra = 6.4 µm, Sa = 6.5 µm). Although the measured vibration amplitude was not extreme, the low cutting speed (49.76 m/min), combined with a high feed rate and depth of cut, likely caused resonant behavior and unstable cutting. This highlights that low cutting speeds under dry machining conditions are not suitable for Ti-6Al-4V, as they lead to increased friction, heat generation and surface degradation.

The significance of this study lies in its practical recommendations for titanium machining. Real-time vibration monitoring and careful control of input parameters can significantly enhance process stability, tool life, and final product quality. The presented data also provide a foundation for developing predictive models and further optimization of matchining processes involving high-performance materials such as Ti-6Al-4V.

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