Effect of ultrasonic oscillations on force and surface roughness in grinding process of Ti6Al4V titanium alloy

Wpływ drgań ultradźwiękowych na siłę i chropowatość powierzchni w procesie szlifowania stopu tytanu Ti6Al4V

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The paper presents the preliminary experimental study results in grinding process of Ti6Al4V titanium alloy. The aim of this study was to determine, through grinding force components and surface roughness analysis, what effect on this process has assisting it with workpiece ultrasonic oscillations.
KEYWORDS: ultrasonic assisted grinding, UAG, Ti6Al4V titanium alloy, measurement of forces in grinding process, surface roughness

Due to the high ductility and tendency to self-curing during cutting, titanium alloys are materials, where high machining efficiency is difficult to obtain if conventional techniques are used [1, 2]. Therefore, new solutions for Ti6Al4V titanium alloy finishing machining (grinding) are being sought. Hybrid processes appear to be where the removal of material occurs through the combination of different energy sources, such as ultrasonic assisted grinding (UAG) [3, 4].

This process requires the implementation into the machine tool-tool-workpiece system additional system that actuates and transduces high frequency vibration onto the workpiece or the tool. This article discusses the case of an oscillating workpiece (fig. 1). This allows the use of different kinematic variations of the grinding process (as opposed to the oscillating of the tool, where the oscillations are transduced only in its axis).

Due to the constructional conditions of the oscillation inducing system (waveguide), assisting the grinding process with workpiece ultrasonic oscillation requires an individual approach in each case. This applies in particular to the waveguide element called sonotrode. The sonotrode, which is in contact with the workpiece and is the last element of the waveguide, must be redesigned for each new workpiece [5].

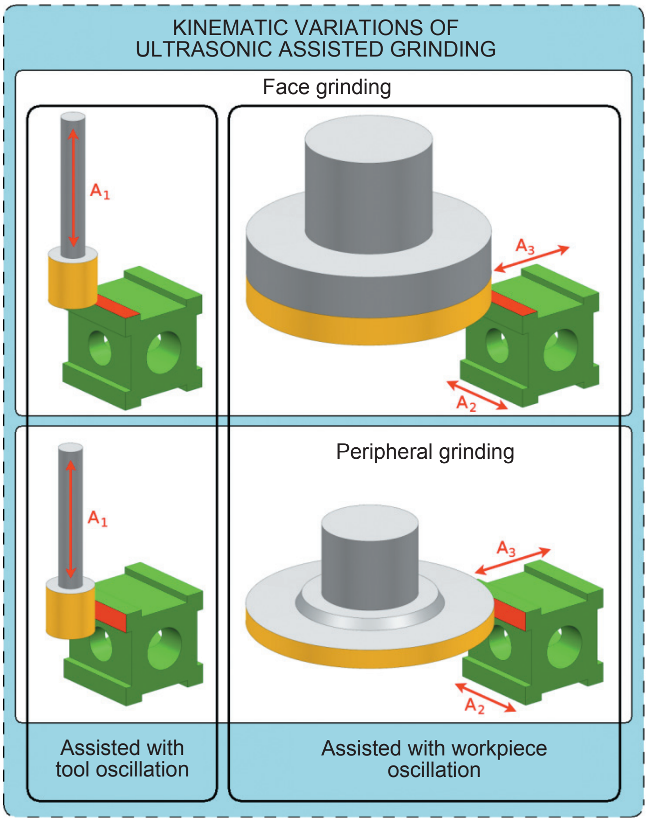

Fig. 1. Kinematic variations of the ultrasonic grinding process: A_1 – vibration along the tool axis, A_2 – vibration longitudinal to the feed direction, A_3 – vibration transverse to the feed direction, A_2 + A_3 – combination of longitudinal and transverse vibrations

Experimental study conditions

The experiment was carried out on a CNC test stand designed for the PBS2/B6/17/2013 project [6] and equipped with an HAAS VF-2YT machining center where the control system was replaced with the Sinumerik 840D sl, which was dictated by the need to control the ultrasonic generator parameters from the level of technological program. Dynamometer based on four Kistler 9601A3110000 type piezoelectric sensors was used to measure the force components in ultrasonic assisted

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grinding process, and Mahr stylus profilometer MarSurf PS 10 for surface roughness measurements. The waveguide, the most significant system in this process, that can actuate ultrasonic vibrations at frequencies in the order of 20 kHz consist of: high voltage alternating current generator, transducer with nominal resonance frequency of 20 kHz, oscillation booster with amplitude magnification factor 1:1.5 and sonotrode with attached workpiece.

Themachined material was titanium alloy Ti6Al4V with a microstructure composed of two phases: α and β. As a tool for machining, face grinding wheel 6A2 100-6/4 D151 K100 H20 B-IIIBK from Urdiamant was used with diamond abrasive, grain size 151 and resin bond. As a cooling agent – 5% synthetic emulsion was supplied to the grinding zone.

The tests were carried out in face grinding setup with the oscillating workpiece (fig. 1) mounted on the front face of the sonotrode. The grinding passes of the grinding wheel was performed at a passes perpendicular to the mechanical wave axis forcing ultrasonic vibrations (fig. 2). During the research project [6], a special workpiece geometry and adjusted for it sonotrode with a 21,093 kHz resonance frequency and mechanical fixture of the workpiece, was developed (fig. 2). The shape of the workpiece made it possible to grind a flat surface with

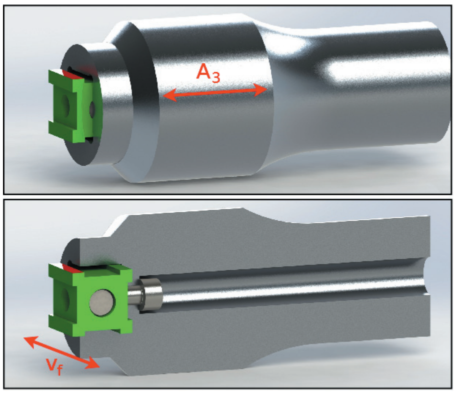

Fig. 2. View and cross section of the sonotrode with attached workpiece: A_3 – direction of vibration, v_f – feed rate direction

a width of 3 mm and a length of 20 mm – thus ensuring a constant cross-section of cut.

In order to guarantee constant test conditions, the grinding wheel conditioning was performed prior to each test program (with mean values from the following variability ranges of the tested technological parameters) – so that the initial running-in process did not interfere with the measurement results. Prior to each measurement pass, workpiece truing pass and five sparking passes without ultrasonic vibrations were performed. After each measurement pass eight sparking passes were performed.

As inputs, affecting the tangential and normal components of grinding force and surface roughness, the following technological parameters were adopted:

- grinding speed v_s = 10÷30 m/s,
- feed rate v_f = 2000÷4000 mm/min,
- grinding depth a_e = 0.02÷0.05 mm (the maximum value depends on the average size of the abrasive grain).

In order to investigate the influence of individual parameters on the grinding force and surface roughness, three times completely randomized design was used, in which input parameters were technological parameters mentioned before. They took values at three levels of variability. The design required to perform in random order the measurements (repeated five times) for three setups in which one parameter changed its value, while the other two assumed mean values of the variability ranges. Input values for individual measurement setups are shown in the table. It should be noted that, for comparative purposes, all measurements were made both without the aid of the ultrasound process and with the aid, with a vibration amplitude of 5.8 μm. The values measured in this process were the grinding force (normal component F_n and tangent component F_t) and the surface parameter Ra in the perpendicular and parallel direction to the feed rate.

TABLE. Test conditions

Machine tool	Haas VF-2YT		
Machining type	flat surface grinding		
Ultrasonic assisted grinding	on/off		
Vibration amplitude A, μm	5,8/0		
Fixing of workpiece	mechanical, frontal		
Workpiece	titanium alloy Ti6Al4V		
Cutting	face grinding wheel 6A2 100-6/4 D151 K100 H20 B-IIIBK		
Average size of abrasive grain D, μm	151		
Number of sparking passes	1		
Number of measurements passes	8		
Number of measurements repetitions	5		
Grinding length l_s, mm	20		
Grinding width a_p, mm	3		
Process cooling	flood		
Coolant	5% synthetic emulsion		
Test program	I	II	III
Grinding speed v_s, m/s	10 20 30	20	20
Feed rate v_f, mm/min	3000	2000 3000 4000	3000
Grinding depth a_e, mm	0,035	0,035	0,02 0,035 0,05

Results

The grinding process assisted by workpiece ultrasonic oscillation (with UAG) and, for comparative purposes, a conventional grinding process (without UAG) was carried out under the same test conditions. The main purpose of the study was to determine the influence of ultrasonic vibrations of the Ti6Al4V alloy workpiece on the grinding force components and the surface roughness. Fig. 3 shows the comparison of the values of the grinding force components comparison in examined processes. For each value in the graph, the confidence interval calculated for the five measurements and the significance level of 0.05 is shown.

The study confirmed the beneficial effect of assisting the Ti6Al4V alloy grinding process with ultrasonic oscillation on normal and tangential grinding force components. As can be seen in fig. 3, along with the increase in the grinding speed v_s, there is a decrease in the component

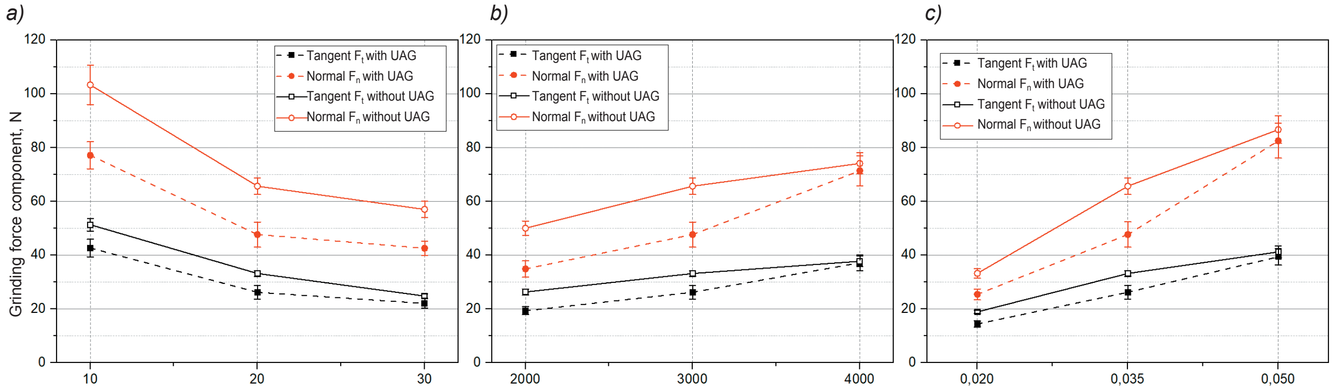

Fig. 3. Dependence of normal F_n and tangential component F_t from: a) grinding speed v_s, b) feed rate v_f, c) grinding depth a_e – in ultrasonic assisted grinding process (with UAG) and conventional grinding (without UAG)

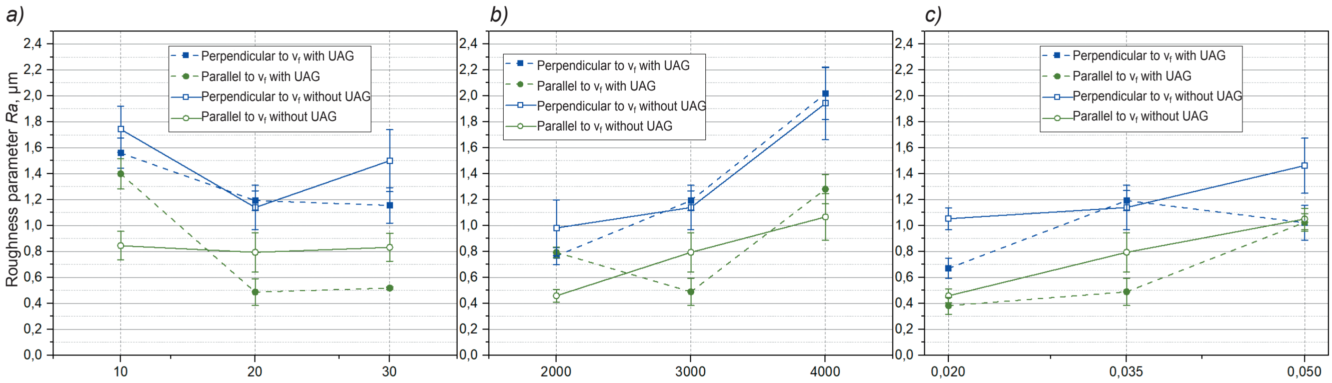

Figure 4. Dependence of surface roughness parameter *Ra* from: a) grinding speed v_s, b) feed rate v_f, c) grinding depth a_e – in ultrasonic assisted grinding (with UAG) and conventional grinding process (without UAG)

values of F_n and F_t of the grinding force, and the increase – along with the increase of the feed rate v_f and the grinding depth a_e. At the same time, in each case the values of the grinding force components in the ultrasonic assisted process was lower than in the conventional process.

Fig. 4 shows the comparison of *Ra* roughness values obtained in respective processes. Evaluation of these values is not as clear as in the case of grinding force because the results are obtained from a very wide range of values. However, in the case of conventional grinding, the roughness measured perpendicular to the feed direction was significantly greater than the roughness measured parallel to the feed direction. In the ultrasonic assisted process this difference was smaller.

Conclusions

The experimental results lead to the following conclusions:

- applying ultrasonic vibration in the studied process allowed to reduce the normal force F_n by 2÷27% and the tangential force F_t by 4÷30%;
- the favorable influence of ultrasonic oscillation on the grinding force components values grinding force for the largest feedrate v_f and grinding depth is minor. The force components analogical in the assisted process are about 4% lower than the conventional values in the conventional process, which may be due to the operation characteristics of the waveguide. The transducer is controlled by an automatic frequency control system that provides a constant amplitude value. However, depending on the load applied to the operating part of the sonotrode, a plane shift follows (wavelength change), in which maximum amplitude value occurs. Increasing the material removal rate (increase in feed rate and grinding depth) can reduce the vibration amplitude in the grinding zone, although clarifying the cause of this phenomenon requires more thorough investigation;
- introducing workpiece oscillation to the grinding process resulted in value change of *Ra* parameter: measured in the direction perpendicular to the feedrate – from a 5% increase to a 36% decrease direction to the feed rate – from a 73% increase to a 39% reduction;
- due to the wide range of *Ra* parameter values obtained, further extended studies are required, concerning the influence of ultrasonic vibration in Ti6Al4V alloy grinding process assisted by workpiece ultrasonic oscillation.

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