Comparative machinability and surface integrity in grinding of titanium

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***Abstract*—** This paper investigates the surface grinding process to evaluate the effect of input parameters of titanium, which is commonly known to have poor machinability. Dry and wet grinding experiments have been carried out and optimal conditions for grinding titanium have been identified with respect to feed rate, wheel speed and depth of cut. The incorporation of cooling improves integrity of ground surface which significantly extended resistance to wear. Moreover, comparative ANOVA roughness model has been derived. This model approved an interaction among all input parameters.

***Keywords*—**ANOVA, Surface Integrity, Surface Grinding, Titanium.

I. Introduction

Grinding is one of the crucial technology to achieve the desired surface quality of the components. It is categorized as the last technological operation that takes only a small amount of material, by a tool that has a stochastic structure [1], [2]. Although external feature characteristics of the tool are definable, the layout, size and geometry of the micro tools - abrasive grains – therefore cannot be determined clearly. Even though grinding is much used in industry remains perhaps the least understood machining method. Even if grinding is one of the oldest ways of machining today, does not lose its importance. Grinding technology may not only be used as a finishing operation, but in the case of in-depth, high-performance grinding becomes a high stock removal technique [3]-[5]. Most of the materials can be ground. Grinding is successfully used for machining of metals and non-metallic materials, such as plastics [6]. It is the only method that allows conventional way to machine brittle materials, superalloys and difficult-to-machine metals [7]. The tool is a grinding wheel composed of abrasive grains of superhard materials [8], [9], such as Cubic Boron Nitride (CBN) or diamond.

Surface integrity describes the state of the layer close to the surface in the terms of macro and micro evaluation and classification of possible flaws. Surface roughness describes the micro scale of the surface. Surface roughness generated by the grinding process determines a range of component characteristics such as the minimal tolerances, the ability of lubrication, reflectance, durability, [10] etc. The grinding is a complex material removal process, with a great number of influencing factors which are also nonlinear and difficult to quantify [11]-[13].

Surface quality of grinding is influenced by following parameters: [14]

a) wheel characteristic: grain material, size, grade, structure, binder, dimensions, etc.

b) workpiece material: mechanical properties and chemical composition.

c) process parameters: cutting speed, feed rate, depth of cut, dressing, etc.

d) machine parameters: static and dynamic behavior, table and clamping system [15], spindle system, etc.

Nevertheless, it is an effort to describe and predict the grinding process and quantify resulting surface roughness. If we consider all the input characteristics, a complete prediction of surface topography is a complex problem [16], [17]. The typical parameter which is used in the industry to evaluate the surface arithmetic mean roughness is value of *Ra*. It is a widespread parameter, although does not carry comprehensive information of surface roughness. Another parameter is the maximum peak to valley height of the profile *Rz* in a single sampling length. It is an important parameter in manufacturing of components for the automotive industry, since is an indicator for highly stressed parts where difference between the peaks and heights of the profile is the area prone to cracking. Generally, the longitudinal surface roughness has a lower value than traversal value, and therefore is more frequently used in industry [18]. Roughness parameter *Ra* is generally defined as:

$$Ra = \frac{1}{lr}\int_{0}^{lr} |Z(x)|dx \tag{1}$$

describing the roughness profile on the sampling length *lr* from the profile height function *Z*(*x*). While parameters *Rz* is expressed as:

$$Rz = Rp + Rv \tag{2}$$

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where peak roughness *Rp* is attributed to highest point and *Rv* to the deepest valley in the roughness profile. Should be noted that in the article is surface roughness *Rz* determined according to international standards, as stated in the equation above. Nevertheless, in engineering practice appears the earlier *Rz* parameter defined in accordance with DIN, and which is known as 10-point height parameter. Consensus is reached, if applies $Rz_{DIN} = Rz5_{ISO}$, and standard measured sampling lengths is quintuple.

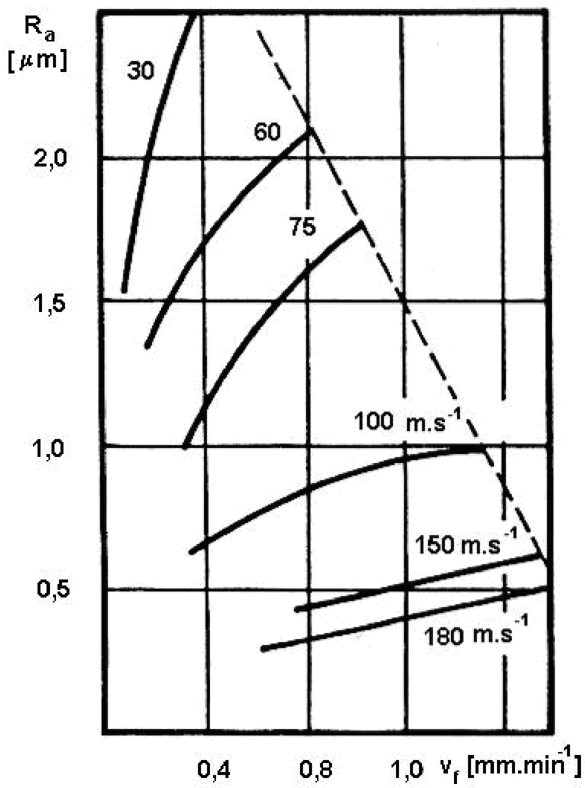


Fig. 1 Surface roughness *Ra* as influenced by feed rate v_f and wheel speed [19]

Selection of optimal cutting conditions during grinding is not as strongly influenced by the requirement of keeping the optimum tool life as is the case to other machining processes [20]. Grinding is in most cases finishing operation, and the cutting conditions are chosen particularly in terms of compliance with the prescribed surface quality. Resulting surface quality is to a large extent influenced by setting the correct input parameters based on previous research (Fig. 1). Another fact that governs the determination of the cutting conditions during grinding is a criterion of achieving the maximum material removal per unit of time [21].

The choice of cutting conditions during grinding is therefore complex and is influenced by multiple factors. More than any other machining operation is the surface integrity influenced by stiffness of the machine tool and workpiece clamping device. Further, depth of the withdrawn material influences the roughness of the ground surface more than the feed rate. For example, rising depth of cut from 0.01 mm to unusual 0.1 mm increases roughness parameter more than 3 times [22]. In contrast, when the reducing the longitudinal feed rate between the centers of the grinding wheel from 0.9 × wheel thickness to 0.1 × wheel thickness, roughness parameter *Ra* decreases though not significantly within the range 1.2 to 1.3 times.

The choice of cutting conditions shall be governed by the critical values of grinding wheels. When grinding with the grinding wheels with ceramic bond is recommended range of cutting speed 25-30 m/s, grinding wheels with ceramic bond and mechanical feed unit 30-35 m/s, and special types of grinding wheel mostly with polymer binding may exceed 100 m/s [23].

The surface of titanium and titanium alloy is easily disrupted during grinding due to their poor machinability [24]. Titanium and titanium alloys are widely used in the aerospace, chemical, petrochemical industry and for fabrication of medicinal prosthetics. Titanium is characteristic by their low density compared to other structural metals and alloys, excellent corrosion resistance, high level of proof strength. On the other hand, have poor wear resistance and suffer embrittlement at higher temperatures [25]. Titanium and titanium alloys are among the most difficult-to-machine materials [26], [27]. Low thermal conductivity and high chemical reactivity cause heat generation during machining and strong adhesion between the tool and the workpiece material. That is also the cause of poor surface quality [28]-[31].

This paper presents a statistical analysis of the arithmetic mean roughness *Ra* and roughness height *Rz*, depending on the diameter of the wheel depth of cut and feed rate of titanium material. The method of analysis of variance (ANOVA) was used to evaluate the correlation with titanium to other metal materials. Dry grinding results are compared in addition to the grinding process using a coolant.

II. Experiment Settings

To understand the effect of process conditions on the surface quality of the grinding was applied statistical analysis. The aim is to understand the impact of process conditions during grinding of titanium. The input parameters of the experiment are cutting depth, feed rate and the diameter of the grinding wheel. Details are presented in Table I.

Table I Process parameters and cutting conditions

Grinding machine	BRH 20.03F
Type of grinding wheel	99A90J9V
Grinding wheel diameter	195, 250 mm
Depth of cut	0.01, 0.02, 0.03, 0.04 mm
Feed rate	8, 12, 16, 24 m/min
Revolution of grinding wheel	2 500 min^{-1}

The first group of experiments was carried out under dry machining environment. Another group of experiments assessed the effect of coolant on the surface roughness depending on the grinding wheel diameter and hence the cutting speed. All samples were the same size (50x50x20 mm) and their chemical composition is shown in Table II, while the mechanical properties are given in Table III.

The last group of experiments was focused on the surface roughness while grinding of titanium by comparison with other metallic materials. Their ultimate strength was the categorization parameter added on the graphical axis. Ultimate strength of copper was 245 N/mm^2, 270 N/mm^2 for aluminum alloy, 530 N/mm^2 for structural steel C45 (1.1191), 668 N/mm^2 for bearing steel 100Cr6 (1.3505), 825 N/mm^2 for stainless steel X46Cr13 (1.4034), and 2850 N/mm^2 for tool steel X210Cr12 (1.2080). Specification of particular work materials are listed in tables IV-IX.

Table II Nominal chemical composition of the titanium

Work material	Chemical composition (wt. %)		
	Fe	C	Addition of
Ti	0.08	0.01	Al, V, Mn, Si

Table III Mechanical properties of work material

Work material	Ti
Ultimate tensile strength	350 N/mm^2
Modulus of elasticity	116×10^3 N/mm^2
Hardness	970 HV

For industrial purposes was selected measurement and classification of surface as a two-dimensional (2D) analysis of surface roughness. The value of *Ra* was calculated from equation (1) from the measured 2D roughness profile. Roughness was measured after grinding onto clean and dry sample in the direction of the largest surface roughness, in a direction transverse to the feed rate vector. The surface roughness measurements were carried out with a stylus type testing instrument Mitutoy SJ-301 according to ISO 3274, ISO 4287 and ISO 4288 international standards and specification.

Table IV Mechanical properties and chemical composition of copper material

Type of work material	Copper Cu-FRHC
Chemical composition (wt. %)	Cu min. 99.9, others 0.04 in total
Ultimate tensile strength	245 N/mm^2
Modulus of elasticity	125×10^3 N/mm^2
Hardness	100 HV

Table V Mechanical properties and chemical composition of aluminum alloy

Type of material	Aluminum, 5086-H116
Chemical composition (wt. %)	Al 93.7, Cu 4.3, Mg 1.4, Mn 0.6
Ultimate tensile strength	270 N/mm^2
Modulus of elasticity	72×10^3 N/mm^2
Hardness	88 HV

Table VI Mechanical properties and chemical composition of C45 material

Type of material	C45
Chemical composition (wt. %)	C 0.45, Mn 0.6, Si 0.27, Cr max. 0.25, Ni max. 0.30, Cu max. 0.3
Ultimate tensile strength	530 N/mm^2
Modulus of elasticity	211×10^3 N/mm^2
Hardness	200 HV

Table VII Mechanical properties and chemical composition of 100Cr6 material

Type of material	100Cr6
Chemical composition (wt. %)	Cr 1.45, C 0.9, Mn 0.4, Si 0.25, Ni max. 0.30, Cu max. 0.25
Ultimate tensile strength	668 N/mm^2
Modulus of elasticity	206×10^3 N/mm^2
Hardness	208 HV

Table VIII Mechanical properties and chemical composition of X46Cr13 material

Type of material	X46Cr13
Chemical composition (wt. %)	Cr 15, C 0.45, Mn max. 0.9, Si max. 0.7
Ultimate tensile strength	825 N/mm^2
Modulus of elasticity	215×10^3 N/mm^2
Hardness	257 HV

Table IX Mechanical properties and chemical composition of X210Cr12 material

Type of material	X210Cr12
Chemical composition (wt. %)	Cr 12, C 2.1, Si 0.35, Mn 0.4 P max. 0.03, S max. 0.03
Ultimate tensile strength	2850 N/mm^2
Modulus of elasticity	210×10^3 N/mm^2
Hardness	220 HV

III. Results and Discussions

It appears that with increasing cutting depth in all experiments increase the surface roughness Fig. 2-5. However, with increasing feed rate is conversely surface roughness lower and thus the surface quality better Fig. 6. Similar but slightly lower values of surface roughness *Ra* is obtained by changing the diameter of the grinding wheel from the initial 250 mm to smaller diameter of 195 mm Fig. 7-11, while keeping constant all other process parameters.

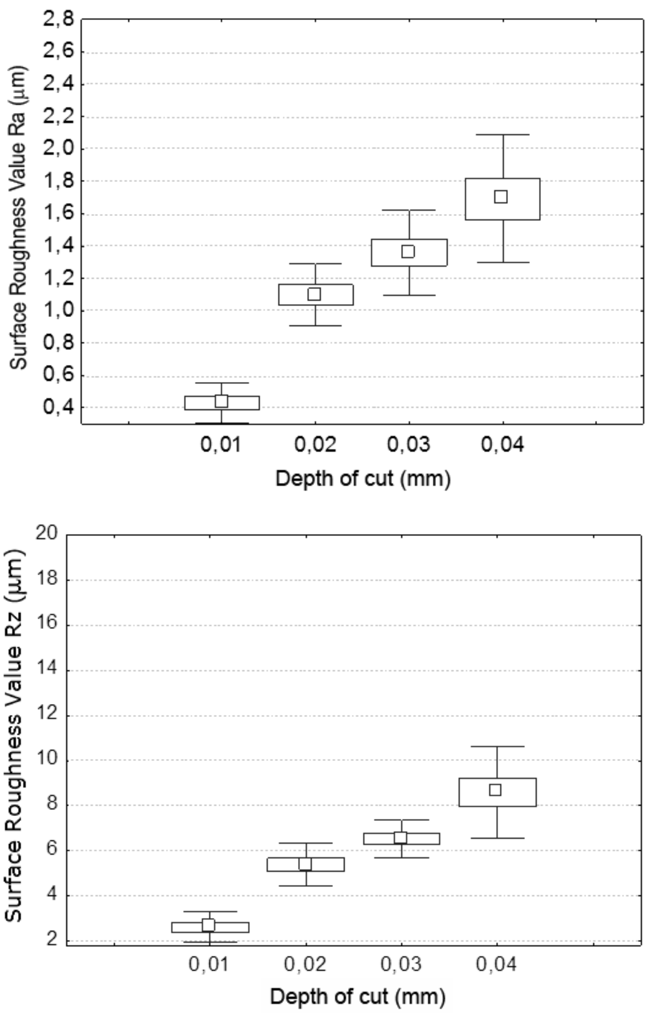
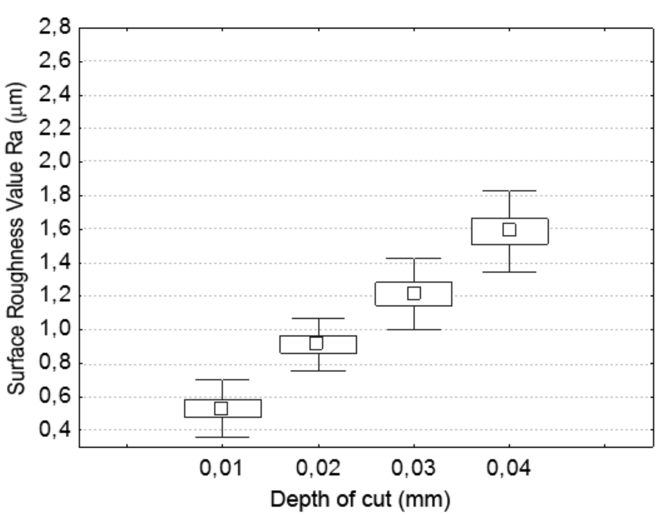


Fig. 2 The relationship between surface roughness and depth of cut when grinding at feed rate of 8 m/min and grinding wheel diameter 250 mm



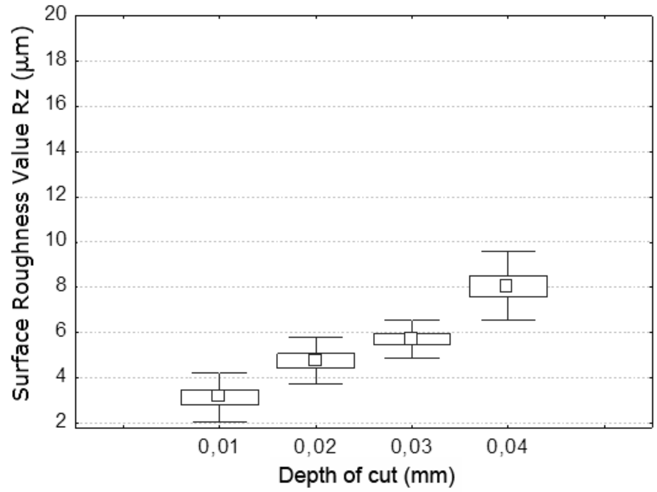


Fig. 3 The relationship between surface roughness and depth of cut when grinding at feed rate of 12 m/min and grinding wheel diameter 250 mm

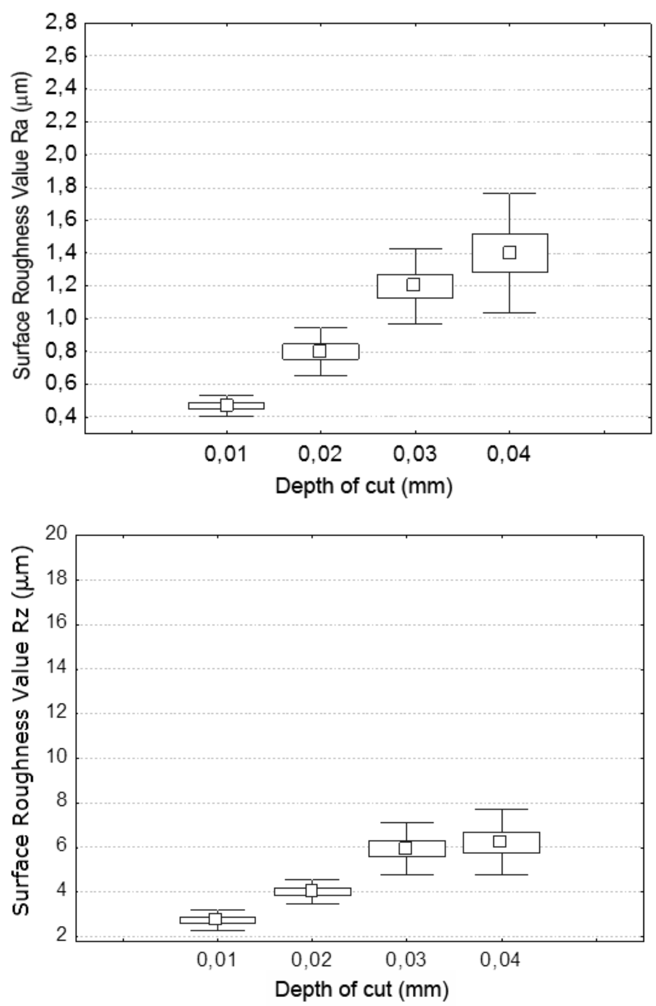


Fig. 4 The relationship between surface roughness and depth of cut when grinding at feed rate of 16 m/min and grinding wheel diameter 250 mm

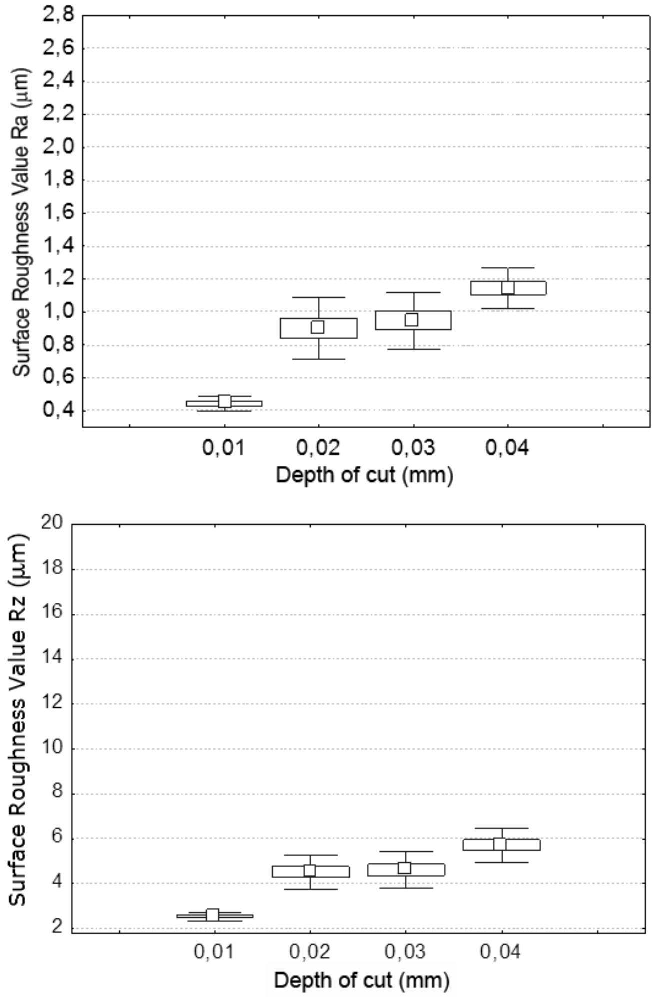


Fig. 5 The relationship between surface roughness and depth of cut when grinding at feed rate of 24 m/min and grinding wheel diameter 250 mm

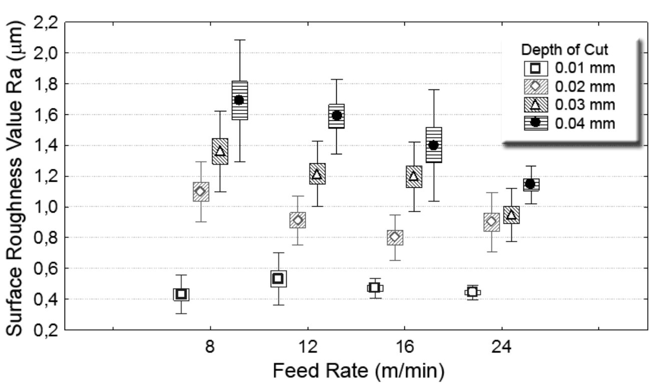


Fig. 6 Surface roughness value *Ra* vs feed rate and depth of cut for grinding wheel diameter 250 mm

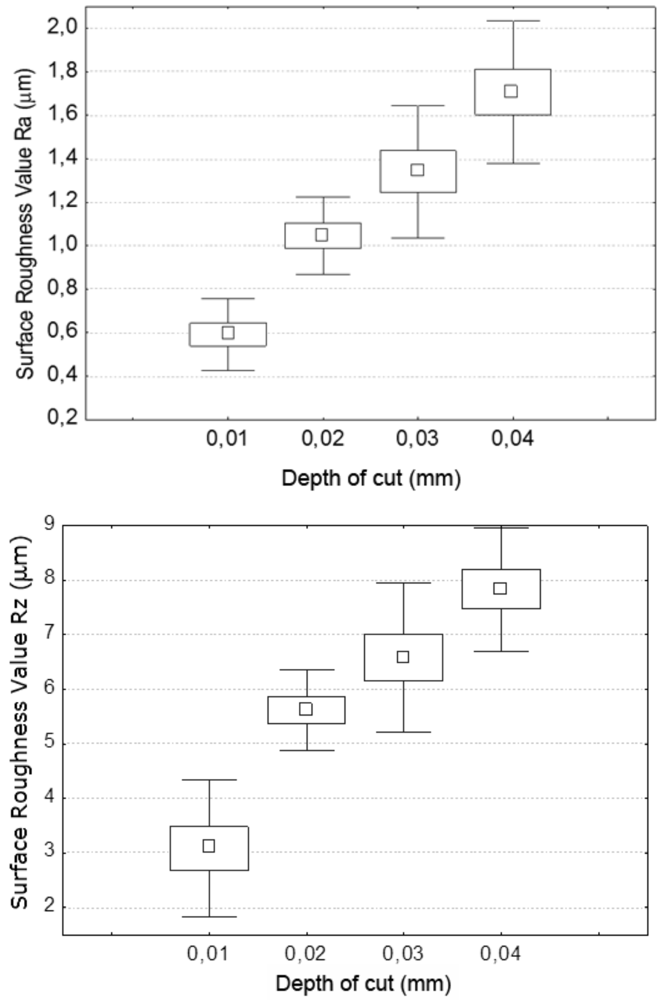
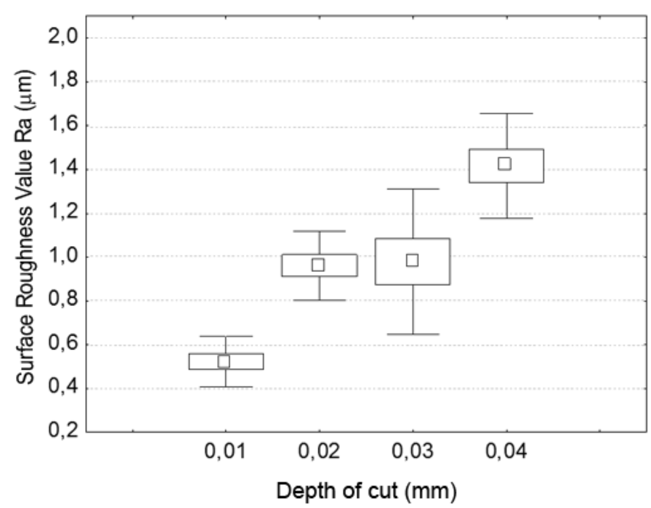


Fig. 7 The relationship between surface roughness and depth of cut when grinding at feed rate of 8 m/min and grinding wheel diameter 195 mm



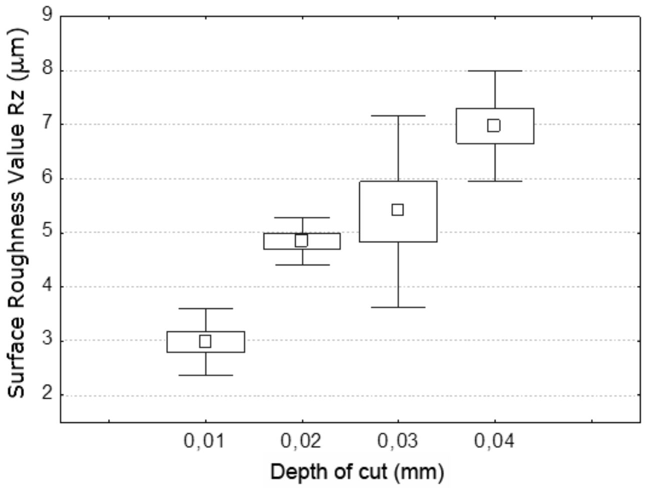
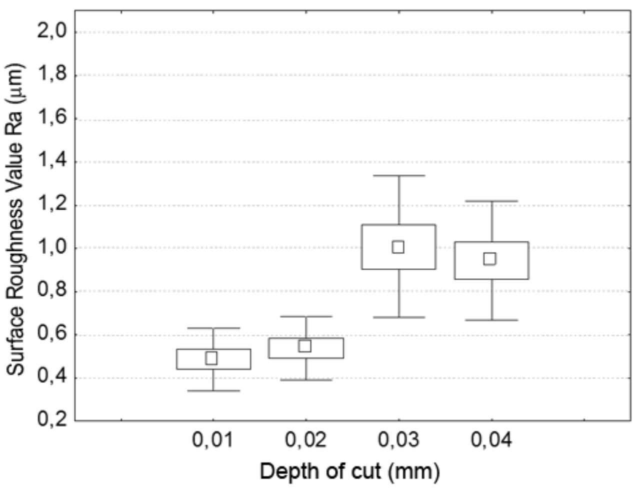


Fig. 8 The relationship between surface roughness and depth of cut when grinding at feed rate of 12 m/min and grinding wheel diameter 195 mm



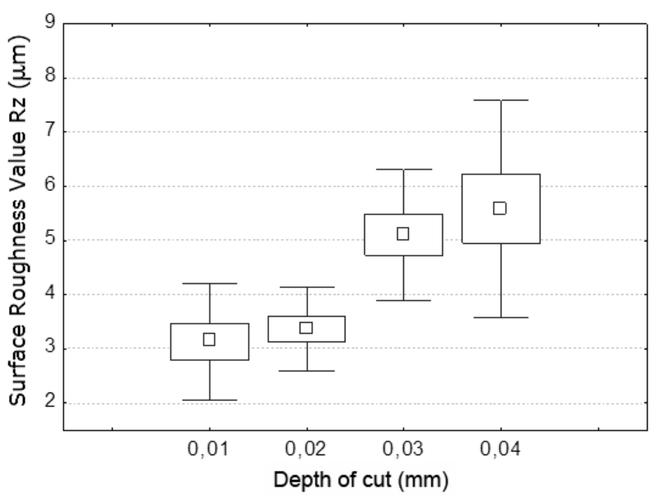
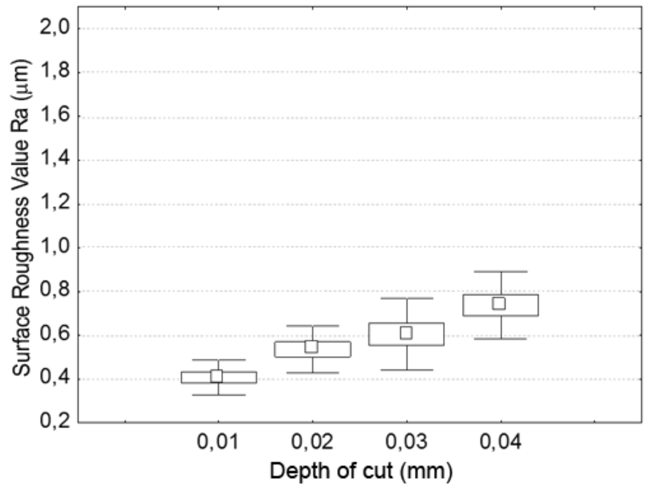


Fig. 9 The relationship between surface roughness and depth of cut when grinding at feed rate of 16 m/min and grinding wheel diameter 195 mm



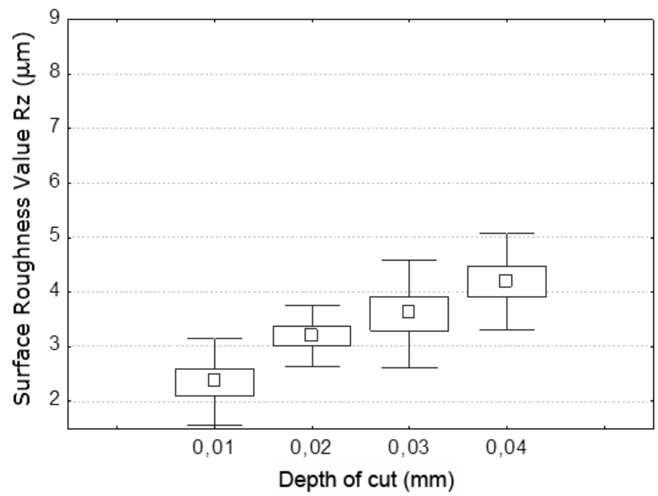


Fig. 10 The relationship between surface roughness and depth of cut when grinding at feed rate of 24 m/min and grinding wheel diameter 195 mm

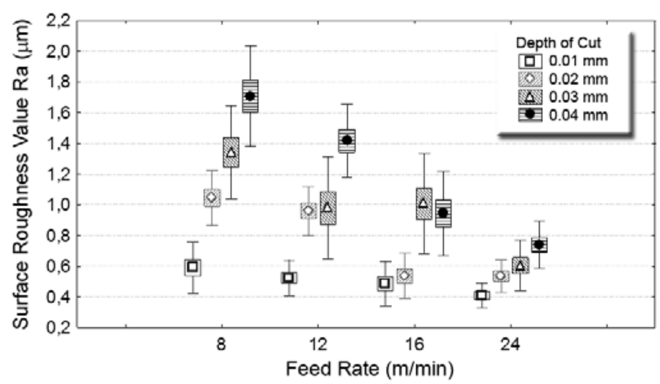


Fig.11 Surface roughness value *Ra* vs feed rate and depth of cut for grinding wheel diameter 195 mm

In addition, it was proven that cooling has the significant effect on surface roughness while grinding. Cooling not only considerably changes the roughness profile (Fig. 12 and Fig. 13) but it also affects the surface roughness value *Ra*. The best value (Fig. 14) of surface roughness is achieved by grinding the titanium with coolant and a smaller diameter of the wheel.

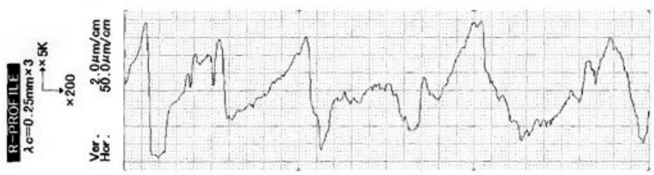


Fig. 12 Roughness profile of dry grinding

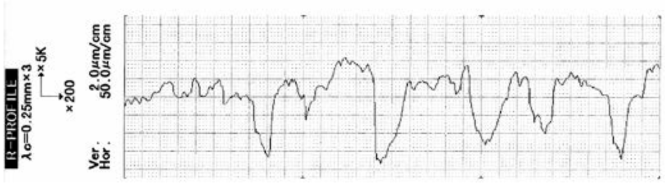


Fig. 13 Roughness profile of grinding with coolant

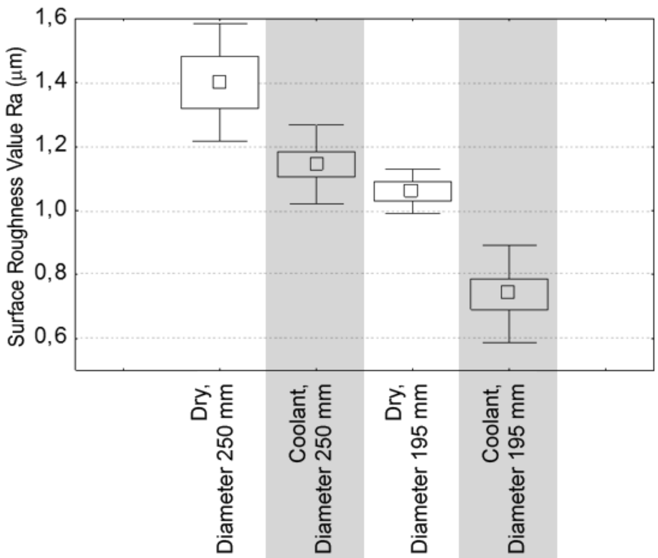


Fig.14 The effect of coolant and grinding wheel diameter on surface roughness *Ra*

The behavior of other materials at the same cutting conditions is shown in Fig. 15-20.

Finally was performed ANOVA to take into consideration the influence of input factors (feed rate, depth of cut, ultimate strength). In one-dimensional tests of significance came out statistically significant effect of all studied factors including their mutual interaction (p = 0.00001). The Figure 21 presents a designed regression model of influencing factors on the surface roughness *Ra* after grinding. The expected model is disrupted at ultimate strength of 350 N/mm^2, corresponding to titanium material. As one of the metals has a significantly different behavior depending on process parameters. Normalized model the behavior of metallic materials without titanium is compared in Figure 22.

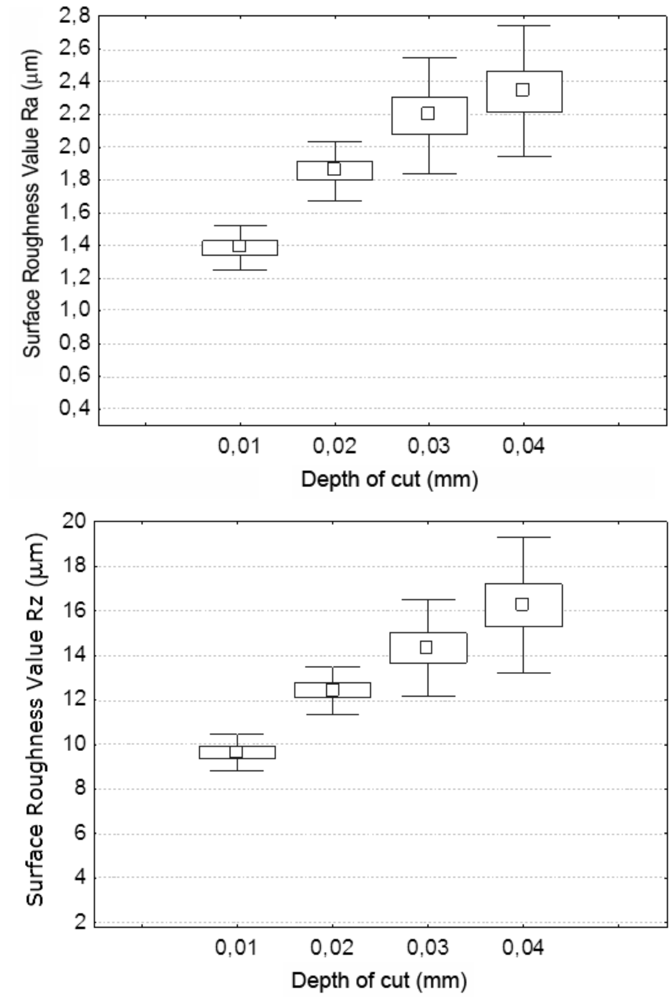
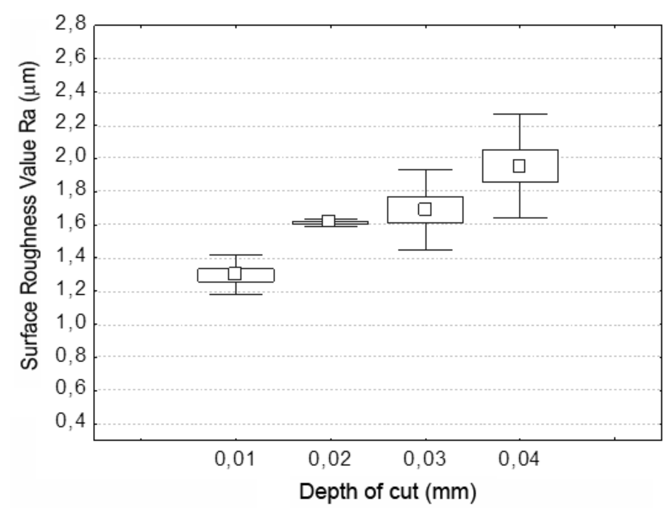


Fig. 15 The effect of grinding condition on surface roughness for copper work material (coolant, feed rate 24 m/min, wheel diameter 250 mm)



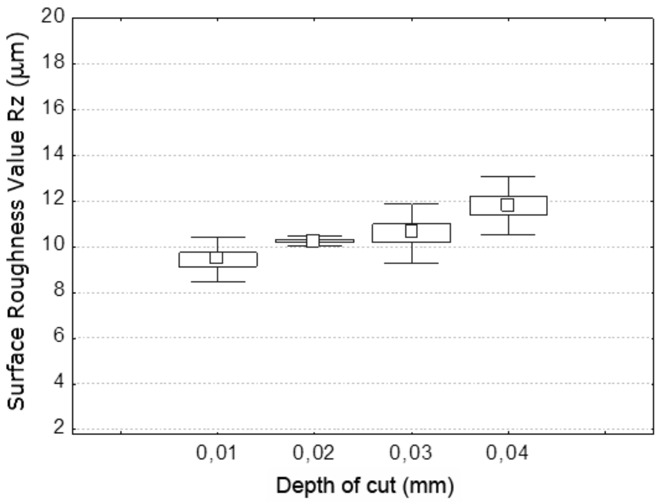
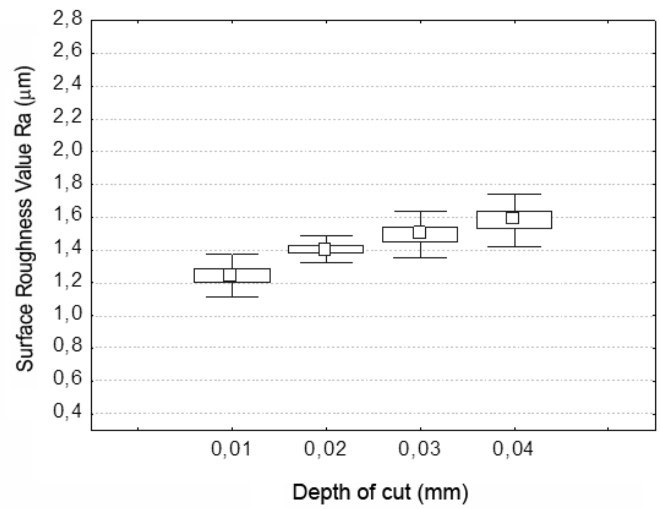


Fig. 16 The effect of grinding condition on surface roughness for aluminum alloy work material (coolant, feed rate 24 m/min, wheel diameter 250 mm)



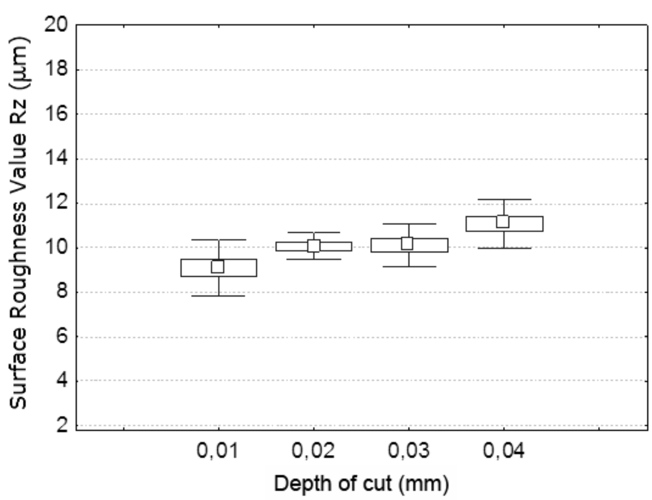
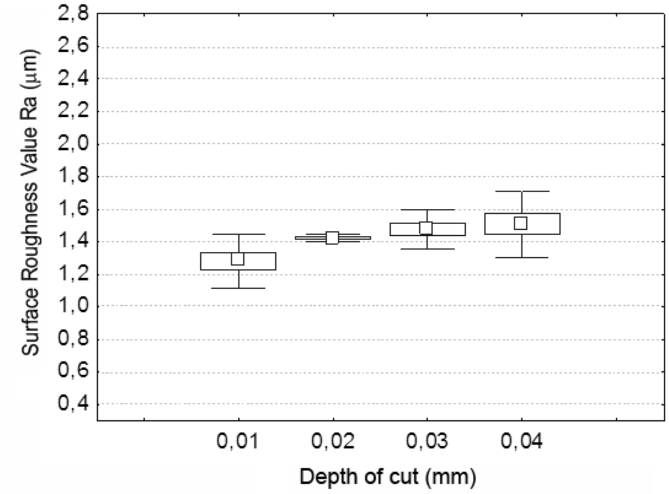


Fig. 17 The effect of grinding condition on surface roughness for steel C45 work material (coolant, feed rate 24 m/min, wheel diameter 250 mm)



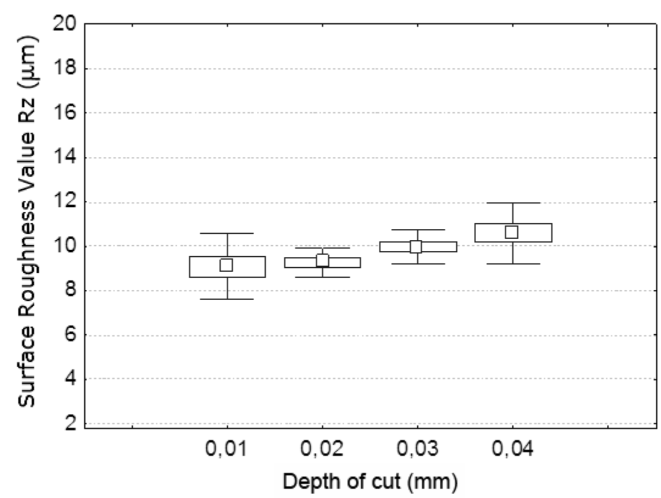
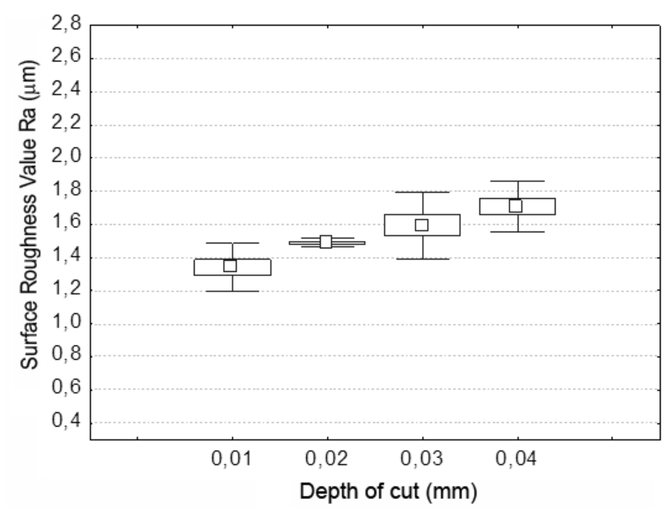


Fig. 18 The effect of grinding condition on surface roughness for steel 100Cr6 work material (coolant, feed rate 24 m/min, wheel diameter 250 mm)



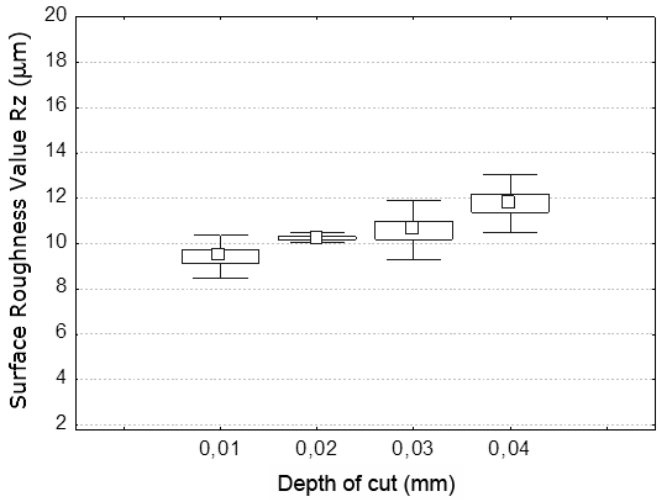


Fig. 19 The effect of grinding condition on surface roughness for steel X46Cr13 work material (coolant, feed rate 24 m/min, wheel diameter 250 mm)

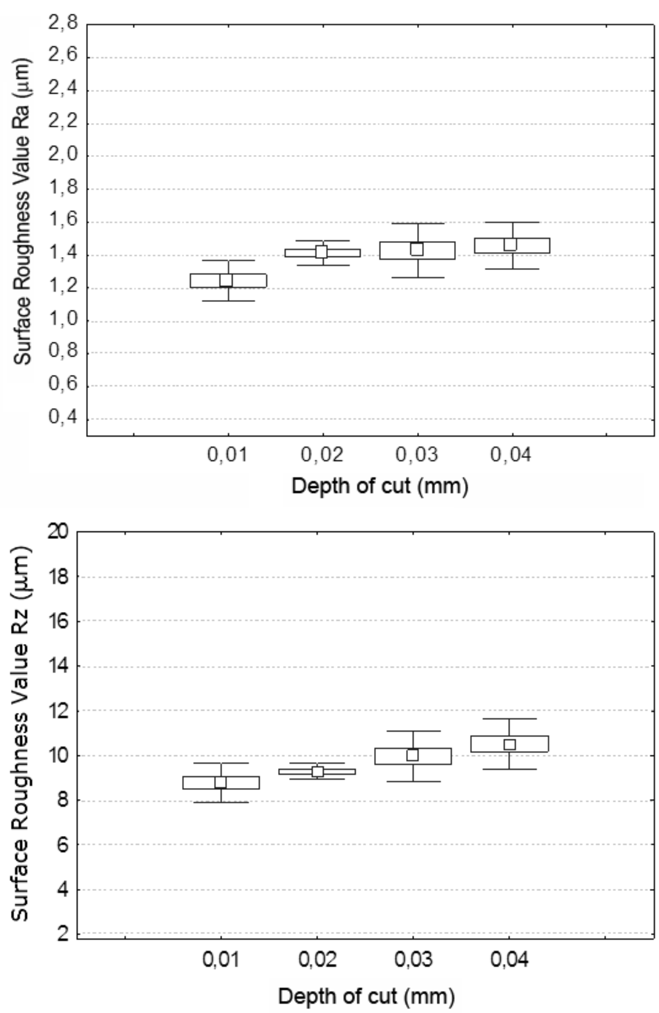


Fig. 20 The effect of grinding condition on surface roughness for steel X210Cr12 work material (coolant, feed rate 24 m/min, wheel diameter 250 mm)

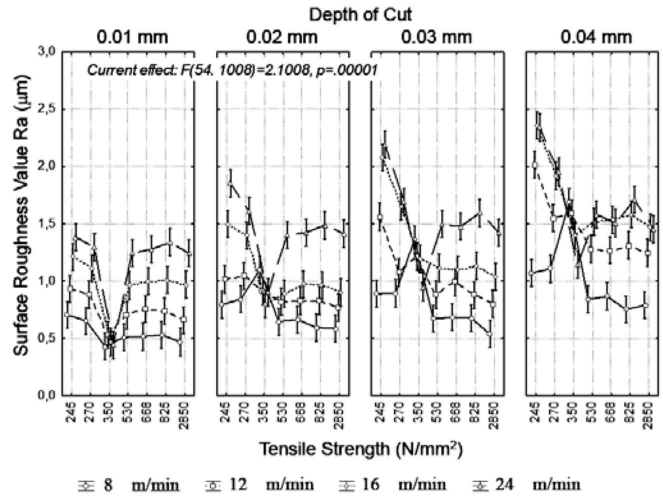


Fig. 21 Analysis of variance considering process condition and tensile strength of metallic materials

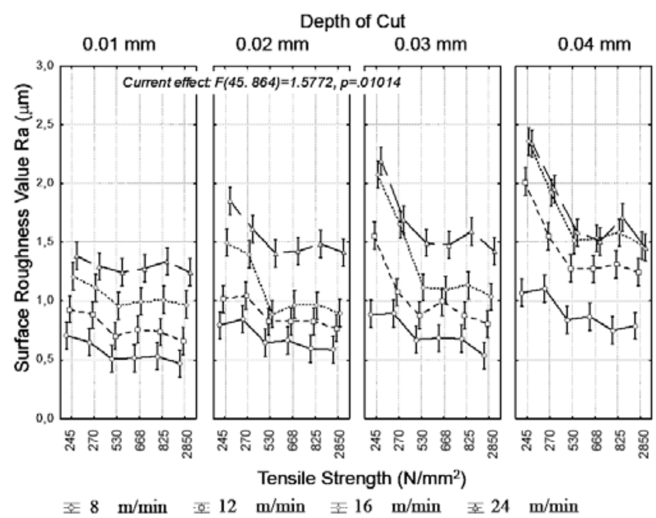


Fig. 22 Normalized analysis of variance considering process condition and tensile strength of metallic materials exclusive of titanium

IV. Conclusions

In this investigation, the effect of process conditions on the surface quality was compared in grinding titanium. Based on the statistical analysis of the measured data and trend behavior may be predicted that with increasing depth of cut, the surface roughness deteriorates, whereas with increasing feed rate, the surface roughness becomes better. Change of the grinding wheel diameter, and thereby reducing peripheral speed, results in better surface roughness as well as application of coolant. To achieve high surface quality of titanium is strongly advised to use cooling during the grinding process that increases the resistance to wear. Furthermore, the ANOVA analysis determined that all observed input parameters are significant and an interaction among them.

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