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Experimental investigation of abrasive electrodischarge grinding of Ti6Al4V titanium alloy

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ABSTRACT

Purpose: This work is focused on determination of effects of grinding conditions on effectiveness of abrasive electrodischarge grinding (AEDG) process applied for removal of machining allowance and forming of surface geometrical texture (SGT). These results were compared with one obtained for conventional grinding.
Design/methodology/approach: The experimental investigations of deep-seated surface grinding of Ti6Al4V titanium alloy using CBN grinding wheel with metal bond were the ground for this elaboration. The effectiveness of AEDG process was assessed based on specific tangential grinding force and energy of spark electric discharge and machining results were estimated on geometrical structure parameters.
Findings: The effectiveness of machining allowance removal depended on conditions of AEDG process. Significant differences in SGT formed by AEDG process and conventional grinding were revealed.
Practical implications: Abrasive electrodischarge grinding is useful to be particularly suitable for efficient and effective grinding of very hard structural materials such as high-alloy steel, sintered carbides, metal-based composite materials etc.
Originality/value: AEDG experiments were carried out using the typical surface finishing grinder and especially adapted generator of spark discharge pulses. The majority of such experiments in the world were performed with the electrodischarge machine tool equipped with extra grinding wheel mounted on the grinding pin and functioning as one of the electrodes put into operation via pneumatic drive.
Keywords: Machining; Abrasive electrodischarge grinding; Surface roughness; Energy of spark

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1. Introduction

Titanium alloys are very attractive constructional material and used in many fields of industry: automotive, aircraft, aerospace, armaments, chemical and medical, for production of implants. These materials are characterised by very advantageous strength ratio to their mass, great fatigue strength, corrosion resistance and high temperature etc. Unfortunately titanium alloys belong to "hard materials" because of their machinability which is very difficult. Poor machinability is also caused by: chemical reactivity to tool material, low modulus of elasticity and small thermal conductivity. The problems of poor machinability of titanium alloys are especially revealed in the finishing process realized by grinding machining [1,2].

Besides another drawback of the machining problems poor are mechanical properties of Ti6Al4V. In order to improve the surface parameters of these alloys several surface treatments are being conducted [3-6].

During conventional grinding those alloy present great cutting resistance and high temperatures which are generated in the machining zone. Very often during the grinding process are also present microchips sticking to machining surface and this effect disadvantageously influence on the surface texture.

The new, hybrid approaches, in which different forms of energy are simultaneously involved in removal of machining allowance, were devised [7,8]. The abrasive electrodischarge grinding process (AEDG) is one of them [9,10]. In this method, the machining allowance is removed through concerted (synergic) action of spark electric discharges among the grinding wheel and the surface of the workpiece and grinding of the cutting surface of grinding wheel (CSGW) with abrasive grains. In this process occurred synergic mechanical energy and energy of electric spark discharges faster increase the machining productivity and increase of surface quality [11,12].

This work is focused on determination of effects of grinding conditions on effectiveness of AEDG process applied for removal of machining allowance and forming of surface geometrical texture (SGT). These results were compared with those obtained for conventional grinding.

2. Workstand, method and grinding conditions

AEDG experiments were carried out using the workstand shown in Figure 1 and equipped with a surface finishing ECBT8 grinder, a GMP75 generator of spark discharge pulses, controllers of grinding parameters and a triaxial piezoelectric dynamometer. The results were recorded by the computer system.

Experimental trials comprised deep grinding of surfaces through conventional or AEDG methods. Flat - bottom workpieces (20x55x5 mm) made of Ti6Al4V titanium alloy were ground using a CBN grinding wheel (CBN 125/100 M75). Both conventional grinding and AEDG process were carried out using the distilled water.

To compare both processes, the following parameters were measured: the tangential grinding force (F'_t [N/mm]), parameters of roughness (Ra [μm]) and wavy finish (Wa [μm]) of the ground surfaces. The first quantity characterised the course of grinding, and the two other parameters characterised the results of grinding. The tangential grinding force was measured using 9257B dynamometer (produced by KISTLER) providing records with 100 Hz frequency of sampling.

The measurements of surface roughness were executed in the 2D system by the Hommelwerke profilometer, and in 3D system by PGM-1C profilometer (IOS, Kraków, Poland). The parameters of roughness and wavy finish of the surfaces were expressed as the means from 5 independent measurements of randomly chosen surface fragments. The variable input attributes of AEGD process were electric parameters of the generator of electric pulses, such as working voltage U and intensity of electric current I and electric pulse duration and pause. Kinematics grinding parameters such as the speed of longitudinal feed of the workpiece v_f, the in-feed of grinding wheel a, were constants and established in the earlier author's works [13,14]. Experimental conditions are displayed in Table 1.

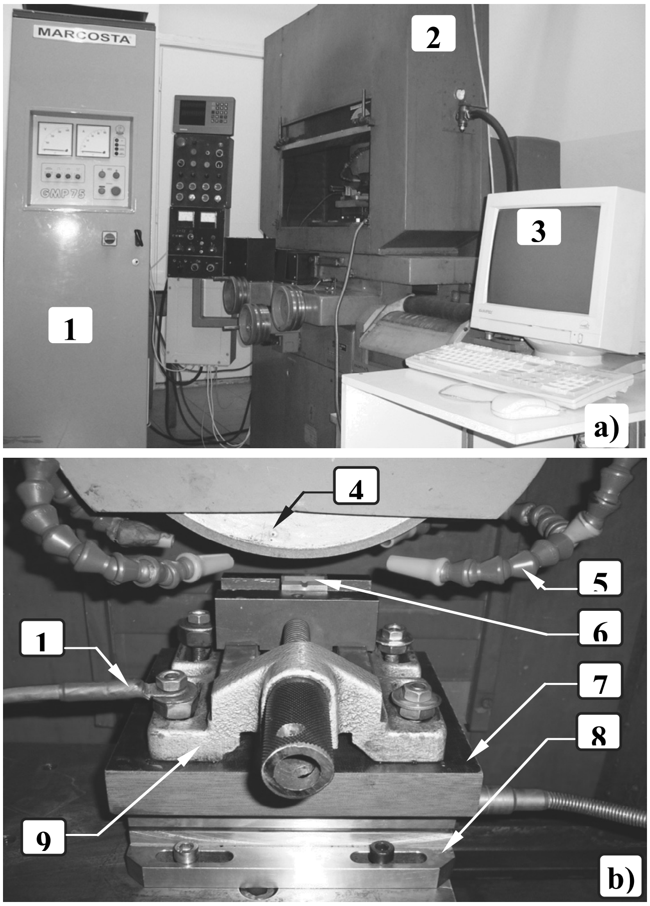

Fig. 1. Workstand: a) overview, b) grinding system; 1-generator of electric pulses, 2- ECBT8 grinder,3- PC computer, 4-grinding wheel, 5-dielectric feed pipe, 6-workpiece, 7-isolating plate, 8-piezoelectric dynamometer, 9-vice, 10- feeder cable from the generator of electric pulses

The energy of spark electric discharges was estimated on the basic of recorded courses of variation in the voltage and intensity of electric current during AEDG process. Run of variation in the voltage $-i_e$ and voltage drop $-u_e$ was recorded on HAMEG - HM 407 digital oscilloscope, equipped with the probe voltage and ISM 5P/50 LEM shunt. Recorded run of variation on the oscilloscope was transmitted to PC computer by RS-232 connection to perform the calculation of energy of spark electric discharge.

HAMEG SP107 computer program was used to calculate by the integral method the average of energy of spark electric discharges (E_{EDM}) with the help of recorded run on variation of the voltage and intensity of electric current:

$$E_{EDM} = \int_0^t u(t)i(t)dt \quad [J]. \qquad (1)$$

Table 1.
Conditions of grinding process

Experimental conditions	
dielectric	water distiller
grinding speed - v_s [m/s]	30
grinding wheel - in-feed a [μm]	20
longitudinal feed of the workpiece - v_f [m/min]	0.5
number of sparking passages	0-4
working voltage - U [V] test step - ΔU [V]	100-200 50
striking current - [A]	1.5
intensity of electric current – I [A] test step - ΔI [A]	4-12, (25) 4
pulse duration t_i - [μs]	2-125
pulse pause t_o - [μs]	4-250

In order to record the runs of variation courses of electric discharge in AEDG process meter circuit unit shown in Figure 2 was used.

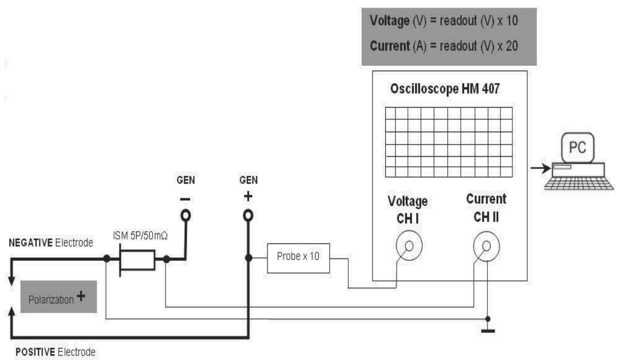

Fig. 2. Scheme of meter circuit unit used to record the courses of electric discharge in AEDG process

3. Experiments

Presented experiments aimed at determination of effects of AEDG conditions on effectiveness of removal of machining allowance. It was estimated on the basis of measurements of the tangential grinding force and energy of spark electric discharge. The accuracy of forming of surface geometrical texture was evaluated by means of determination of surface roughness and wave finish parameters in 2D and 3D systems. The experiments comprised influence of:

- polarization of electrode on the specific grinding force,
- variation in the pulse duration and pause on the specific grinding force,
- variation in the voltage and intensity of electric current during AEDG process on the specific grinding force, the energy of spark electric discharges and parameters of roughness and wavy finish of the ground surfaces.

3.1. Effectiveness of AEDG used for removal of machining allowance

Results of studies of the effect of polarization electrode on the tangential grinding force are shown in Figure 3. Experiments were conducted when the positive polarization (+) - feeder cable from the generator of electric pulses was connected to vice with the workpiece. Negative polarization (–) - used when negative feeder cable from the generator of electric pulses was connected to vice with the workpiece (Figure 1b).

Presented data demonstrate that for AEDG process realized with the negative polarization are not effective. There are no significant changes in the value of tangential grinding force (probe 2) to compare with that of conventional grinding (probe 1).

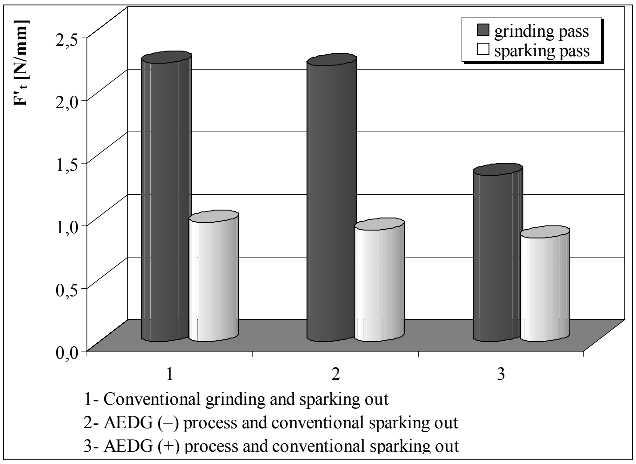

Fig. 3. Comparison of specific tangential grinding force after conventional grinding and AEDG process: t_i=32 μs, t_p=63 μs

Significant decrease of value of tangential grinding force was obtained when AEDG process was realized with the positive polarization (probe 3). In case of AEDG process, the highest percentage decrease in the tangential grinding force was approximately 40% in grinding passes and 10% in sparking passes.

The experiments proved that application of AEDG (+) process had a strong impact on effectiveness of removal of machining allowance. In the next experimental steps concerning the grinding of Ti6Al4V titanium alloy positive polarization was used. Problems connected with the selection of polarity of electrode in AEDG processes are still not diagnosed. The experiments connected with this issue will be continued.

Effects of electric parameters, such as working voltage and intensity of electric current supplied by the generator of electric pulses on the tangential grinding force for AEDG process are displayed in Figure 4.

The results indicate that the latter quantity was inversely proportional to the working voltage and intensity of electric current. This relationship confirmed the higher effectiveness of machining allowance removal by electrodischarge grinding. The greatest decrease in the tangential grinding force was achieved for the working voltage of 200 V and feed current of 25A. This force was approximately 60% smaller than in conventional grinding. In AEDG process the tangential grinding force was also relatively small at 100-200V and 12A (around 40-50% less than in conventional grinding). These relationships are of importance for determination of technological conditions of AEDG process.

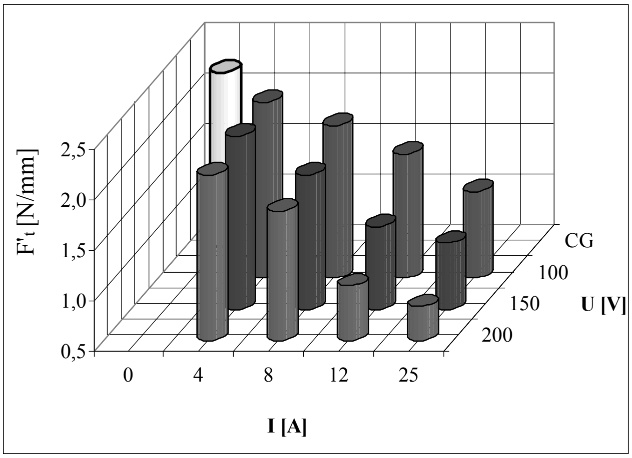

Fig. 4. Effects of working voltage and intensity of electric current on the tangential grinding force for conventional grinding (CG) and AEDG process; t_i=32 µs, t_o=63 µs

Pulse duration and pause on the effectiveness of AEDG process used for removal of machining allowance was analyzed by the measurement of the specific tangential force. AEDG process was realized under voltage of U=200V and current intensity of I=25A. For those parameters higher effectiveness of AEDG process used for removal of machining allowance was obtained.

Representative results of studies on effects of pulse duration and pause during AEDG process on the tangential grinding force are shown in Figure 5.

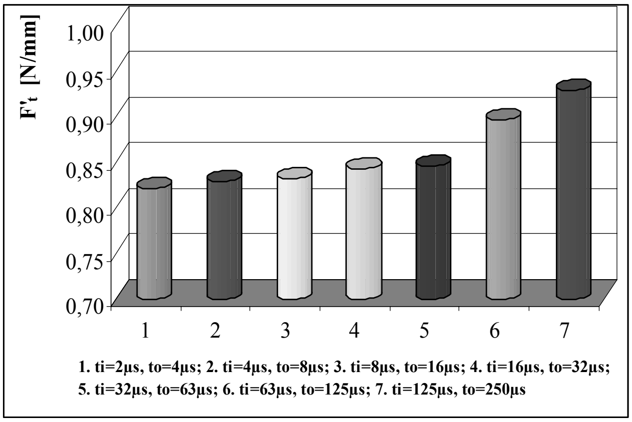

Fig. 5. Effects of pulse duration and pause on the tangential grinding force within grinding passages; I=25 A, U=200 V

These parameters were found to have ambiguous influence on the tangential grinding force. For short pulse duration (t_i=2-32 µs) the increments in tangential grinding force did not exceed 5%. The tangential grinding force was significantly worse (by about 10%) when pulse duration exceeded t_i=63 µs. It is to note that under these grinding conditions, the effectiveness of electrodischarge removal of machining allowance was considerably lower.

Results of experiments of the influence of electric parameters of generator of electric pulses on the energy of spark electric discharges for AEDG process are displayed in Figure 5-6.

Measurements of the energy of spark discharge were carried out using the workstand equipped with meter circuit courses of electric discharge shown in Figure 2. The meter circuit recorded courses of variation in the voltage and intensity of electric current during AEDG process. On the ground of those records, energy of spark electric discharges was defined according to formula (1).

Experiments realized for three generator parameters range P_1, P_2, P_3, were established and presented in work [14]. AEDG process was carried out using electric parameters:

- P_1: U=100V, I=8A,
- P_2: U=150V, I=12A,
- P_3: U=200V, I=25A.

Representative courses of variation in the voltage and intensity of electric current during AEDG process are shown in Figure 6. They were the basic information for determination of energy of spark electric discharges in AEDG process. Values of the average energy of spark electric discharges for AEDG process are displayed in Table 2.

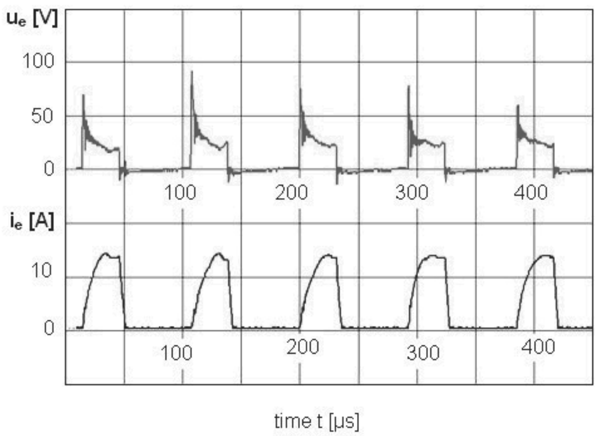

Fig. 6. Run of variation current impulse: voltage drop of electrical discharge - u_e and current intensity – i_e during AEDG; U=150V, I=12A

The results indicate (table 2) that a rise in working voltage and intensity of electric current increases the energy of spark electric discharges. The highest values of energy of spark in AEDG process were obtained with the greatest settings of voltage and intensity of electric current (P_3).

In case of AEDG process value of energy of spark electric discharge was higher (about 65%) comparing AEDG process realized within low settings of voltage and current intensity (P_1). For range P_2 low increase value of energy was observed and carried out 30% for comparable AEDG process.

Table 2.
Results of determination of effects of selected electric parameters of generator of electric pulses on the energy of spark electric discharges for AEDG process

Realized process	Value of energy of spark electric discharges E_{EDM} [J]
AEDG process P_1: (U=100V, I=8A)	177.2
AEDG process P_2 : (U=150V, I=12A)	251.0
AEDG process P_3 : (U=200V, I=25A)	496.4

The increase of energy of spark electric discharges for AEDG process proves the great participation of electric discharge in removal allowance. Simultaneously part of grinding energy of the cutting surface of grinding wheel (CSGW) with abrasive grains was decreased. Confirmation of this fact noticeably decreased the grinding force (Figure 4). For realised AEDG process at low voltage and current intensity lower value of energy of spark discharges was obtained. This fact confirms the greater part of grinding energy of the cutting surface of grinding wheel was used with abrasive grains for removal allowance.

3.2. Evaluation of surface geometrical texture shaped by AEDG process

Evaluation of the effects of conditions of AEDG process and conventional grinding on the surface geometrical texture of ground workpieces was based on comparison of characteristic parameters of roughness and wavy finish of surface, which were analysed in 2D and 3D systems.

Experiments on grinding of Ti6Al4V titanium alloy proved that AEDG process yielded worse (i.e. slightly higher) parameters of roughness and wavy finish as compared to the conventional grinding, both after grinding and discharging passes [13]. These parameters were reduced through an additional sparking-out phase (without the electrodischarge phase) in the final stage of AEDG process. The latter approach resulted in an appreciably lesser surface roughness, comparable to that achieved by conventional grinding.

Representative plots presenting effects of conventional and AEDG machining conditions on roughness and wavy finish of surface of Ti6Al4V titanium alloy, analysed in 3D system, are shown in Figures 7-8.

Qualitative and quantitative differences between SGT formed by both processes were detected. Profilograms of surface roughness after conventional grinding (Figure 7a) revealed that apart from random effects also the periodically dominating component of the grinding feed direction contributed to the ultimate results. SGT profilograms recorded after AEDG process (Figure 7b) were additionally characterised by random, anisotropic shaping of SGT. These profilograms (Figure 7b) revealed numerous, peak points, characteristic of surfaces formed by AEDG process.

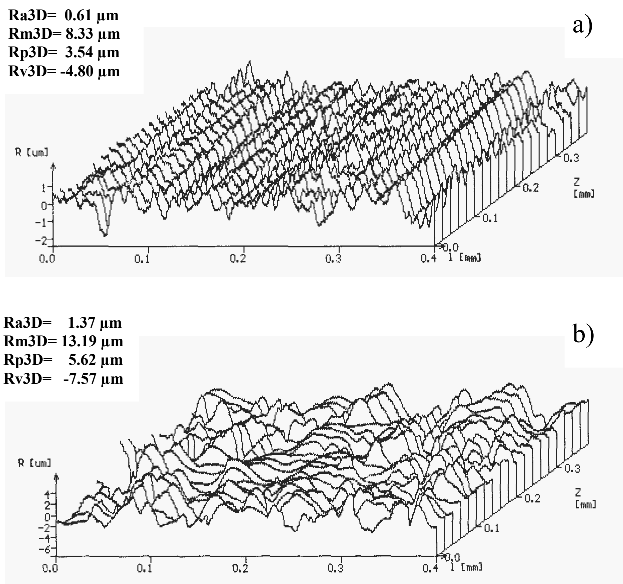

Fig. 7. Surface roughness analysed in 3D system: a) conventional grinding, b) AEDG (+) process; U=150V, I=12A

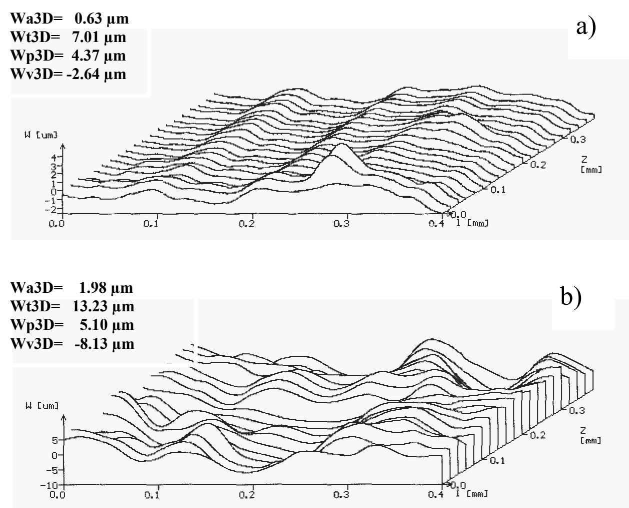

Fig. 8. Wavy finish of surface analysed in 3D system: a) conventional grinding, b) AEDG (+) process; U=150V, I=12A

The similar differences were noticed between profilograms of wave finish of the compared surfaces, analysed in 3D system. The wavy finish of surface shaped by conventional grinding (Figure 8a) was characterised by dominating regular waves arranged along the direction of grinding feed. The surface shaped by AEDG process (Figure 8b) was characterised by additional, randomly deposited, perpendicular components of wavy finish. These differences in SGT are supposed to be a result from unevenness of electric spark discharges, occurring during AEDG process and giving rise to craters on the surface of a workpiece.

4. Conclusions

Effects of grinding conditions on effectiveness of machining allowance removal and forming of surface geometrical texture (SGT) through abrasive electrodischarge grinding (AEDG) of Ti6Al4V titanium alloy were determined. Results of the studies proved that the effectiveness of machining allowance removal depended on electric conditions of AEDG process. Significant differences in SGT formed by AEDG process and conventional grinding were revealed. These differences are believed to affect the tribological characteristics of machined materials. It provides an evidence that conditions of rough and finishing grinding by AEDG method have to be set more precisely and the studies on estimation of tribological characteristics of surface layer formed through this process have to be continued.

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