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ANALYSIS OF CUTTING FORCES DURING GRINDING OF TITANIUM ALLOY AND CORROSION-RESISTANT STEEL BY DIAMOND, ELECTROCORUNDUM AND CUBIC BORON NITRIDE WHEELS

The object of research is the process of circular and surface grinding of titanium alloy and corrosion-resistant steel, namely, the cutting forces arising from mechanical processing. One of the most problematic areas in work is the selection of the required grinding modes, material and grinding wheel grain size.

In the course of the experiment, we used samples of VT8 titanium alloy and 12X18N9T steel, on which the grinding process was studied with wheels made of various materials (electrocorundum, cubic boron nitride (CBN), diamond). The values of the cutting forces P_y and P_z were obtained in the latitude of permissible modes, which are most often used in circular and flat grinding, and can reach maximum values, respectively, $P_y = 27$ N, $P_z = 15.5$ N. The data were obtained at a low wheel speed from electrocorundum, about 15 m/s and grain size 8. By reducing the grain size of the wheel, we get the effect of increasing the energy consumption of the grinding process, due to the increase in the values of the cutting forces. If we compare the cutting forces arising from grinding with different wheels, then the following can be noted. Compared to electrocorundum wheels, when using CBN wheels, the cutting forces are reduced by 20–25 %, and when grinding with diamond wheels (despite the high wear of the diamond wheel), the effect of cutting forces is reduced by 25–30 %. This is due to the fact that cutting conditions are the most favorable for diamond and CBN grains, which makes it possible to use more intense cutting conditions.

The results of the study allow predicting the performance of the grinding wheel, reducing the energy consumption of production, and also adjusting the processing mode of the part to obtain the necessary quality indicators of the surface layer and the geometric dimensions of the part.

Keywords: titanium alloy VT8, cutting forces, technical strength, structural strength, reduction of energy consumption for grinding.

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1. Introduction

Obtaining products from titanium and its alloys is a modern and promising production, especially in the aero-

space industry of the world economy. Titanium is a light, heat-resistant, corrosion-resistant construction material. The weight of titanium products is significantly reduced due to its low density ($\rho_{Ti} = 4.5$ g/cm³). Compared to the

density of steel, it is twice as light ($\rho_{met}=7.9 \text{ g/cm}^3$). Titanium and its alloys have a fairly high limit of short-term strength ($\sigma_B=30\text{--}55 \text{ kg/mm}^2$) and good elongation at break ($\delta=20\text{--}30 \%$) [1]. Titanium alloys alloyed with aluminum, nickel, iron, molybdenum, vanadium, chromium, have high mechanical strength. This property increases the possibility of using titanium and its alloys at elevated temperatures, in contrast to high-strength alloys of aluminum and magnesium.

To obtain the exact size and the required surface roughness of particularly precise parts made of titanium and its alloys, a necessary condition will be the grinding operation.

The cutting forces that occur during the grinding process show the amount of energy consumption of this treatment. The grinding machine, or rather its elastic system, is deformed under the influence of cutting forces, and this clearly affects the accuracy of the grinding operation. Variable cutting forces due to errors in the geometric shape of the part can cause vibration and oscillating loads on the elastic system of the grinder.

Based on the above, it is firmly possible to say that the urgent task today is to study the cutting forces when grinding parts made of titanium alloys.

2. The object of research and its technological audit

The object of research is the process of round and flat grinding of titanium alloy and corrosion-resistant steel, namely the cutting forces that occur during machining.

The subject of research – cutting forces when grinding surfaces or parts of titanium alloys on the example of titanium alloy VT8.

A very valuable property of titanium and its alloys is the preservation of its high mechanical qualities and strength at low and ultra-low temperatures.

Along with many advantages, titanium has significant disadvantages, about the methods of combating which there is now a lot of scientific work and research. Significant disadvantages, in addition to the cost and use of titanium production waste, include its poor and rather complex machining. This is due to the presence of various modifications of titanium [1].

There are two known allotropic modifications of titanium: BDP (bounded densely packed) α -modification, which exists up to $882.5 \text{ }^\circ\text{C}$, above this temperature β -titanium has a VCC (volume-centered cubic) lattice. During the transition $\alpha \rightarrow \beta$ and during melting, the specific volume of the metal decreases slightly.

Titanium alloys on the structure, which is formed according to the accepted in the industry modes of heat treatment, can be divided as follows:

- α -alloys, the structure of which is represented by the α -phase;
- β -alloys, the structure of which is represented by a stable thermodynamic β -phase;
- $\alpha+\beta$ -alloys, the structure of which is represented mainly by α - and β -phases;
- alloys based on intermetallic – pseudo- α -alloys, the structure of which is represented mainly by the α -phase and a small amount of β -phase (not more than 5 %);
- pseudo- β -alloys, the structure of which in the annealed state is represented by the α -phase and a small amount of β -phase. In these alloys by hardening or normalization it is easy to obtain a single-phase β -structure.

Titanium alloys with a crystal lattice type α include compounds using aluminum, zirconium and tin as alloying

elements. The connection of titanium with aluminum or tin allows to obtain a titanium rod from heat-resistant alloys, which is used in the manufacture of heat-resistant parts operating at elevated temperatures in critical areas. Such alloys retain their technical and structural strength at temperatures up to $400 \text{ }^\circ\text{C}$. Additional main properties of α -alloys are as follows: good weldability; high fluidity; low hardening limit. If in α -alloys the percentage of alloying elements is minimal, then such compounds are called technical titanium. Technical titanium is well suited for cold stamping and other types of machining.

Titanium alloys of the second category, so-called β -alloys, have the following properties: higher ductility; creep resistance; ability to cold machining; possibility of strengthening by various methods. The only disadvantage of titanium alloys in this category is the relatively low thermal limit of the operating mode – at temperatures above $300 \text{ }^\circ\text{C}$ metals of this group are prone to brittleness.

Finally, biphasic titanium alloys ($\alpha+\beta$) are the broadest group of titanium compounds used on an industrial scale. These metals have absorbed all the valuable properties of the two above-mentioned options, with the exception of good weldability – due to the peculiarities of the crystal lattice structure on the welds of titanium alloys ($\alpha+\beta$) the phenomena of brittleness and cracking can be observed.

Grinding of titanium products and its alloys is a very important task.

3. The aim and objectives of research

The aim of research is to experimentally analyze the patterns of changes in cutting forces in the grinding process of samples of titanium alloys and corrosion-resistant steel on grinding wheels made of cubic boron nitride (CBN), electrocorundum and diamond. Research objectives:

1. Choose the necessary method of measuring the cutting forces when grinding billets of titanium alloys and corrosion-resistant steel.
2. Experimentally determine the dependences of the cutting forces P_z and P_y on the parameters of the grinding process.

4. Research of existing solutions to the problem

A number of studies have been devoted to the grinding process of titanium alloys. Thus, in [2] the influence of force and temperature factors on deformations during cutting is considered, but the issue of grinding with wheels made of superhard materials was not considered. In [3], the influence of the cooling rate of titanium alloys on the formation of a fine plate α -structure with a high level of internal residual stresses was considered, and the lattice parameter of undoped (pure) Ti- β at low temperatures was determined by extrapolation to zero concentration curves «composition-period of the lattice». However, the effect of cutting force was not considered. But in the study [4] the purpose of the tests was to determine the optimal orientation of the cutter, at which the normal cutting force applied to the treated surface is minimal. Experiment and modeling have shown that the orientation of the tool has a decisive influence on the resulting cutting force and the component perpendicular to the treated surface. However, the grinding process was not considered.

In the materials of [5] the possibilities of obtaining β -titanium alloys with given characteristics were considered. In the work [6] the main problems associated with the processing of titanium, as well as tool wear were considered. In [7], the surface quality of Ti-6Al-4V alloy was investigated in terms of surface roughness and microhardness after grinding the surface with a silicon carbide wheel at different cutting modes. But in all three cases, research on cutting forces was not conducted.

In [8] the technology of obtaining and parameters of the deformation regime during forging and unrolling of rings made of titanium alloy VT8 are considered. And also the technique of designing of technological process of manufacturing of rings from VT8 alloy taking into account change of microstructure in the course of processing by pressure is developed. However, the grinding process was not considered.

In [9], the issues of re-prevention of deposition were considered to obtain the optimal purity of the titanium alloy surface. And in [10] researches of forces of cutting and roughness only for abrasive wheels from electrocorundum are carried out. Thus, analyzing the data available in the literature, it is possible to conclude that the issues of the influence of speed, grain size, deformation and temperature in the grinding process of titanium alloys are well covered. However, there is little data on how the characteristics of titanium alloys change after exposure to grinding forces, the values of which can be quite significant.

5. Methods of research

Studies of cutting forces were performed on the example of a sample of two-phase titanium alloy ($\alpha+\beta$) VT8 and to compare the cutting forces on samples of corrosion-resistant steel of austenitic class 12X18H9T. In steel 12X18H9T quite high indicators of tensile strength ($\sigma_B=540$ MPa) and elongation ($\delta=40\%$), which can be compared with the mechanical characteristics of titanium alloys. Grinding wheels made of CBN, electrocorundum and diamond were used. During the study, the method of experiment planning was used. Cutting forces were measured using a dynamometer UDM 50 (Ukraine).

The plan of the experiment was carried out in the form of $2^3 - 8$ tapes. The highest and lowest level of the components of the grinding mode was as follows: $V_w=50-15$ m/s, $V_{sp}=0.33-0.83$ m/s, grinding depth $t=0.04-0.01$ mm. The results of the experiment were processed according to the method [11], which allowed to obtain power dependences, by which the result was obtained at an arbitrary combination of modes. 3 measurements were performed on each combination of modes; the average value of measurements was processed according to the method [11]. The error of the experiment was equal to the error of the electrical network of the measurement, i. e. $\pm 10\%$, based on fluctuations in the electrical network. The points on the graphs show the average values of the measured values, taking into account the error of $\pm 10\%$.

6. Research results

As a result of experimental studies, it was found that when grinding titanium alloys with diamond, electrocorundum and CBN wheels, the cutting forces can reach maximum values within $P_y=27$ N (Fig. 3, a). And when grinding corrosion-resistant steel 12X18H9T, the forces of P_y and P_z are twice less. This can be traced by analyzing the experimental data, summarized in graphs and presented in Fig. 1–6.

For grinding wheels made of electrocorundum, diamond and KNB, changing their grain size from 25 to 8, it is possible to observe an increase in the magnitude of the cutting forces from 2–2.5 times, respectively. This phenomenon can be explained as follows: reducing the grain size of the grinding wheel, let's observe a significant increase in the number of cutting grains per unit area of the wheel, and therefore in the spot of contact of the grinding wheel with the workpiece. This reduces the force load on a single grain, but the increase in the number of grains provides an increase in cutting force. It should be noted that the cutting forces also increase due to friction between the grinding surface and the bond of the wheel when using fine-grained wheels.

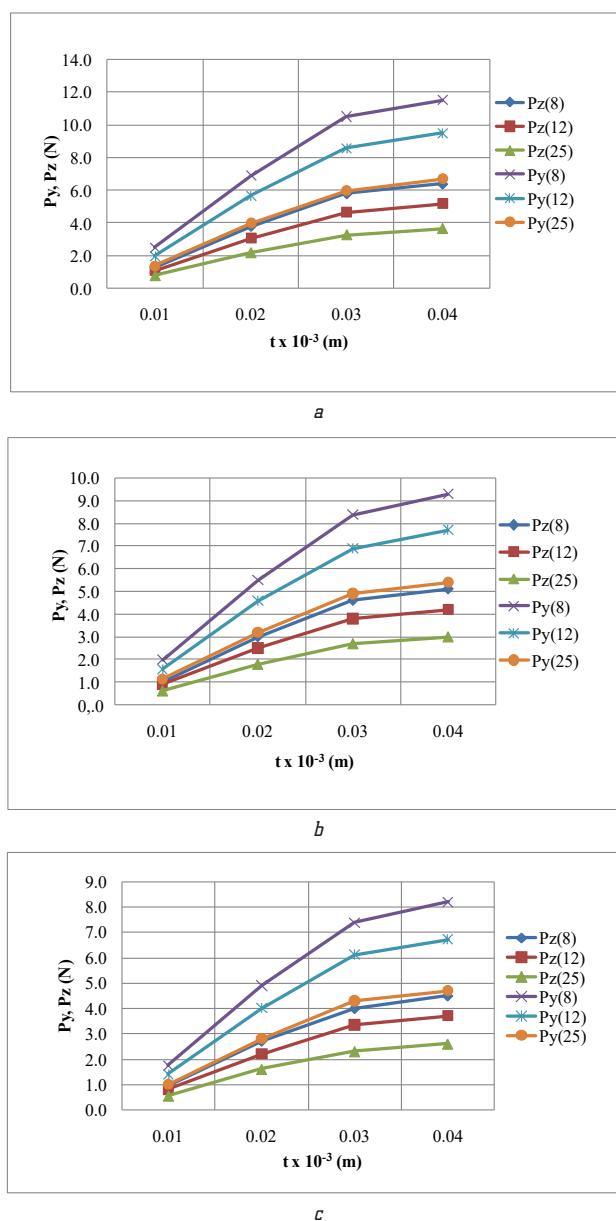


Fig. 1. Dependence of the change in the magnitude of the force P_y and P_z of titanium alloy VT8 on the depth of grinding (t) for different grain size of the wheel: *a* – ceramic wheels (electrocorundum): 25A8SM1K, 25A12SM1K, 25A25SM1K; *b* – wheels from cubic boron nitride: L080/60C10 100 %, L0120/100 C10 100 %, L0250/200C10 100 %; *c* – diamond circles: A5080/60C10 100 %, A50120/100C10 100 %, A50250/200C10 100 %. Modes: $V_w=35$ m/s; $V_{sp}=0.1$ m/s; $S=2$ mm/stroke

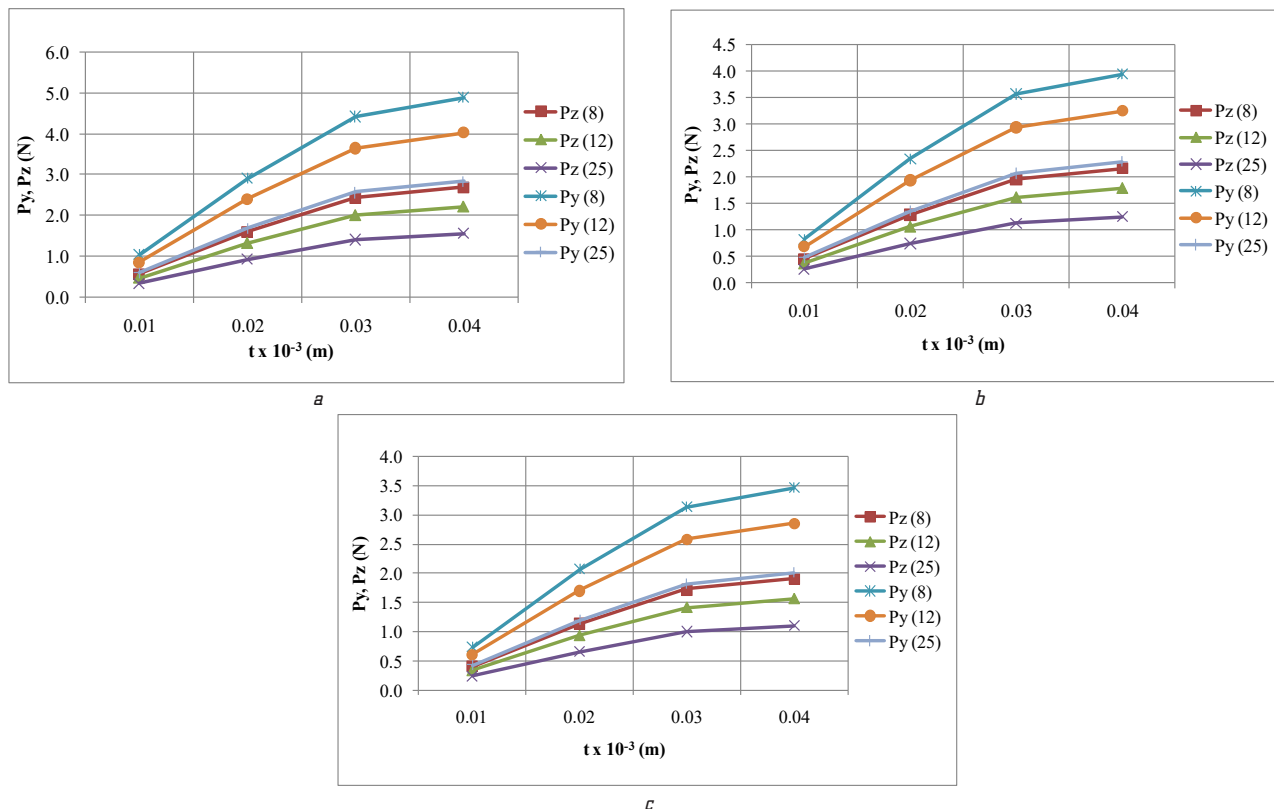


Fig. 2. Dependence of the change in the magnitude of the force P_y and P_z of corrosion-resistant steel 12X18H9T on the depth of grinding (t) at different grain size of the wheel: *a* – ceramic wheels (electrocorundum): 25A8SM1K, 25A12SM1K, 25A25SM1K; *b* – wheels from cubic boron nitride: L080/60C10 100 %, L0120/100 C10 100 %, L0250/200C10 100 %; *c* – diamond wheels: A5080/60C10 100 %, A50120/100C10 100 %, A50250/200C10 100 %. Modes: $V_w=35$ m/s; $V_{sp}=0.1$ m/s; $S=2$ mm/stroke

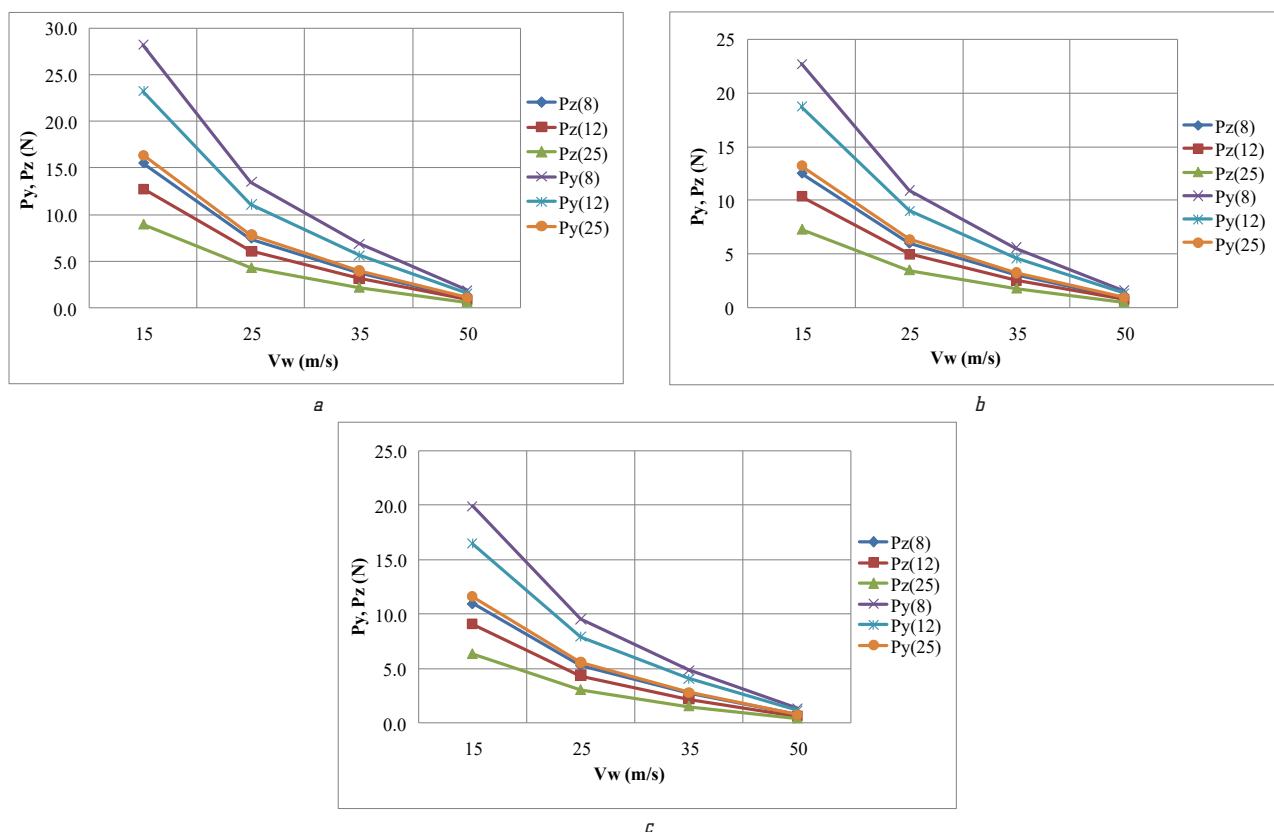


Fig. 3. Dependence of the change in the magnitude of the force P_y and P_z of titanium alloy VT8 on the speed of the circle (V_w) for different grain size of the wheel: *a* – ceramic wheels (electrocorundum): 25A8SM1K, 25A12SM1K, 25A25SM1K; *b* – circles from cubic boron nitride: L080/60C10 100 %, L0120/100C10 100 %, L0250/200C10 100 %; *c* – diamond wheels: A5080/60C10 100 %, A50120/100C10 100 %, A50250/200C10 100 %. Modes: $t=0.01 \cdot 10^{-3}$ m; $V_{sp}=0.1$ m/s; $S=2$ mm/stroke

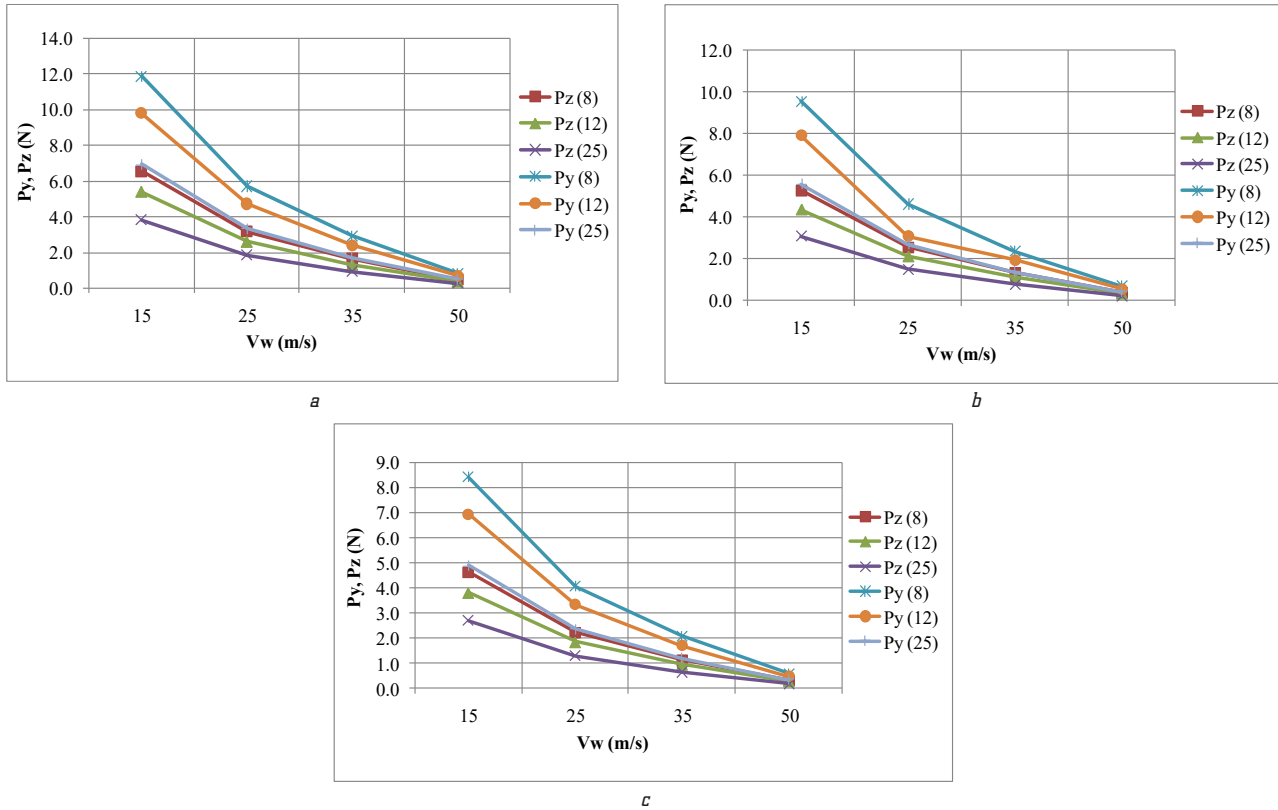


Fig. 4. Dependence of change of size of force P_y and P_z of corrosion-resistant steel 12X18H9T on speed of a circle (V_w) at different grain size of a wheel: *a* – ceramic wheels (electrocorundum): 25A85M1K, 25A125M1K, 25A255M1K; *b* – wheels from cubic boron nitride: L080/60C10 100 %, L0120/100C10 100 %, L0250/200C10 100 %; *c* – diamond wheels: AS080/60C10 100 %, AS0120/100C10 100 %, AS0250/200C10 100 %. Modes: $t=0.01 \cdot 10^{-3}$ m; $V_d=0.1$ m/s; $S=2$ mm/stroke

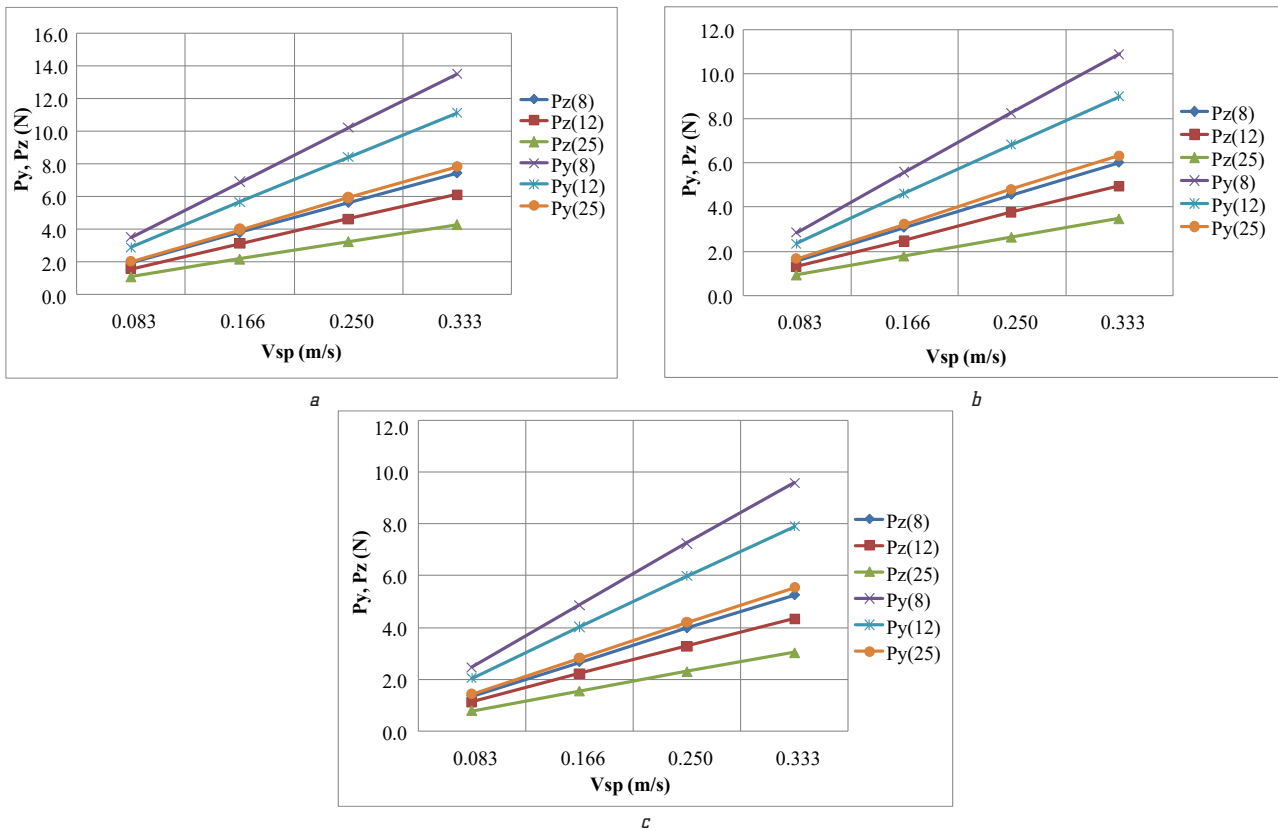


Fig. 5. Dependence of the change in the magnitude of the force P_y and P_z of titanium alloy VT8 on speed of the spacemen (V_{sp}) for different grain size of the wheel: *a* – ceramic wheels (electrocorundum): 25A85M1K, 25A125M1K, 25A255M1K; *b* – wheels from cubic boron nitride: L080/60C10 100 %, L0120/100C10 100 %, L0250/200C10 100 %; *c* – diamond wheels: AS080/60C10 100 %, AS0120/100C10 100 %, AS0250/200C10 100 %. Modes: $t=0.01 \cdot 10^{-3}$ m; $V_w=35$ m/s; $S=2$ mm/stroke

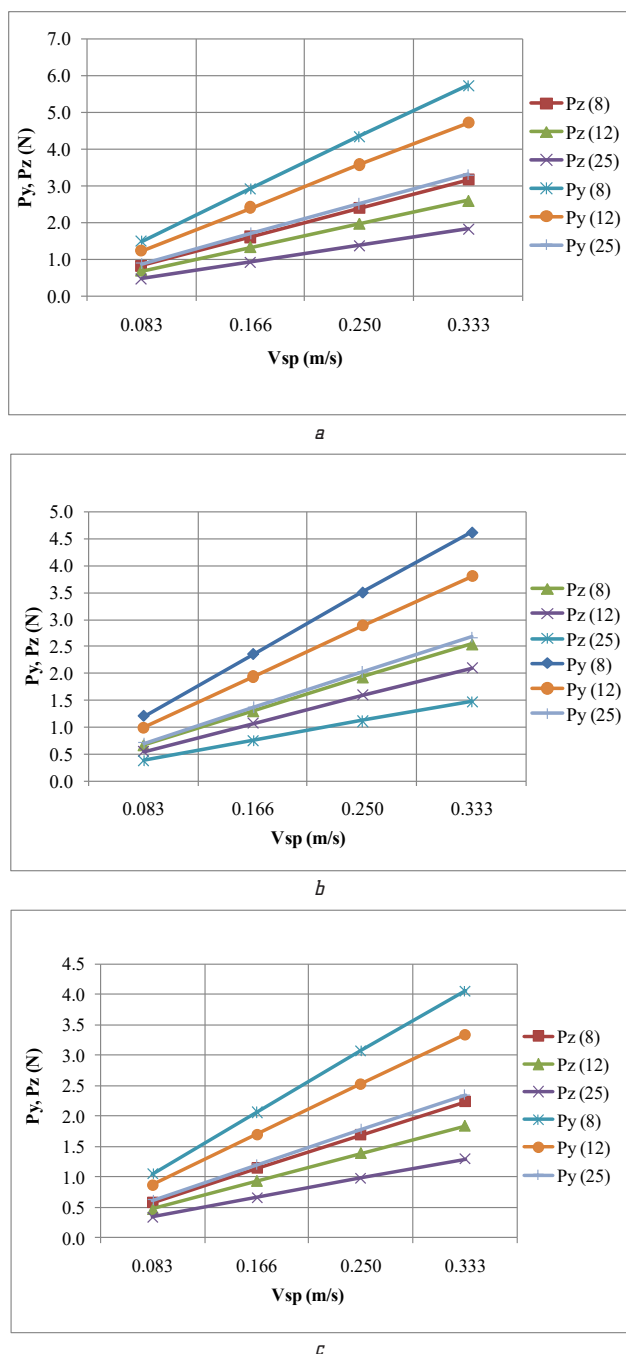


Fig. 6. Dependence of change of size of force P_y and P_z of corrosion-resistant steel 12X18H9T on speed of a spacemen (V_{sp}) at various grain size of a circle: *a* – wheels ceramic (electrocorundum): 25A8CM1K, 25A12CM1K, 25A25CM1K; *b* – wheels from cubic boron nitride: L080/60C10 100 %, L0120/100C10 100 %, L0250/200C10 100 %; *c* – diamond circles: AS080/60C10 100 %, AS0120/100C10 100 %, AS0250/200C10 100 %. Modes: $t=0.01 \cdot 10^{-3}$ m; $V_w=35$ m/s; $S=2$ mm/stroke

As a result of the research, it was possible to experimentally determine the existing relationship between the cutting forces R_y and P_z , which averages 1.75.

During the experiment it was found that the maximum cutting forces P_y and P_z in the width of the allowable modes, which are most often used in round and flat grinding using an electrocorundum wheel with a grain size of 8, can reach the following values, respectively:

- depending on the depth of grinding – $P_y=11.5$ N, $P_z=6.5$ N;

- from the speed of the circle – $P_y=27$ N, $P_z=15.5$ N;
- from the speed of the part – $P_y=13.5$ N, $P_z=7$ N.

Reducing the grain size of the wheel, let's obtain the effect of increasing the energy costs of the grinding process, by increasing the magnitude of the cutting forces.

If to compare the cutting forces that occur when grinding with different wheels, it is possible to note the following. In comparison with electrocorundum circles, when using CNB wheels, the cutting forces are reduced by 20–25 %, and when grinding with diamond wheels, the effect of cutting forces is reduced by 25–30 %.

It should be noted that the cutting forces increase with increasing longitudinal feed and depth of cut, and with increasing speed of rotation of the circle is the opposite – the magnitude of the cutting forces decreases.

7. SWOT analysis of research results

Strengths. The study of the grinding process, namely the analysis of cutting forces in the processing of titanium alloys and corrosion-resistant steel makes it possible to assign rational modes for grinding wheels of different abrasives, especially from KNB and diamond.

Weaknesses. Grinding on electrocorundum and diamond wheels is not recommended for titanium processing due to the high wear rate.

Opportunities. When implementing the grinding modes used in this study, which give the lowest values of cutting forces, it is guaranteed to obtain minimal energy consumption and quality surface layer of the part.

Threats. The experiments did not take into account the effect of lubricating and cooling fluids, because they are quite a lot and their effect requires a separate study.

8. Conclusions

1. In the course of work the technique of measurement of cutting forces by means of a tensometric table of UDM 50 is chosen. This technique gives the chance to measure cutting forces with high reliability. On the example of grinding of titanium alloy VT8 and steel 12X18H9T it can be stated that in the process of machining it is necessary to choose wheels with the maximum grain size, which is permissible according to the requirements of surface roughness. The speed of rotation of the circle must be chosen at least 30 m/s or slightly higher.

2. The values of cutting forces P_y and P_z in the width of the permissible modes, which are most often used in circular and flat grinding, and can reach maximum values, respectively $P_y=27$ N, $P_z=15.5$ N. The data obtained at low speed of the circle with electrocorundum, of the order of 15 m/s and a grain size of 8. Reducing the grain size of the wheel, let's obtain the effect of increasing the energy costs of the grinding process, by increasing the values of the cutting forces. If to compare the cutting forces that occur when grinding with different wheels, it is possible to note the following. Compared to electrocorundum wheels, when using wheels with CBN, the cutting forces are reduced by 20–25 %, and when grinding with diamond wheels (despite the high wear of the diamond wheel), the influence of cutting forces is reduced by 25–30 %. This is due to the fact that the cutting conditions are most favorable for diamonds and grains from the CBN, which makes it possible to use more intense cutting modes.

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