Analytical and Experimental Investigation of the Process of Microcutting During Grinding of Titanium Alloys and Steels with Cubic Boron Nitride Wheels

Vladimir Lebedev, Nikolaieva Tatiana, Chumachenko Tatiana, Omelchenko Yevhen and Bespalova Alla

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ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF THE PROCESS OF MICROCUTTING DURING GRINDING OF TITANIUM ALLOYS AND STEELS WITH CUBIC BORON NITRIDE WHEELS

Lebedev Vladimir 1[0000-0003-2891-9708], Nikolaieva Tatiana 1[0000-0003-2670-3401], Chumachenko Tatiana 1[0000-0001-7390-0198], Omelchenko Yevhen 1 [0000-0003-3713-0610], Bespalova Alla 2 [0000-0003-3713-0610]

1 Odessa Polytechnic State University, 1, Shevchenko avenue, Odessa, 65044, Ukraine

2 Odessa State Academy of Civil Engineering and Architecture, st. Didrihsona, 4, m. Odessa, 65029, Ukraine

65029, Ukraine;
chumachenko-1981.28@ukr.net

Abstract. The article deals with titanium alloys with anti-corrosion resistance, structural strength and refractoriness, as well as case-hardened carbon steel 12X2H4A.

The high chemical passivity of titanium surpasses that of the best grades of stainless steels. These properties are present to varying degrees in various titanium alloys, which leads to a high demand for this group of metals in various industries. Titanium alloys are obtained by traditional alloying of pure titanium with additional metals and minerals, which makes it possible to obtain materials with different physical and chemical properties at the output. Aluminum, nickel, copper, iron, chromium, vanadium, etc. are the main alloying elements in titanium alloys.

The object of research is the process of flat and round grinding of a titanium alloy and carbon case hardened steel, namely, the cutting microforces that occur during grinding. One of the most problematic places in the work is the selection of the necessary grinding modes, grinding wheel and its grain size. In the course of the research, samples of titanium alloy VT8 and steel 12X2N4A were used. They tested the grinding process with circles of cubic boron nitride (hereinafter referred to as CBN).

The results of this study make it possible to predict the performance of the grinding wheel, to minimize the energy costs of production, and also to refine the parameters of the part processing mode to obtain the necessary indicators of the quality of the surface layer and the geometric dimensions of the part.

The purpose of the study is to experimentally, using a CBN grinding wheel, to establish the patterns of change in unit cutting forces in the process of microcutting when grinding specimens from titanium alloys and carbon case hardened steel.

Key words: Microcutting, microtemperature, titanium alloy grinding, crack resistance.

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1 Introduction

The processing of durable materials, for example, titanium alloys, is used in mechanical engineering, aviation, rocket and space technology, metallurgy, oil and gas industries.

In the process of processing titanium blanks, the period of wheel life decreases by 15-20 times, and the cost of dressing reaches 60-70% of the total time spent on work.

Complicated and finishing. Burns may appear on the alloys, the chips stick to the grains of the circle, and the interatomic bonds in the oxide film are destroyed. All this leads to product defects.

Grinding of such workpieces must be carried out at low machine speeds with special modes. Parts can be hardened by plastic deformation to achieve higher quality.

The temperature in the contact zone of the wheel with the part is the most important characteristic of the grinding process. Under the influence of the grinding temperature, phase and structural transformations occur in the surface layer, which reduce the reliability and durability of operation by 2–3 times. It should be noted that any temperature value causes the appearance of some residual stresses, then phase and structural transformations occur when the temperature of the Ac_1 and Ac_3 points is reached.

The cutting forces in the machining of titanium alloys are approximately the same as those of steels, and their lower machinability is associated with lower thermal conductivity and an increased coefficient of friction, which increase the temperature in the cutting zone. In addition, titanium alloys have a lower modulus of elasticity than steel products, and this reduces the rigidity of parts and vibrations occur. This mostly happens in hard grinding conditions.

At present, the mechanical processing of titanium is a little-studied area. There are more questions than answers in working with such workpieces, so there is a need to study how the characteristics of titanium alloys change after the action of cutting forces during grinding.

Most of the studies were carried out on titanium alloy VT8 and carbon case hardened steel 12X2N4A. As a result of the experiments, it was found that when grinding with CBN wheels, a significant role in the cutting process is played by the values of the cutting force, which change during processing.

In the course of the experiment, it was found out that unit cutting forces R_y and P_z in the breadth of permissible modes, which are most often used in round and flat grinding, can reach maximum values, respectively:

- for titanium alloy R_y = 8.376 N, P_z = 4.607 N,
- for steel - R_y = 9.861 N, P_z = 5.423 N.

The data was obtained at a low CBN wheel speed of about 35 m/s and a grit size of 12.

By reducing the grain size of the wheel, we get the effect of increasing the energy consumption of the grinding process, due to an increase in the magnitude of the cutting forces.

Titanium alloys alloyed with the main alloying elements listed in the introduction have high mechanical strength. This property increases the possibility of using titanium and its alloys at elevated temperatures, in contrast to high-strength aluminum and magnesium alloys. In order to obtain the exact size and the required surface

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roughness of highly precise parts made of titanium and their alloys, a grinding operation will be a necessary condition.

The cutting forces that occur during the grinding process show the amount of energy consumption of this processing. 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. Changeable cutting forces arising from the error in the geometric shape of the part can cause vibration and oscillatory loads on the elastic system of the grinding machine.

Based on the foregoing, it can be firmly stated that an important task today is the study of unit cutting forces in the grinding of parts made of titanium alloys.

2 Literature Review

In the study [1], the purpose of the tests was to determine the optimal orientation of the cutter, at which the normal cutting force applied to the machined surface is minimal. Experiment and simulation have shown that the orientation of the tool has a decisive influence on the resulting cutting force and the component perpendicular to the machined surface. However, the process of grinding titanium alloys was not considered.

The materials [2] considered the possibility of obtaining β-titanium alloys with desired characteristics.

In [3], the main problems associated with the processing of titanium, as well as tool wear, were considered.

In [4], the quality of the surface of the Ti-6Al-4V alloy was studied in terms of surface roughness and microhardness after grinding the surface with a silicon carbide wheel under different grinding modes. But in all three cases, the grinding forces were not studied.

In [5], the issues of re-prevention of deposition were considered in order to obtain the optimal surface finish of a titanium alloy. And in [6], cutting forces and roughness were studied only for abrasive wheels made of electrocorundum. Grinding with CBN wheels was not considered.

In [7], the issues of the state of the MSS surface after grinding with elastic wheels on organic bonds are considered. Titanium alloys are not considered.

The paper [8] investigates the cutting forces during MSS grinding, but only when grinding with electrocorundum wheels. Cutting forces during grinding with CBN wheels are not considered.

In the source [9], cutting forces are considered during cryogenic processing of a ground surface.The issues of grinding with wheels made of superhard materials are not considered.

The paper [10] considers temperature and energy issues during abrasive grinding of MSS. Cutting forces are not considered.

The work [11] considers residual stresses after grinding the MSS with CBN wheels. Titanium alloys and carbon case hardened steel are not considered.

The paper [12] considers the issues of surface roughness during MSS grinding. Cutting forces are not considered.

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The paper [13] considers the issues of microcutting in the processing of MSS. Cutting forces are not considered.

In [14], the effect of aging regimes on the properties of MSLs is considered. Issues of cutting forces during grinding are not affected.

The work [15] studies the process of grinding titanium alloys using grinding wheels made of silicon carbide. Cutting forces have not been studied.

In [16], the wear resistance of grains made of diamond and cubic boron nitride during grinding is studied. Cutting forces are not considered.

Thus, analyzing the data available in the literature, we can conclude that the issues of the behavior of maraging steels during operation, as well as the influence of speed, grain size, deformations and temperature in the process of grinding titanium alloys and carbon case hardened steel, are fairly well covered. However, there is little data on how their characteristics change after the action of grinding forces, the values of which can be quite significant.

3 Research Methodology

Currently, there are a lot of methods for measuring grinding temperatures. In this article, the shear semi-artificial microthermocouple method is used, which is the most accessible and convenient.

A microthermocouple consists of a metal being processed and a thermoelectrode placed in the ground part, which gives a visual temperature distribution in the cutting zone and allows recording and measuring the cutting temperatures of individual abrasive grains directly in the grinding zone. One of the electrodes of such a microthermocouple is a workpiece, and the second thermoelectrode is a constantan wire with a diameter of 20 μm. The diameter of the wire is much smaller than the distance between the cutting grains of almost any grain size, which excludes its cutting by several grains at once. [17]

The thermocouple "thermoelectrode-part" is being formed and the signal of such a thermocouple will correspond to the temperature of the thermocouple, while it is necessary to determine the surface temperature of the part. Both the surface temperature and the thermoelectrode end temperature can be described by expression (1):

$$T_S = \frac{1{,}12Q\sqrt{\tau}}{F \times \varepsilon} \tag{1}$$

where: Q is the power of the heat source, W;

τ - is the contact duration;

F - is the area of the contact patch of the wheel with the part, m^2;

Ts – determined surface temperature, ºC;

ε – coefficient of thermal activity J/m2 ºC $sec^{0.5}$, and:

$$\varepsilon = \sqrt{\lambda C \rho}$$

where: λ – coefficient of thermal conductivity, J/m×s, deg;

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C - is the specific heat capacity J/kg deg;

ρ - is the density kg/m^3.Using the dependences of contact heat transfer, we obtain an expression for the surface temperature:

$$T_S = T_{th}\frac{\varepsilon_S+\varepsilon_{th}}{2\varepsilon_S} \quad (2)$$

or

$$T_S = T_{th}\frac{\varepsilon_S+\varepsilon_{th}}{2\varepsilon_S} \times E \times j = k_1 \times k_2 \times E \quad (3)$$

where in:

$$k_1 = T_{th}\frac{\varepsilon_S+\varepsilon_{th}}{2\varepsilon_S} \times j\ , \quad (4)$$

where E - is the thermos EMF value,

j - is the coefficient of connection between the temperature of the thermal junction and the thermo-EMF current (thermo-EMF),

k_2 - is the loop gain,

T_s - is the surface temperature during grinding,

T_{th} - is the temperature of the microthermocouple junction.

ε_s - is the coefficient of thermal activity of the surface to be ground,

ε_{th} - is the coefficient of thermal activity of the microthermocouple connection.

$$P_{z1} = \frac{2T_z\lambda\sqrt{\pi}}{V_{kr}\sqrt{a\tau}\left(1-e^{-\frac{rh}{2a\tau}}\right)} \quad (5)$$

$$P_{y1} = \frac{P_{z1}}{0{,}55} \quad (6)$$

Using the method described above, calculations were carried out from the data obtained during the experiment, which are confirmed by the graphs (Fig. 1, c; Fig. 2, c).

Also, the calculation of individual cutting forces was carried out and the results are summarized in Table 1 and Table 2.

Tab. 1. Calculated values of unit cutting forces (×10^{-4} N) when grinding titanium alloy VT8 depending on the depth of grinding and the grain size of the grinding wheel.

t·10^{-3}	**Pzsr (8)**	**Pysr (8)**	**Pzsr (12)**	**Pysr (12)**	**Pzsr (25)**	**Pysr (25)**
0,01	1,365	2,482	1,899	3,453	3,449	6,272
0,02	2,684	4,879	3,731	6,784	6,771	0,123
0,03	3,314	6,025	4,607	8,376	8,358	0,152
0,04	3,174	5,771	4,412	8,022	8,005	0,145

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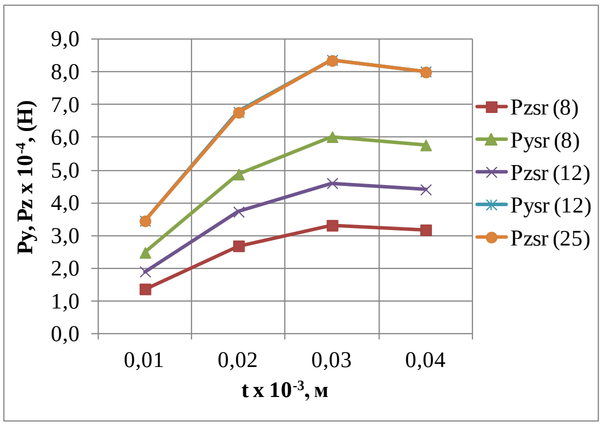
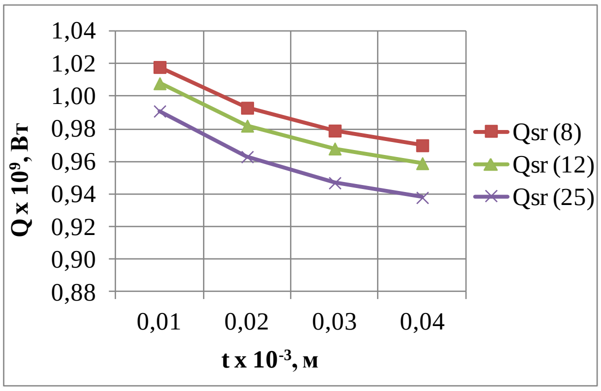
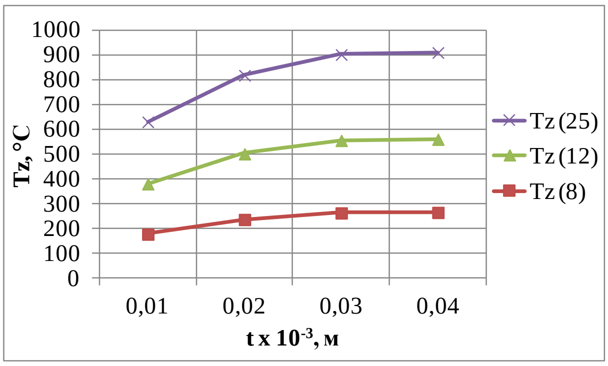

9,0
8,0
7,0
6,0
5,0
4,0
3,0
2,0
1,0
0,0
Py, Pz x 10-4, (Н)
0,01
0,02
0,03
0,04
t x 10-3, м
Pzsr (8)
Pysr (8)
Pzsr (12)
Pysr (12)
Pzsr (25)

а)


1,04
1,02
1,00
0,98
0,96
0,94
0,92
0,90
0,88
Q x 109, Вт
0,01
0,02
0,03
0,04
t x 10-3, м
Qsr (8)
Qsr (12)
Qsr (25)

б)


1000
900
800
700
600
500
400
300
200
100
0
Tz, °C
0,01
0,02
0,03
0,04
t x 10-3, м
Tz (25)
Tz (12)
Tz (8)

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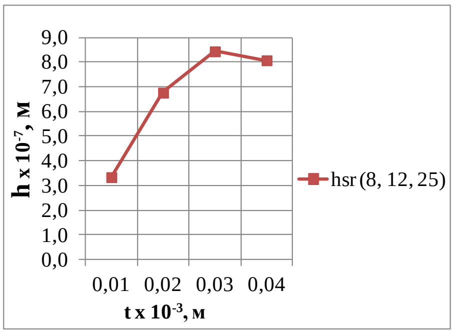
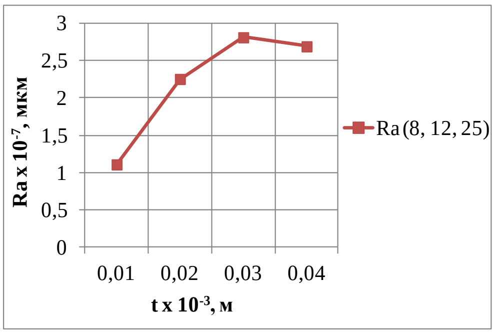
в)





г) д)

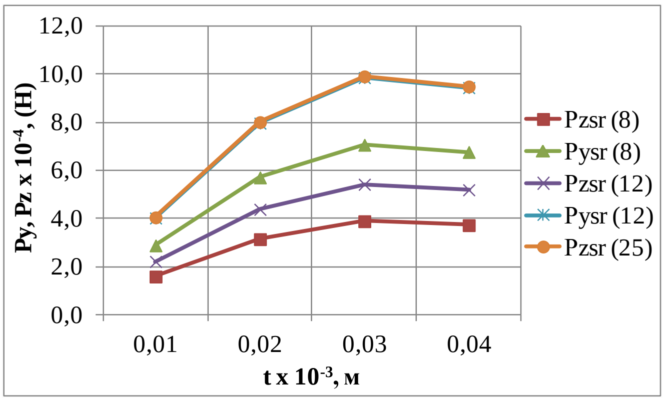
Fig.1. Dependence of the change in the values of: unit forces Py and Pz (a), power Q (b), microtemperature Tz (c), depth h (d), roughness Ra (e) of the VT8 titanium alloy on the grinding depth at different grain sizes of the wheel.

Modes: Vcr = 35 m / s; Vd = 0.16 m / s; S = 4 mm / stroke.

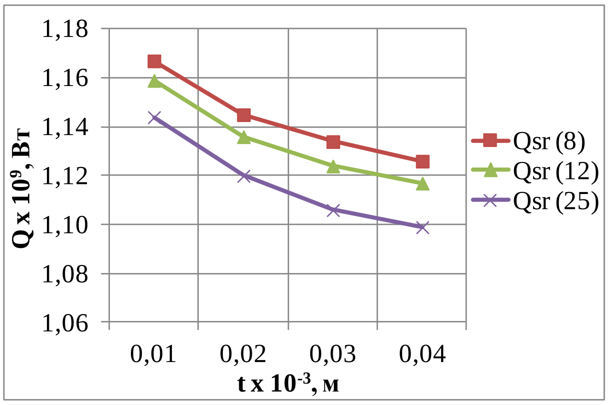
CNB circles: DEX 30, DEX 40, DEX 50.

Tab. 2. Calculated values of unit cutting forces ($\times 10^{-4}$ N) when grinding steel 12X2H4A depending on the depth of grinding and the grain size of the grinding wheel.

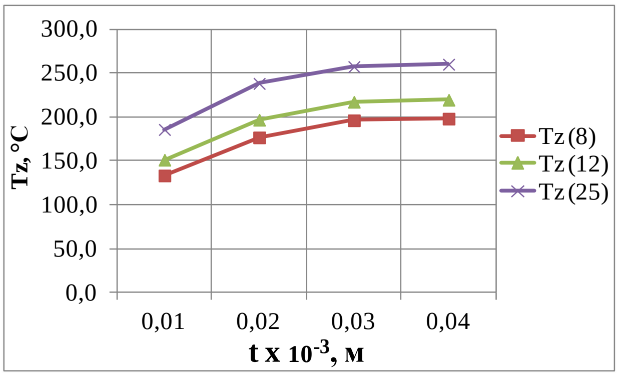
$t \cdot 10^{-3}$	Pzsr (8)	Pysr (8)	Pzsr (12)	Pysr (12)	Pzsr (25)	Pysr (25)
0,01	1,583	2,878	2,211	4,020	4,046	7,356
0,02	3,138	5,706	4,381	7,965	8,008	1,456
0,03	3,885	7,065	5,423	9,861	9,911	1,802
0,04	3,721	6,765	5,194	9,443	9,491	0,173


12,0
10,0
8,0
6,0
4,0
2,0
0,0
Py, Pz x 10⁻⁴, (Н)
0,01
0,02
0,03
0,04
t x 10⁻³, м
Pzsr (8)
Pysr (8)
Pzsr (12)
Pysr (12)
Pzsr (25)

а)


1,18
1,16
1,14
1,12
1,10
1,08
1,06
Q x 10⁹, Вт
0,01
0,02
0,03
0,04
t x 10⁻³, м
Qsr (8)
Qsr (12)
Qsr (25)

б)


300,0
250,0
200,0
150,0
100,0
50,0
0,0
Tz, °C
0,01
0,02
0,03
0,04
t x 10⁻³, м
Tz (8)
Tz (12)
Tz (25)

в)

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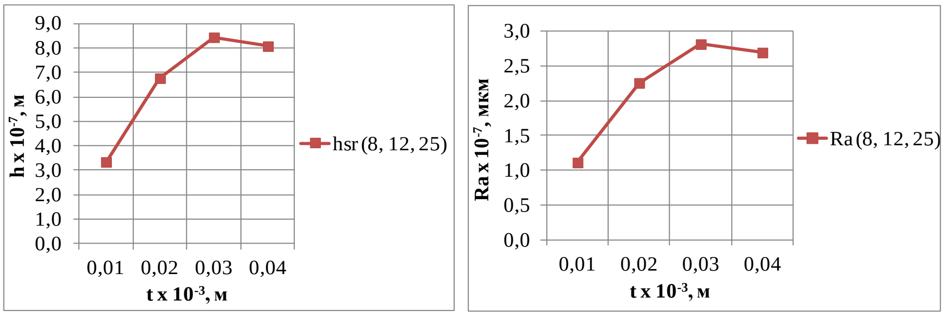

г) д)

Fig.2. Dependence of the change in the values: unit forces Py and Pz (a), power Q (b), microtemperature Tz (c), depth h (d), roughness Ra (d) of steel 12X2H4A on the depth of grinding at different grain sizes of the wheel.

Modes: Vcr = 35 m / s; Vd = 0.16 m / s; S = 4 mm / stroke.

CNB circles: DEX 30, DEX 40, DEX 50.

where V_{kr} - the speed of rotation of the circle, V_d - the speed of the longitudinal feed, S-value of the transverse feed.

In the course of the experiment, it was found out that unit cutting forces Py and Pz in the breadth of permissible modes, most often used in round and flat grinding, can reach the following values:

1) for titanium alloy:

- with a circle structure of 8, they come to values from 1.365 till 6.025 × 10^{-4} N,
- with a circle structure of 12, they come to values from 1.899 till 8.376 × 10^{-4} N,
- with the structure of the circle 25 come to values from 0.145 till 8.358×10^{-4} N;

2) for carbon case hardened steel 12X2H4A:

- with a circle structure of 8, they come to values from 1.583 till 7.065 × 10^{-4} N,
- with a circle structure of 12, they come to values from 2.211 till 9.861 × 10^{-4} N,
- with a circle structure of 25, they come to values from 0.173 till 9.911 × 10^{-4} N.

Reducing the granularity of the circle, we get the effect of increasing the energy costs of the grinding process due to an increase in the value of unit cutting forces.

It should be noted that the unit cutting forces increase with an increase in the longitudinal feed and depth of cut.

The study of the grinding process, namely the analysis of unit cutting forces in the processing of titanium alloys and steel 12X2H4A, allows you to assign rational modes when grinding with CBN wheels.

During the experiments, the influence of cutting fluids was not taken into account, since there are quite a lot of them and their influence requires a separate study. With the introduction of grinding modes used in this study, which give the smallest values of unit cutting forces, we are guaranteed to obtain minimal energy consumption and a high-quality surface layer of the part.

For grinding wheels made of CBN, changing their grain size from 8 to 25, one can observe an increase in the value of unit cutting forces from 1.1 to 2.5 times, respectively. This phenomenon can be explained as follows: by reducing the grain size of the grinding wheel, we observe a significant increase in the number of cutting grains per unit surface of the wheel and, consequently, in the contact patch of the grinding wheel with the workpiece. In this case, there is a decrease in the power load on a single grain, but an increase in the number of grains provides an increase in the cutting force. It should be noted that cutting forces also increase due to friction between the grinding surface and the wheel bond when using fine-grained wheels.

4 Results

As a result of the research, it was possible to experimentally determine the existing ratio between the cutting forces Py and Pz, which averages 1.82.

During the experiment, it was found that the maximum cutting forces Py and Pz in the breadth of permissible modes, which are most often used for circular and flat grinding when using an CBN wheel with a grain size of 12, can reach the following values, depending on the grinding depth, respectively:

– for titanium alloy VT8 P_y = 8.376 N, P_z = 4.607 N;

- for steel P_y = 9.861 N, P_z = 5.423 N. With a decrease in the grain size of the wheel, we get the effect of increasing the energy costs of the grinding process due to an increase in the magnitude of the cutting forces.

5 Conclusions

Grinding parts made of titanium alloys is a difficult task. Using the example of grinding titanium alloy VT8 and carbon case hardened steel 12X2H4A, it can be argued that in the process it is necessary to choose wheels that have the maximum grain size, which is only acceptable to meet the existing requirements for the surface roughness of the part and meets the requirements of labor protection.

The chosen technique for measuring cutting forces using a strain gauge table UDM 50 makes it possible to measure cutting forces with high reliability.

The rotation speed of the circle should be chosen at least 30 m/s or slightly higher.

6 References

1. Lazoglu I., Ehsan LayeghKhavidaki S., Mamedov A. (2014) Mechanics of Titanium Machining. In: Davim J. (eds) Machining of Titanium Alloys. Materials Forming, Machining and Tribology. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-43902-9_3

2. Xing H., Sun J. (2008) Deformation defects in a metastable β titanium alloy. In: Richter S., Schwedt A. (eds) EMC 2008 14th European Microscopy Congress 1–5 September 2008, Aachen, Germany.Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-85226-1_338

3. Ezugwu, E.G. and Wang, Z.M., 1997. Titanium alloys and their machinability - a review. JournalofMaterialsProcessing Technology, Vol. 68, Is. 3, 15 August 1997, P. 262-274https://www.sciencedirect.com/science/article/abs/pii/S0924013696000301

4. Rosemar B. S., Álisson R. M., Rogério V. G., Anselmo E. D., Rodolfo F. M. O. Surface Grinding of Ti-6Al-4V Alloy with SiC Abrasive Wheel at Various Cutting

`

Conditions. 45th SME North American Manufacturing Research Conference, NAMRC 45, LA, USA. Vol. 10, 2017, Procedia Manufacturing, P. 590-600https://doi.org/10.1016/j.promfg.2017.07.057

5. Turley D. M.(1985). Factors affecting finishing when grinding titanium and a titanium alloy(Ti–6Al–4V). Wear 104:323–335.Vol. 104, Is. 4, 15 August 1985,P.323335https://www.sciencedirect.com/science/article/abs/pii/0043164885900407

6. Yun CHEN (2015).A study of the cutting forces andvibration characteristics in titaniummachining. Doctor of Philosophy School of Mechanical and Manufacturing Engineering The University of New South Wales

7. Shouguo S., Beizhi Li, Weicheng Guo. Surface integrity in grinding of C-250 maraging steel with resin-bonded and electroplated CBN grinding wheels. The International Journal of Advanced Manufacturing, Technology. 2019. № 103, P. 1079–1094.

8. Weicheng Guo, Beizhi Li, Shouguo Shen, Qinzhi Zhou. Experimental study on force model in grinding of maraging steel 3J33. Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science. 2018. P. 3475-3486. DOI: https://doi.org/10.1177/0954406218814041

9. APynachalam S. S. B., Kannan C., APyn V. K., Hariharan K., Danil Y. P., Khaled G., Krzysztof N. Effect of CPyogenic Grinding on Fatigue Life of Additively Manufactured Maraging Steel. Materials. Materials (Basel). 2021 Mar; 14(5): 1245 URL:https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7961498/

10. Zishan D., Beizhi L., Omar F., Yamin S., Steven Y., Lianga,B. Investigation of Temperature and Energy Partition During Maraging Steel Micro-grinding. 9th International Conference on Digital Enterprise Technology - DET 2016 – "Intelligent Manufacturing in the Knowledge Economy Era. 2016. P. 284-288. DOI:10.1016/j.procir.2016.10.084

11. Shouguo S., Beizhi Li, Weicheng Guo. Residual Stresses Distributions in Grinding of 3J33 Maraging Steel with Miniature Electroplated CBN Wheel. The 5th International Conference on Mechatronics and Mechanical Engineering. MATEC Web Conf. 2019. № 256. DOI:10.1051/matecconf/201925601002

12. Jindrich F., Tomas B., Miroslav Z. Grinding of Maraging Steel 1.2709 with SiC Grinding Wheels and Effect of Grinding Conditions on the surface Roughness and Wear of the Wheels. Manufacturing Technology. 2020, 20(1): P.18-22. | DOI: 10.21062/mft.2020.018

13. Zhongpeng Z., Yan Jin Lee, Jiayi Z., Xin Jin, Hao Wang. Ultra-precision micro-cutting of maraging steel 3J33C under the influence of a surface-active medium. Journal of Materials Processing Technology. 2021. №292. DOI: 10.1016/j.jmatprotec.2021.117054

14. Demir H., Guldibi A. S. Aging Effect on MicrostPycture and Machinability of Corrax Steel. Engineering, Technology and Applied Science Research. 2020. № 10, P. 5168-5174. URL: https://doi.org/10.48084/etasr.3265

15. Kremen Z. I. A new generation of high-porous vitrified cnb grinding wheels//IDR. 2003. № 4. P. 53–56. http://www.amg-nv.com/Innovation/Titanium-Aluminide/default.aspx.

16. K. Philip Varghese, Ph. D. Group Leader, Emerging Trends in Grinding of Materials, Advanced Application Engineering. 12–17 сентября 2016. McCormick Place. Чикаго, Иллинойс.

http://www.mapyourshow.com/MYS_Shared/imts16/handouts/KPhilipVargheseIMT...

17. Bezpalova A., Lebedev V., Chumachenko T., Frolenkova O., Klymenko N. (2022) Methods for Measuring Grinding Temperatures. In: Tonkonogyi V., Ivanov V., Trojanowska J., Oborskyi G., Pavlenko I. (eds) Advanced Manufacturing Processes III. InterPartner 2021. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-91327-4_14

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