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The influence of cutting mode elements on the technological parameters of the process of milling blanks of titanium alloy thin-walled parts

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Abstract: The purpose of a rational mechanical processing mode remains an urgent task of pre-production engineering. Known recommendations and methods for selecting this mode are focused on the processing of solid blanks and do not take into account the fact that when processing thin-walled blanks, the temperatures in the processing zone and the surface layer of the blank differ. The study is aimed at identifying patterns in changing the parameters of the milling process of thin-walled blanks depending on the mode elements, as well as developing recommendations for selecting this mode. The authors performed numerical simulation of technological parameters of the milling process of solid and thin-walled blanks made of titanium alloy under various modes. The cutting speed, cutting depth and feed per cutter tooth were varied. The cutting force, power and densities of heat sources and the temperature in the surface layer of the blank, in the contact zones of the cutter tooth with the blank and the chips with the front surface of the tooth were calculated. It has been found that when milling thin-walled blanks, the temperature field differs significantly from that formed when processing solid blanks due to low heat removal from the unprocessed surface. Increasing the feed per tooth by 45 % leads to an insignificant decrease in temperatures in the cutting zone (by 5...12 %). Increasing the cutting speed by 25 %, on the contrary, leads to an increase in temperatures by 5...10 %. Increasing the cutting depth leads to an increase in the temperature in the chip-tooth contact zone by 1.5 times and to an increase in the temperature in the tooth-blank contact zone.

Keywords: cutting mode; technological parameters of milling process; temperature field; yield strength; thin-walled blank; cutting force; cutting zone temperature.

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INTRODUCTION

The temperature field formed during mechanical processing of thin-walled blanks differs from the field during processing of blanks of parts of considerable thickness [1; 2]. The reason is that during processing of a thin-walled blank, its surface opposite to the processed one has a significant effect on the temperature field. However, known recommendations and methods for selecting the mode are focused on the processing of solid blanks, and do not take into account the fact that when processing thin-walled blanks, the temperatures in the processing zone and the surface layer of the blank differ. This is caused by the low level of heat removal from the unprocessed surface – heat removal to the environment is significantly less than that occurred during heat removal to the underlying layers of a solid blank [2; 3].

Knowledge of the patterns of thermal processes of mechanical treatment, and the ability to control these processes, are necessary to increase processing productivity and ensure the quality of processed parts. The temperature of the surface layers of the blank affects their structural and phase composition, microhardness and stress state of the material [4]. The temperatures of the tool surfaces contacting with the blank and chip determine the wear resistance and service life of the tool, i.e. its operability [5; 6]. However, the influence of thermal processes on the cutting process is often not considered as a significant factor [7; 8].

The arguments of the dependencies for calculating the powers of heat sources are the cutting forces, which, in turn, depend on the mechanical characteristics of the material of the processed blank (yield strength and tensile strength). To determine the mechanical characteristics, it is necessary to know the temperature in the plastic deformation zone. To determine this temperature, a dependence is proposed, the argument of which is the average tangential stresses in the conventional shear surface depending on the temperature in this zone. This circumstance complicates the possibility of determining the yield strength of the blank material in the plastic deformation zone.

It is possible to ensure the operability of the tool, and the quality parameters of thin-walled parts by selecting a rational processing mode, but there are no corresponding recommendations in the literature. Studies related to the determination of a rational mode for processing thin-walled blanks, take into account the elastic deformation of the technological system elements, including the blank itself [9; 10]. Vibrations and pulsations of cutting forces are taken into account, which is also relevant for thin-walled blanks [11–13]. Temperature fields and the effect of temperatures on the mechanical properties of the blank material, during processing were studied for solid blanks [14]. However, it was not taken into account that the temperature field formed, when processing thin-walled blanks, is different from that when processing solid blanks, and the effect of the blank temperature on the yield strength of its material was not considered [15; 16]. In [17; 18], the processes of machining thin-walled blanks, as well as blanks with a complex profile, were studied, but recommendations for choosing cutting modes were not provided.

The patterns of changing the parameters of the milling process of thin-walled blanks made of titanium alloys depending on the mode elements, have not been studied.

The aim of this study is to investigate the influence of the elements of the milling mode of thin-walled titanium alloy blanks on the technological parameters of the process, including the forces and temperatures arising during the processing.

METHODS

The friction forces of the chip on the tooth front surface, the tooth back surface on the blank, and the main component of the cutting force, were calculated using the dependencies obtained by transforming the corresponding dependencies proposed in [19; 20]. These forces were obtained under the condition that the assessment of the blank material destruction is carried out, based on the flow plasticity theory ("flow plasticity method") used in [12; 18]. One of the main factors determining this process is the yield strength of the blank material, which depends on the deformed layer temperature:

$$\sigma_{st} = f(T_d),$$

where T_d is the temperature of the deformed layer of the blank material, K.

The calculation of the σ_{St} parameter was performed using the formula [7; 17]:

$$\sigma_{st} = \sigma_s \cdot \left(1 - \frac{T_d}{T_p}\right),$$

where σ_S is the yield stress of the blank material at a temperature of 293 K, Pa;

T_p is the melting temperature of the material, K.

The powers and densities of heat sources in the zone of deformation and in the contact zones of the tooth with the chip and the blank were calculated using the dependencies [20; 21].

The authors assumed that the blank material (VT6 titanium alloy, the closest analogue according to DIN is 3.7164) is isotropic, and the phase transformations during its heating were not taken into account in the calculation. This assumption is valid, since numerical simulation and experiments have found that the temperature in the surface layer of the blank does not reach the values at which the transformations occur.

To calculate the milling process parameters, we used our own software, implementing the temperature field calculation using the finite element method. It allowed calculating the temperature of the deformed layer of the blank material T_d and the yield strength of the blank material σ_{St} at this temperature.

The time during which heat exchange occurs is divided into finite small intervals. The deformable layer temperature calculated for a certain moment in time is used to calculate the yield strength of the blank material at the next moment in time.

The σ_{st} parameter is the argument of the dependencies for calculating the friction forces, and the main component of the cutting force P_z. The forces per 1 mm of the cutter tooth height were calculated.

The adequacy of the physical and mathematical models adopted for calculating the temperatures to real conditions, was checked by comparing the average temperature in the surface layer of the machined blank made of VT6 titanium alloy, obtained by calculation, with the results of measurement by a semi-artificial thermocouple. By averaging the temperature of the surface layers of a solid blank, at different moments in time, and at different points at a distance from the blank surface equal to the diameter of the thermocouple wire (0.05 mm), the average calculated temperature was obtained. Milling mode: feed per cutter tooth is S_z=0.16 mm/tooth; cutting speed is V=120 and 150 m/min; cutting depth is t=0.3 mm; feed rate is V_s=1.91 m/min. The other experimental conditions corresponded to those used in the subsequent numerical simulation. At speeds V=120 and 150 m/min, the calculated temperatures were 686 and 701 K, and the experimental values were 618 and 623 K.

The discrepancies between the calculated and experimental temperature values recorded at different cutting speeds do not exceed 12 %, which indicates the possibility of using the proposed methods for the thermophysical analysis of the milling process.

The parameters of the milling process of blanks made of VT6 titanium alloy, were numerically simulated using the cylindrical surface of an end mill made of T5K10 hard alloy with a diameter of 20 mm. The thermophysical characteristics of the blank and cutter material (density, thermal conductivity and heat capacity coefficients) depending on the temperature and the yield stress of the blank material at a temperature of 293 K were determined from reference data. The process parameters were recorded during cutting of the blank by the twenty-fifth tooth of the successive series of working teeth of the cutter. The process of cooling the cutting zone with a lubricating fluid was simulated, taking the coefficient of heat transfer from the surfaces contacting with the coolant to be 5000 W/(m^2·K); the heat transfer coefficient of the surfaces contacting with air was taken to be 40 W/(m^2·K).

The authors simulated the process of milling a solid blank with a thickness of 10 mm, as well as blanks with a thickness of 0.7 and 0.5 mm after processing. The following mode elements were varied: feed per cutter tooth S_z – 0.11 and 0.16 mm/tooth; cutting speed V – 120 and 150 m/min; milling depth t – 0.3 and 0.5 mm. The process parameters were recorded at the last moment of contact between the cutter tooth and the blank (this time depends on the milling mode elements) and at a time that was $8\cdot10^{-5}$ s less than the last.

Table 1 shows a plan for numerical simulation of the parameters for processing thin-walled blanks with varying mode elements.

RESULTS

The studies carried out during the machining of blanks made of VT6 titanium alloy, showed that blanks with a thickness of 10 mm and more are classified as solid blanks; during their machining, the surface opposite to the blank does not affect the temperature field in the blank.

Tables 2 and 3 present the results of calculating the milling process parameters for a solid blank with a thickness of 10 mm and thin-walled blanks, the thickness of which after the allowance removal is 0.7 and 0.5 mm. Under these conditions and cutting mode, visible changes in the temperature field were recorded when milling blanks with a thickness of 1 mm after machining. When machining a thin-walled blank, the temperatures in the zones of contact of the chip with the tooth front surface, the tooth rear surface with the blank and in the deformation zone are higher than when machining a solid blank. An increase in the temperature of the deformed layer of the blank material T_d leads to a decrease in the yield strength of the material of the thin-walled blank σ_{st}.

Tables 4 and 5 present the results of calculating the parameters of the milling process for a 0.7 mm thick workpiece, after removing the allowance for different mode elements. Table 6 presents the results of calculating the temperatures. With an increase in the feed S_z from 0.11 to 0.16 mm/tooth (by 45 %), the maximum depth of tooth penetration into the workpiece a_{max} (on average by 45 %), and the maximum length of contact of the chip with the front surface of the tooth l increase. The parameter l increases to a greater extent at a cutting depth of t=0.3 mm – by 64 %. An increase in the parameters a_{max} and l is the reason for an increase in the friction forces and the main component P_z of the cutting force. The effect of the feed on the friction force of the tooth on the workpiece F_2 is insignificant; the friction force of the chip on the front surface of the tooth F_1 and the force P_z increase by 15…42 % and 14…21 %, respectively. This leads to an increase in the power of heat sources in the chip-tooth contact zones W_1 and in the deformation zone W_g; the power of the heat source in the tooth-to-workpiece contact zone W_2 increases insignificantly.

With an increase in the cutting speed V from 120 to 150 m/min, i.e. by 25 %, the power of all heat sources increases by 17...27 %. This leads to an increase in the average and maximum temperatures T_1 and T_2 by 5...10 %. Consequently, with an increase in the cutting speed V, the temperature of the surface layer of the workpiece increases.

The kinematic parameters of the milling process – the length of the tooth-to-workpiece contact trajectory l_K, the maximum tooth penetration depth into the workpiece a_{max} and the maximum length of chip contact with the front surface of the tooth l – are not affected by the cutting speed.

An increase in the cutting depth leads to an increase in the kinematic parameters. With increasing parameter a_{max}, the friction force F_1 and the force P_z, as well as the powers of the heat sources W_1 and W_g, increase. The friction force F_2 and the power of the source W_2 are not affected by the change in the cutting depth.

***Table 1.** Numerical simulation plan*
***Таблица 1.** План численного моделирования*

Experiment number	Varying parameters			
	Feed per cutter tooth S_z, mm/tooth	**Cutting speed V, m/min**	**Milling depth t, mm**	**Feed speed V_s, m/min**
1	0.11	120	0.3	1.05
2	0.16	120	0.3	1.52
3	0.11	150	0.3	1.31
4	0.16	150	0.3	1.91
5	0.11	120	0.5	1.05
6	0.16	120	0.5	1.52
7	0.11	150	0.5	1.31
8	0.16	150	0.5	1.91

Table 2. *Milling process parameters at various sizes (thicknesses) of a processed blank:*
S_z*=0.16 mm/tooth;* V*=150 m/min;* t*=0.5 mm; feed speed* V_s*=1.91 m/min*
Таблица 2. *Параметры процесса фрезерования при различных размерах (толщинах) обработанной заготовки:*
S_z*=0,16 мм/зуб;* V*=150 м/мин;* t*=0,5 мм; скорость подачи* V_s*=1,91 м/мин*

Blank size (thickness) after processing, mm	Force of friction of a chip on a tooth front surface F_1, N	Force of friction of a tooth on a blank F_2, N	Cutting force major component P_z, N	Heat source power, W, in the zone of		
				deformation W_g	chip-tooth contact W_1	tooth-blank contact W_2
10	54.8/62.7	54.3/55.1	118.1/128.1	109.0/124.9	82.2/94.1	163.0/165.4
0.7	54.7/62.6	54.2/55.0	117.7/127.8	108.7/124.6	82.0/93.9	162.5/165.0
0.5	53.4/61.3	54.0/49.8	117.0/127.2	108.2/124.1	81.6/93.5	162.0/164.5

Note. F_1, F_2, P_z *are forces per 1 mm of the cutter tooth height.*

The denominators represent the process parameters recorded at the last moment of contact between the cutter tooth and the blank, and the numerators represent the same parameters at the previous moment.

Примечание. F_1, F_2, P_z *– силы, приходящиеся на 1 мм высоты зуба фрезы.*

В знаменателях представлены параметры процесса, зафиксированные в последний момент времени контакта зуба фрезы с заготовкой, в числителях – в предыдущий момент.

Table 3. *Temperatures at various sizes (thicknesses) of a processed blank:*
S_z*=0.16 mm/tooth;* V*=150 m/min;* t*=0.5 mm;* V_s*=1.91 m/min*
Таблица 3. *Температуры при различных размерах (толщинах) обработанной заготовки:*
S_z*=0,16 мм/зуб;* V*=150 м/мин;* t*=0,5 мм;* V_s*=1,91 м/мин*

Blank size (thickness) after processing, mm	Average temperature in the contact zone of		Temperature of the deformed layer of the blank material T_d, K	Yield strength of the blank material σ_{st}, MPa	Temperature of a blank T_3, K at a distance from the processed surface	
	a tooth with a blank T_2, K	a chip with a tooth T_1, K			30 µm	180 µm
10	1,000/1,018	1,004/1,012	365/337	784/796	484/478	389/390
0.7	1,006/1,023	1,008/1,013	371/341	782/794	497/ 491	406/406
0.5	1,014/1,031	1,014/1,015	379/347	778/791	514/506	425/425

Note. The denominators represent the process parameters recorded at the last moment of contact between the cutter tooth and the blank, and the numerators represent the same parameters at the previous moment.

Примечание. В знаменателях представлены параметры процесса, зафиксированные в последний момент времени контакта зуба фрезы с заготовкой, в числителях – в предыдущий момент.

With increasing cutting depth, the average value of temperature T_2 decreases at S_z=0.11 mm/tooth, and increases at S_z=0.16 mm/tooth. The maximum value of temperature T_2 increases for all combinations of parameters S_z and V, except for S_z=0.11 mm/tooth and V=150 m/min. The workpiece temperature T_3 at a depth of 30 µm increases with increasing cutting depth for all combinations of parameters S_z and V, except for S_z=0.16 mm/tooth and V=150 m/min. The temperature at the tooth tip T_E slightly decreases with increasing parameter t, except for the calculation for the mode S_z=0.11 mm/tooth and V=120 m/min.

DISCUSSION

When milling thin-walled blanks, the cutting force P_z and the power of the heat sources are somewhat lower due to the lower value of the σ_{st} parameter. However, due to less intense heat removal from the zone of processing thin-walled blanks, the contact temperatures are somewhat higher [3] than when machining solid ones (Tables 2 and 3). The temperatures in the surface layer of the blanks increase to a greater extent, and the greater the distance from the machined surface, the greater the difference in temperatures between the solid and thin-walled blanks.

Table 4. *Process technological parameters at various milling mode elements*
Таблица 4. *Технологические параметры процесса при различных элементах режима фрезерования*

Experiment number according to Table 3	Path length of the tooth-blank contact l_K, mm	Maximum depth of tooth penetration in a blank a_{max}, μm	Maximum length of a contact of a chip with the tooth front surface l, μm	Temperature of the deformed layer of the blank material T_d, K	Yield strength of the blank material σ_{st}, MPa
1	2.46	26.8	76.5	385/366	776/784
2	2.46	39.0	125.8	376/354	779/789
3	2.46	26.8	85.2	388/365	774/784
4	2.46	39.0	125.8	376/351	779/790
5	3.18	34.4	111.0	394/365	772/784
6	3.18	50.1	161.5	371/345	781/792
7	3.18	34.4	111.5	396/363	781/792
8	3.18	50.1	161.5	371/341	782/794

Note. The denominators represent the process parameters recorded at the last moment of contact between the cutter tooth and the blank, and the numerators represent the same parameters at the previous moment.

Примечание. В знаменателях представлены параметры процесса, зафиксированные в последний момент времени контакта зуба фрезы с заготовкой, в числителях – в предыдущий момент.

Table 5. *Process parameters at various milling mode elements*
Таблица 5. *Параметры процесса при различных элементах режима фрезерования*

Experiment number	Force of friction of a chip on a tooth front surface F_1, N	Force of friction of a tooth on a blank F_2, N	Cutting force major component P_z, N	Heat source power, W, in the zone of		
				deformation W_g	chip-tooth contact W_1	tooth-blank contact W_2
1	28.0/31.5	53.8/54.4	86.2/90.8	46.0/51.8	35.0/39.4	134.4/135.8
2	38.4/45.0	54.0/54.7	98.8/106.9	63.7/74.3	48.3/56.2	135.0/136.6
3	28.0/31.5	53.7/54.3	86.0/90.8	55.1/62.2	41.9/47.2	161.0/163.0
4	38.8/45.2	54.0/54.7	99.0/107.2	76.7/89.6	58.2/67.8	162.0/164.1
5	39.8/44.1	53.5/54.3	99.6/105.5	65.6/72.8	49.7/55.1	133.7/135.8
6	54.0/61.7	54.2/54.9	116.9/126.7	89.4/102.4	67.5/77.1	135.4/137.3
7	39.7/44.1	53.4/54.4	99.5/105.6	78.6/87.4	59.6/66.2	160.3/163.2
8	54.7/62.6	54.2/55.0	117.7/127.8	108.7/124.6	82.0/93.9	162.5/165.0

Note. F_1, F_2, P_z *are forces per 1 mm of the cutter tooth height.*

The denominators represent the process parameters recorded at the last moment of contact between the cutter tooth and the blank, and the numerators represent the same parameters at the previous moment.

Примечание. F_1, F_2, P_z *– силы, приходящиеся на 1 мм высоты зуба фрезы.*

В знаменателях представлены параметры процесса, зафиксированные в последний момент времени контакта зуба фрезы с заготовкой, в числителях – в предыдущий момент.

Table 6. *Temperatures at various milling mode elements*
Таблица 6. *Температуры при различных элементах режима фрезерования*

Experiment number	Temperature in the tooth-blank contact zone T_2, K		Temperature in the chip-tooth contact zone T_1, K		Temperature at the tip of the cutter tooth T_E, K	Blank temperature T_3, K
	average	maximum	average	maximum		
1	967/972	1,282/1,288	874/871	961/961	1,025/1,017	532/525
2	922/936	1,301/1,317	959/934	1,277/1,290	1,019/1,010	506/496
3	1,042/1,052	1,462/1,475	946/958	1,305/1,312	1,036/1,025	539/531
4	966/987	1,441/1,467	963/970	1,384/1,403	1,013/1,001	502/491
5	957/960	1,285/1,294	948/946	1,273/1,277	1,034/1,024	542/537
6	956/969	1,330/1,348	967/970	1,380/1,393	1,014/1,001	507/500
7	1,011/1,017	1,424/1,437	986/985	1,380/1,388	1,027/1,016	539/535
8	1,006/1,023	1,477/1,504	1,008/1,013	1,506/1,528	1,008/991	497/491

Note. Blank temperature T_3 was determined at a distance of 30 µm from the processed surface.

The denominators represent the process parameters recorded at the last moment of contact between the cutter tooth and the blank, and the numerators represent the same parameters at the previous moment.

Примечание. Температура заготовки T_3 определена на расстоянии 30 мкм от обрабатываемой поверхности.

В знаменателях представлены параметры процесса, зафиксированные в последний момент времени контакта зуба фрезы с заготовкой, в числителях – в предыдущий момент.

The densities of all heat sources increase insignificantly, since with an increase in the feed, both the power of the heat sources and their areas increase. The average temperatures in the contact zone of the tooth with the blank T_2, the temperature at the tip of the cutter tooth T_E and the temperature of the blank T_3 in almost all cases decrease insignificantly, with an increase in the feed (by 5...12 %). This can be explained by a decrease in the time the blank is opposite the heat source with an insignificant increase in the densities of the heat sources. The average and maximum temperatures in the chip-tooth contact zone T_1 increase with increasing feed.

The blank temperature at a distance of 30 µm from the machined surface does not change, or decreases slightly, with increasing speed V, which is explained by a decrease in the time of action of the heat source on the blank.

At the last moment of contact of the tooth with the blank, the temperature of the deformed layer is slightly lower than at the previous one. This is a consequence of the fact that the tooth comes into contact with the blank material heated to a lesser extent as a result of the operation of the previous teeth. Therefore, at the last moment of time, the yield strength σ_{st} is higher, as, consequently, are the cutting and friction forces, and the power and density of heat sources. For all milling modes, the values of the average and maximum temperature T_2 are higher at this moment of time than at the previous one. The blank temperature T_3, the temperature at the tooth tip T_E and the temperature of the deformed layer, are slightly lower at the last moment of time than at the previous one. The maximum value of temperature T_1 is higher at the last moment of time, and the average value of this temperature changes insignificantly. Therefore, the following dependencies for evaluating the process parameters were obtained for: the average value of temperature T_2 and force P_z recorded at the last moment of contact time; temperatures T_E and T_3 – at the previous moment; when calculating the average temperature T_1, the temperature averaged for two moments of time was used.

When machining thin-walled blanks, a mode should be used that ensures forces and temperatures that do not exceed those that occur when machining solid [14] blanks at maximum productivity.

The studies performed allow selecting the required mode. For example, if mode No. 6 according to Table 3 is used (t=0.5 mm; S_z=0.16 mm/tooth and V=120 m/min), then the force P_z, as well as the average and maximum values of temperatures T_1 and T_2 are expected to be lower than when machining a solid blank (Tables 2 and 3). In this case, the feed rate will decrease from 1.91 to 1.52 m/s, i.e. the productivity during processing of thin-walled blanks will slightly decrease. There are also other modes of processing thin-walled blanks providing lower forces P_z and temperatures in comparison with processing of a solid blank, however, under these modes, productivity decreases significantly.

It is difficult to provide recommendations concerning processing of thin-walled blanks due to the ambiguous influence of any mode element on the process parameters with various combinations of others. Therefore, to determine the rational mode, one can use the following dependencies obtained as a result of processing the results of numerical simulation:

$$\begin{aligned}T_1 &= 223.9+1141.3\cdot S_z+31.095\cdot V+272\cdot t-141.3\cdot S_z\cdot V-\\&-2400\cdot S_z\cdot t-30.68\cdot V\cdot t+355.56\cdot S_z\cdot V\end{aligned};$$

$$\begin{aligned}T_2 &= 1320+13110\cdot S_z+905{,}4\cdot V+4184\cdot t-5340\cdot S_z\cdot V-\\&-25900\cdot S_z\cdot t-16900\cdot V\cdot t+11000\cdot S_z\cdot V\end{aligned};$$

$$\begin{aligned}T_E &= 439.3+3820\cdot S_z+296.6\cdot V+1351\cdot t-1760\cdot S_z\cdot V-\\&-8600\cdot S_z\cdot t-576\cdot V\cdot t+3000\cdot S_z\cdot V\end{aligned};$$

$$\begin{aligned}T_3 &= 306.9+1110\cdot S_z+118.8\cdot V+525\cdot t-680\cdot S_z\cdot V-\\&-2500\cdot S_z\cdot t-188\cdot V\cdot t+800\cdot S_z\cdot V\cdot t\end{aligned};$$

$$\begin{aligned}P_z &= 37.12+1141.3\cdot S_z+6.52\cdot V+63.8\cdot t-62\cdot S_z\cdot V-\\&-70\cdot S_z\cdot t-23.2\cdot V\cdot t+220\cdot S_z\cdot V\cdot t\end{aligned}.$$

Using these dependencies, one can calculate the mode, at which the technological parameters, when processing a thin-walled blank, will not exceed the permissible values.

CONCLUSIONS

1. It has been found that during milling of thin-walled blanks, the temperature field differs significantly from that formed during processing of solid blanks.

2. Regularities in changing the parameters of the milling process of thin-walled blanks depending on the mode elements have been identified.

3. Mathematical dependencies describing the relationship between temperatures and cutting forces with the milling mode elements have been obtained.

4. The results of the research, and the obtained dependencies allow determining the processing mode for a thin-walled blank, at which the technological parameters, including temperatures, will not exceed the permissible values.

REFERENCES

1. Khudobin L.V., Khusainov A.Sh. *Shlifovanie zagotovok klinovidnykh izdeliy* [Grinding of blanks of wedge products]. Ulyanovsk, UlGTU Publ., 2007. 249 p.
2. Hishihara T., Okuyama S., Kawamura S., Hanasaki S. Study on the geometrical accuracy in surface grinding. Thermal deformation of workpiece in traverse grinding. *International journal Japanese society precision engineering*, 1993, vol. 59, no. 7, pp. 1145–1150. DOI: 10.2493/jjspe.59.1145.
3. Kuts V.V., Gridin D.S. Comprehensive study of the process of cutting screw grooves on the inner surface of a cylindrical thin-walled bronze bushing. *Izvestiya Tulskogo gosudarstvennogo universiteta. Tekhnicheskie nauki*, 2020, no. 10, pp. 72–79. EDN: PXWMTS.
4. Ladyagin R.V., Yakimov M.V Study of the effect of force and temperature in the process of high-speed cutting on the accuracy of treatment of the cylinder blade case. *Izvestia of Samara Scientific Center of the Russian Academy of Sciences*, 2020, vol. 22, no. 3, pp. 111–115. DOI: 10.37313/1990-5378-2020-22-3-111-115.
5. Lapshin V.P., Khristoforova V.V., Nosachev S.V. Relationship of temperature and cutting force with tool wear and vibration in metal turning. *Obrabotka metallov / Metal working and material science*, 2020, vol. 22, no. 3, pp. 44–58. DOI: 10.17212/1994-6309-2020-22.3-44-58.
6. Duan Zhenjing, Li Changhe, Ding Wenfeng et al. Milling Force Model for Aviation Aluminum Alloy: Academic Insight and Perspective Analysis. *Chinese Journal of Mechanical Engineering*, 2021, vol. 34, article number 18. DOI: 10.1186/s10033-021-00536-9.
7. Radu P., Schnakovszky C. A Review of Proposed Models for Cutting Force Prediction in Milling Parts with Low Rigidity. *Machines*, 2024, vol. 12, no. 2, article number 140. DOI: 10.3390/machines12020140.
8. Zawada-Michałowska M., Kuczmaszewski J., Legutko S., Pieśko P. Techniques for Thin-Walled Element Milling with Respect to Minimising Post-Machining Deformations. *Materials*, 2020, vol. 13, no. 21, article number 4723. DOI: 10.3390/ma13214723.
9. Eremeykin P.A., Zhargalova A.D., Gavryushin S.S. Problem of technological deformations of thin-walled workpieces during milling. *Obrabotka metallov / Metal working and material science*, 2019, vol. 21, no. 3, pp. 17–27. DOI: 10.17212/1994-6309-2019-21.3-17-27.
10. Kiselev E.S., Imandinov Sh.A., Nazarov M.V. Quality assurance features non-rigid aluminum blanks when milling with ultrasonic vibrations. *Izvestiya Volgogradskogo gosudarstvennogo tekhnicheskogo universiteta*, 2017, no. 12, pp. 14–17. EDN: ZVLFAR.
11. Vasilkov D.V., Aleksandrov A.S., Golikova V.V. Self-oscillations during cutting processing. *Sistemnyy analiz i analitika*, 2018, no. 3, pp. 25–35. EDN: YNNEGL.
12. Vorontsov A.L., Sultan-Zade N.M., Albagachiev A.Yu. Development of a new theory of cutting 7. Mathematical description of the formation of different chips, pulsation of the cutting force, and contact parameters of the machined billet surface and the rear cutter surface. *Russian Engineering Research*, 2008, vol. 28, no. 7, pp. 674–680. DOI: 10.3103/S1068798X08070101.
13. Chen Tao, Liu Jiaqiang, Liu Gang, Xiao Hui, Li Chunhui, Liu Xianli. Experimental Study on Titanium Alloy Cutting Property and Wear Mechanism with Circular-arc Milling Cutters. *Chinese Journal of Mechanical Engineering*, 2023, vol. 36, article number 57. DOI: 10.1186/s10033-023-00887-5.
14. Balyakin A.V., Khaymovich A.I., Chempinskiy L.A. Modeling of the high-speed milling of titanium alloy VT-9. *Izvestia of Samara Scientific Center of the Russian Academy of Sciences*, 2013, vol. 15, no. 6-3, pp. 572–583. EDN: SHQPHB.
15. Evdokimov D.V., Skuratov D.L., Bukatyy A.S. Technological residual deformations prediction of GTE blades by numerical method after end milling. *Izvestia of Samara Scientific Center of the Russian Academy of Sciences,* 2022, vol. 24, no. 1, pp. 11–19. DOI: 10.37313/1990-5378-2022-24-1-11-19.
16. Vasilkov D.V., Aleksandrov A.S., Golikova V.V. Rheology of contact interactions during cutting processing. *Sistemnyy analiz i analitika*, 2018, no. 2, pp. 13–20. EDN: YVMXEW.

17. Unyanin A.N., Semdyankin I.V. Modeling of parameters and temperature field of the process of milling blanks of thin-walled parts with different feed speeds. *Vestnik Ulyanovskogo gosudarstvennogo tekhnicheskogo universiteta*, 2021, no. 1, pp. 40–43. EDN: TCGJNX.
18. Zhilyaev A.S., Kugultinov S.D. Mathematical simulation of thermal processes when milling aluminum alloy formed parts. *Vestnik Koncerna VKO "Almaz – Antey"*, 2019, no. 2, pp. 65–70. EDN: FKRVYF.
19. Vorontsov A.L., Sultan-Zade N.M., Albagachiev A.Yu. Development of a new theory of cutting 9. Practical calculations of cutting parameters in turning. *Russian Engineering Research*, 2008, vol. 28, no. 9, pp. 878–888. DOI: 10.3103/S1068798X08090116.
20. Reznikov A.N., Reznikov L.A. *Teplovye protsessy v technologicheskikh sistemakh* [Thermal processes in manufacturing systems]. Moscow, Mashinostroenie Publ., 1990. 288 p.
21. Unyanin A.N. Analytical research on the temperature field at milling with ultrasonic oscillations superposition. *Vestnik RGATU im. P.A. Soloveva*, 2017, no. 2, pp. 229–235. EDN: YPZFHX.

СПИСОК ЛИТЕРАТУРЫ

1. Худобин Л.В., Хусаинов А.Ш. Шлифование заготовок клиновидных изделий. Ульяновск: УлГТУ, 2007. 249 с.
2. Hishihara T., Okuyama S., Kawamura S., Hanasaki S. Study on the geometrical accuracy in surface grinding. Thermal deformation of workpiece in traverse grinding // International journal Japanese society precision engineering. 1993. Vol. 59. № 7. P. 1145–1150. DOI: 10.2493/jjspe.59.1145.
3. Куц В.В., Гридин Д.С. Комплексное исследование процесса нарезания винтовых канавок на внутренней поверхности цилиндрической тонкостенной бронзовой втулки // Известия Тульского государственного университета. Технические науки. 2020. № 10. С. 72–79. EDN: PXWMTS.
4. Ладягин Р.В., Якимов М.В. Исследование влияния силы и температуры в процессе высокоскоростного резания на точность обработки гильзы блока цилиндров // Известия Самарского научного центра Российской академии наук. 2020. Т. 22. № 3. С. 111–115. DOI: 10.37313/1990-5378-2020-22-3-111-115.
5. Лапшин В.П., Христофорова В.В., Носачев С.В. Взаимосвязь температуры и силы резания с износом и вибрациями инструмента при токарной обработке металлов // Обработка металлов (технология, оборудование, инструменты). 2020. Т. 22. № 3. С. 44–58. DOI: 10.17212/1994-6309-2020-22.3-44-58.
6. Duan Zhenjing, Li Changhe, Ding Wenfeng et al. Milling Force Model for Aviation Aluminum Alloy: Academic Insight and Perspective Analysis // Chinese Journal of Mechanical Engineering. 2021. Vol. 34. Article number 18. DOI: 10.1186/s10033-021-00536-9.
7. Radu P., Schnakovszky C. A Review of Proposed Models for Cutting Force Prediction in Milling Parts with Low Rigidity // Machines. 2024. Vol. 12. № 2. Article number 140. DOI: 10.3390/machines12020140.
8. Zawada-Michałowska M., Kuczmaszewski J., Legutko S., Pieśko P. Techniques for Thin-Walled Element Milling with Respect to Minimising Post-Machining Deformations // Materials. 2020. Vol. 13. № 21. Article number 4723. DOI: 10.3390/ma13214723.
9. Еремейкин П.А., Жаргалова А.Д., Гаврюшин С.С. Проблема технологических деформаций при фрезерной обработке тонкостенных заготовок // Обработка металлов (технология, оборудование, инструменты). 2019. Т. 21. № 3. С. 17–27. DOI: 10.17212/1994-6309-2019-21.3-17-27.
10. Киселёв Е.С., Имандинов Ш.А., Назаров М.В. Особенности обеспечения качества нежестких алюминиевых заготовок при фрезеровании с наложением ультразвуковых колебаний // Известия Волгоградского государственного технического университета. 2017. № 12. С. 14–17. EDN: ZVLFAR.
11. Васильков Д.В., Александров А.С., Голикова В.В. Автоколебания при обработке резанием // Системный анализ и аналитика. 2018. № 3. С. 25–35. EDN: YNNEGL.
12. Воронцов А.Л., Султан-Заде Н.М., Албагачиев А.Ю. Разработка новой теории резания. 7. Математическое описание образования стружки разных видов, пульсации сил резания и параметров контакта обработанной поверхности заготовки с задней поверхностью резца // Вестник машиностроения. 2008. № 7. С. 56–60. EDN: JVNRFJ.
13. Chen Tao, Liu Jiaqiang, Liu Gang, Xiao Hui, Li Chunhui, Liu Xianli. Experimental Study on Titanium Alloy Cutting Property and Wear Mechanism with Circular-arc Milling Cutters // Chinese Journal of Mechanical Engineering. 2023. Vol. 36. Article number 57. DOI: 10.1186/s10033-023-00887-5.
14. Балякин А.В., Хаймович А.И., Чемпинский Л.А. Моделирование режима высокоскоростного фрезерования титанового сплава ВТ-9 // Известия Самарского научного центра Российской академии наук. 2013. Т. 15. № 6-3. С. 572–583. EDN: SHQPHB.
15. Евдокимов Д.В., Скуратов Д.Л., Букатый А.С. Расчетное прогнозирование технологических остаточных деформаций лопаток ГТД на этапе концевого фрезерования // Известия Самарского научного центра Российской академии наук. 2022. Т. 24. № 1. С. 11–19. DOI: 10.37313/1990-5378-2022-24-1-11-19.
16. Васильков Д.В., Александров А.С., Голикова В.В. Реология контактных взаимодействий при обработке резанием // Системный анализ и аналитика. 2018. № 2. С. 13–20. EDN: YVMXEW.
17. Унянин А.Н., Семдянкин И.В. Моделирование параметров и температурного поля процесса фрезерования заготовок тонкостенных деталей с различными скоростями подач // Вестник Ульяновского государственного технического университета. 2021. № 1. С. 40–43. EDN: TCGJNX.
18. Жиляев А.С., Кугультинов С.Д. Математическое моделирование тепловых процессов при фрезеровании сложнопрофильных деталей из алюминиевых сплавов // Вестник Концерна ВКО «Алмаз – Антей». 2019. № 2. С. 65–70. EDN: FKRVYF.

19. Воронцов А.Л., Султан-Заде Н.М., Албагачиев А.Ю. Разработка новой теории резания. 9. Практические расчеты параметров резания при точении // Вестник машиностроения. 2008. № 9. С. 67–76. EDN: JVNSAD.
20. Резников А.Н., Резников Л.А. Тепловые процессы в технологических системах. М.: Машиностроение, 1990. 288 с.
21. Унянин А.Н. Аналитическое исследование температурного поля при фрезеровании с наложением ультразвуковых колебаний // Вестник РГАТУ им. П.А. Соловьева. 2017. № 2. С. 229–235. EDN: YPZFHX.

Влияние элементов режима резания на технологические параметры процесса фрезерования заготовок тонкостенных деталей из титанового сплава

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Аннотация: Назначение рационального режима процесса механической обработки остается актуальной задачей технологической подготовки производства. Известные рекомендации и методики назначения этого режима ориентированы на обработку массивных заготовок и не учитывают того обстоятельства, что при обработке тонкостенных заготовок температуры в зоне обработки и поверхностном слое заготовки отличаются. Исследование направлено на выявление закономерностей в изменениях параметров процесса фрезерования заготовок тонкостенных деталей в зависимости от элементов режима, а также разработку рекомендаций по назначению этого режима. Выполнено численное моделирование технологических параметров процесса фрезерования заготовок массивных и тонкостенных деталей из титанового сплава при различных режимах. Варьировали скорость резания, глубину резания и подачу на зуб фрезы. Рассчитывали силу резания, мощности и плотности источников тепловыделения и температуру в поверхностном слое заготовки, в зонах контакта зуба фрезы с заготовкой и стружки с передней поверхностью зуба. Установлено, что при фрезеровании заготовок тонкостенных деталей температурное поле значительно отличается от формирующегося при обработке массивных заготовок из-за низкого теплоотвода от необрабатываемой поверхности. Увеличение подачи на зуб на 45 % приводит к незначительному снижению температур в зоне резания (на 5…12 %). Увеличение скорости резания на 25 %, напротив, приводит к росту температур на 5…10 %. Увеличение глубины резания приводит к увеличению температуры в зоне контакта стружки с зубом в 1,5 раза, а также к увеличению температуры в зоне контакта зуба с заготовкой.

Ключевые слова: режим резания; технологические параметры процесса фрезерования; температурное поле; предел текучести; тонкостенная заготовка; сила резания; температура в зоне резания.

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