THE SURFACE GRINDING OPTIMIZATION OF TITANIUM PARTS WITH DIFFERENT STIFFNESS GIVEN THE PROCESS STABILITY

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Abstract

This paper considers improving the surface grinding of parts with different stiffness from the titanium alloy VT22 given the process stability based on the multi-criteria optimization according to the performance criteria. The part surface quality includes roughness, flatness deviations, micro hardness, relative supporting portion of surface and standard deviation. The variation ranges of the process parameters are as follows: wheel speed \( v_{wh} = 28 \text{m/min} \), longitudinal feed \( s_{long} = 5 - 18 \text{ m/min} \), transverse feed \( s_{tr} = 2 - 10 \text{ mm/ double stroke} \), depth of cut \( t = 0.005 - 0.02 \text{ mm} \), operational allowance \( z = 0.1 - 0.3 \text{ mm} \). It has been established that the optimal grinding conditions of completely rigid parts given the stability of the process, have not only reduced the standard deviation of the basic parameters by 1.7 times as compared with optimization without taking them into account, but also the basic time of transition by 1.6 times as compared with the recommended standards of grinding. When optimizing the pliable parts grinding (with stiffness \( j = 350 - 11,220 \text{ N/mm} \)), the reduction of high-rise indicators of their surface roughness by 1 – 2 categorical magnitudes, the standard deviation by 2 times, the basic machining time by 1.2 times for the rough stage, and by 1.2 – 3.3 times for the finishing stage compared to the grinding of the completely rigid parts has been noted. The non-rigid parts of titanium alloys should be ground in the longitudinal direction of its variation (by vector \( s_{long} \)). It has been determined that the optimum grinding condition of non-rigid parts allows reducing the main operation time by 4.9 times compared to the standard specifications for completely rigid parts, mainly by increasing \( t \) and reducing \( z \). The results obtained should be used in the robust design of grinding operations.

Keywords: Grinding; optimization; process stability; non-rigid parts; titanium alloy; surface topography.
I. Introduction

Nowadays, at the stage of the production preparation process, the design of operations, including grinding operations is carried out according to the standardized rules of the cutting modes in machine building industry [XIV, VI, I]. However, these documents were developed a few years ago, and cover only a part of the grinding wheels range and do not adequately reflect the design features of the part. With the advent of the grinding tools of the new generation, the problem of their selection connected with the appropriate parameters of the grinding condition emerges since the manufacturers provide consumers only with that data about the grinding wheels that are indicated on their markings [V, XI]. In general, the quality of the parts surface depends more on the finishing machining that should be carefully prepared.

The optimization of the production process is the choice of such control option when the extreme value of criterion that characterizes the quality control is achieved. With this, the optimality criterion (goal function) means the criterion that determines the process quality control. The optimization problem is reduced to finding the extremum of the goal function [XVII].

When optimizing the production process, the criteria of optimality in the form of economic evaluation is used most frequently. With this, the task of grinding process optimality is usually the quality improvement or the required quality provision when improving the process performance. During the grinding process improvement, the optimization on the set of surface quality parameters, taking into account the stability of their formation is equally important.

Modern approaches to the grinding process optimization are based on the basis of artificial intelligence and regression analysis. Among the first direction, the artificial neural networks (ANN) became widely used. *Sathya narayanan* at al. [XIX] used the neuron-network approach to modeling and optimizing the creep-feed grinding of the alloy Ti-6Al-4V and inconel 718. The neural network can be trained to link inputs (supply, depth of cut and type of link) with outputs (surface treatment, force and power), predicting their magnitudes. The optimization results were presented in the form of decision tables and cost diagrams for decision support. *Liao and Chen* in their paper [XIII] also showed the possibility of using ANN for modeling and optimizing the diamond-grinding processes. It was found that ANN had provided the more accurate process of modeling than the regression method and could effectively generate global optimal solutions. The authors Havilah and Limareno [XII] pay special attention to the completeness of the input data for creating the model and adherence to the relationship and influence of input parameters on the result, as well as full consideration of all the technological constraints of the cutting process. However, when optimizing the ANN-based processes, there is no transparency of the information stored inside the ANN and the adequate network design development efforts. The said reduces the effectiveness of the decision (optimization) [III].

To eliminate the indicated shortcomings of artificial intelligence, the regression approach is used with grinding optimization, for example, using the program *Design Expert* [XV]. The paper's authors [II] used this approach for predicting and optimizing the surface roughness when grinding parts made of ceramic material by...
the electrocorundum wheel. The obtained equation in the normalized form gives the error of 3.17%.

It is known that the mechanisms and components of modern machines use a large range of non-rigid parts with thin walls. During machining, under the action of cutting forces, they are subjected to elastic deformation decreasing the performance and machining accuracy. Blades, discs and rings of turbines axial compressors made of titanium alloys [XVIII,IV] are used for manufacturing aircraft.

This study considers improving the surface grinding of parts with different pliability from the titanium alloy VT22 based on the optimization of machining performance when achieving their desired quality given the process stability.

II. Methodology

Full-scale experiments were carried out on the surface-grinding machine of the Model 3E711B. The subject of the study were the samples made of high-strength titanium alloy VT22 (GOST 19807-91) with dimensions \( B \times L \times H = 40 \times 40 \times 50 \) mm grinding along plane \( B \times L \). The samples under study were preliminary ground along the base and surfaces being studying to avoid the effects of the technological heredity. For modeling the parts stiffness, the frame structure accessory is used [XX] that by changing the ribs height and tightening them by bolts at different heights from the installation base made it possible to vary its pliability. The latter one was extended to the workpiece that remained unchanged in size and shape. In course of the study, three levels of stiffness \( j \) were used:

- \( j \in [380; 4174] \) N/mm – low-stiff;
- \( j \in [4174; 7426] \) N/mm – medium-stiff;
- \( j \in [7426; 11220] \) N/mm – high-stiff.

The latter subgroup obtained such name conventionally since it has a greater pliability compared with the completely rigid ones, reviewed above. Due to the rotation of the fixture, the variations of parts pliability in two mutually orthogonal directions \( w = 1; 2 \) coincident with the feed vectors were provided: 1 – in the direction of transverse feed \( s_{tr} \), 2 – in the direction of longitudinal feed \( s_{long} \). The parts were conventionally considered as completely rigid \( (j \rightarrow \infty) \) when they were secured with clamps on the base plate mounted directly on the machine table. Except \( s_{long} \) and \( s_{tr} \) feeds, the models have depth of the cut \( t \), operational allowance \( z \), and the part stiffness \( j \). The last two parameters are usually absent in cutting modes standards.

It is known that process modeling is the first necessary step for optimizing its parameters. For this purpose, grinding was conducted when varying the input factors according to \( D \) - optimal plan. With this, the variation ranges of the process-dependent parameters are shown in Table 1 [XX].
Table 1: Intervals of factors variation in the natural and normalized types when grinding alloy VT22

| Factors                       | Intervals of variations | Factor levels |
|-------------------------------|-------------------------|---------------|
|                               | lower (-1.0) | principle (0.0) | upper (+1.0) |
| A-longitudinal feed \(s_{\text{long}}\), m/min | 6.5          | 5             | 11.5          | 18           |
| B - transverse feed \(s_{\text{tr}}\), mm/double stroke | 4            | 2             | 6             | 10           |
| C - depth of cut \(t\), mm    | 0.0075        | 0.0050        | 0.0125        | 0.0200       |
| D - operational allowance \(z\), mm | 0.1          | 0.1           | 0.2           | 0.3          |
| \(E_r\) - stiffness \(j_{r}\), N/mm | 5,420         | 380           | 5,800         | 11,220       |

Note. Stiffness variation \(E_r (j_{r})\), \(r = 1; 2\) is included in regression only when examining non-rigid parts.

The search for regression models was then carried out for the quality output parameters of the parts under study that included roughness parameters according to GOST 2789-73 [XVI]: \(R_a, R_q, R_z, R_{\text{max}}, S, S_m, t_p, p = 5; 95\%\); shape accuracy indices [VIII]: \(EFE_{\text{max}}, EFE_a, EFE_q\); microhardness \(HV\) and the relative supporting portion (RSP) of surface \(t_M\) suggested by us [XXI].

The latter parameter of \(t_M\) should be determined by the methodology we have developed, called the digital topography. It includes four stages: application of paints to indicate cavities of coarse irregularities; macro photography of the painted surface; the photo file conversion and its transfer to a bitmap with a limited number of possible hues maximum 16; bitmaps processing and definition of RSP surface indicator from the expression [XXI]:

\[
t_{\text{M}} = \frac{1}{n} \left( \sum_{\theta} \left( 1 - \frac{P_{\text{red}}}{\sum P_{k}} \right) \right) \times 100\%,
\]

where \(t_{\text{M}}\) is the average RSP for all experiments in %; \(\sum P_{k}, \sum P_{\text{red}}\) - respectively, the number of pixels of all colors at \(K \leq 16\) and the red spectrum for each \(\theta = 1/n\).
Fig. 1: Photo files of the part surface: a - original photo file, b - photo file represented by a 16-bit colored picture: 1 - cavities of coarse irregularities, 2 - more level zone

As an example you can see the photo files of the part grinding surface made of VT22 under the grinding conditions: $A = D = 0; B = -1; C = 1$ which are divided into two zones: 1 is the cavity of coarse irregularities, 2 is more level zone that forms the supporting portion of the surface (Figure 1). According to their analysis results, the relative supporting portion of the surface is calculated according to (1): $t_{fM} = 48.63\%$. The average RSP of the surface at this point of $D$-optimal experiment at $n = 3$ is 50.52\%.

To study the stability of the grinding process, the standards deviation $SD$ for the quality basic parameters are additionally used: $SD (R_a)$, $SD (R_{max})$, $SD (S_m)$, $SD (EFE_{max})$, $SD (EFE_n)$, $SD (EFE_q)$, $SD (HV)$, $SD (t_{sp})$. Based on the models obtained, the grinding process has been optimized.

In conditions of optimization, the increase in efficiency of the machining process is conditioned upon the reduction in time of the main (machine) $T_0$ calculated from the expression [II]:

$$T_0 = \frac{l_{gr}B_{gr}}{1000\omega_{m}^{14}(\varepsilon/2)^{1/4}}, \text{min,}$$

where $l_{gr} = (l + l_{cut-in} + l_{over})$ is a grinding length, mm; $l$ is a length of the grinding surface, mm; $l_{cut-in}$ is a length of cut-in, mm; $l_{over}$ - over travel length, mm; $B_{gr} = B + 2T + 10$ - grinding width, mm; $T$ - height of the wheel, mm; $i$ - the number of spark-out passes.

In this case $l_{gr} = 40 + 30 = 70 \text{ mm}$; $B_{gr} = 40 + 2\times20 + 10 = 90 \text{ mm}$; $i = 0$ (work without spark-out at the end of the cycle). The rest process parameters are set given the quality of the grinding parts according to the reference literature or optimization results.

To evaluate the efficiency of the selected optimization variant for improving the grinding process performance, the coefficient $k_e$ is used which is defined from the expression:

$$k_e = \frac{T_0(\text{stand})}{T_0},$$

Where $T_0(\text{stand})$ is a processing time of the standard sample, min.
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where \( T_{0(\text{stand})} \) is the basic time calculated according to the standards; \( T_0 \) is the basic time based on the optimization results.

Main results and their discussion.

As shown in the works [VI, XVI], the titanium alloys grinding by the traditional wheels given the quality of grinding surfaces is divided into three stages: rough, finishing and final (Table 2), to each of which different requirements are imposed.

Table 2: Parts surface quality from the titanium alloys after surface grinding [VI, XVI]

| Parameter \( R_a, \mu m \) | Processing stage          |
|----------------------------|---------------------------|
|                            | rough                     | finishing                  | final                      |
| 2.5 – 0.63                 | 0.63 – 0.32               | 0.32 – 0.16                |
| \( EFE_{\text{max}}, \mu m \) | 25 – 16 (TFE8 – TFE7)     | 10 (TFE6)                 | 6 (TFE5)                  |

Note. In the parentheses the accuracy degree according to GOST 24643-81 [IX] is specified.

It has been found that under these grinding conditions of the completely rigid parts, their quality corresponds to the rough and finishing stages of machining. In accordance with this, according to standards [VI] the basic transition time (2) was calculated as follows:

for the rough stage \( T_{0(\text{stand})} = \frac{70 \times 30 \times 0.35}{1000 \times 32 \times 8 \times 0.013} = 0.22 \text{ min} \);

for the finishing stage \( T_{0(\text{stand})} = \frac{70 \times 30 \times 0.25}{1000 \times 32 \times 3 \times 0.007} = 0.78 \text{ min} \).

Initially, let's consider the optimization of these stages when grinding completely rigid parts from VT22 alloy. To achieve high performance, the following goal functions are specified when ensuring the following quality of the parts: for technology factors - maximization for \( s_{\text{long}}, s_{\text{str}}, t \), minimization for \( z \); for \( R_a \) and \( EFE_{\text{max}} \) restrictions based on the machining stage are specified: for rough stage - \( R_a \) to 2.5\( \mu m \), \( EFE_{\text{max}} \) not more than 25 \( \mu m \) (up to TFE8); for finishing stage - \( R_a \) to 0.63\( \mu m \), \( EFE_{\text{max}} \) max. 10 \( \mu m \) (up to TFE6). It is known that in order to improve the operational properties of machine parts, it is desirable to minimize the parameters \( R_c, R_s, R_{\text{max}}, S_m, S, EFE_{\text{as}}, EFE_{\text{q}} \) and maximize the parameters \( t_p \) \((p=5;95), HV, t_{\text{M}}\). For the latter group of parameters there is no any information in the construction documents, so they were specified with corresponding goal functions of ‘minimization’ and ‘maximization’.

To increase the stability of output parameters formation, the goal function ‘minimization’ has been chosen for the standard deviations \( SD(R_a), SD(R_{\text{max}}), SD(S_m), SD(EFE_{\text{as}}), SD(EFE_{\text{q}}), SD(HV), SD(t_{\text{M}}) \).

As an example, when grinding non-rigid parts in the transverse direction of the pliability variation the models for the parameter \( t_{\text{M}} \) according to the averages and standard deviation are presented:
\[ \hat{t}_{fM(1)} = (7.15 - 0.44A - 1.24B - 0.75C - 0.43D - 0.24AE_1 - 0.52BD - 1.28E_1^2)^2, \%; \]

(4)

\[ \overline{SD}_{fM(1)} = (2.85 - 0.075A - 0.19B - 0.059C - 0.11D - 0.12AD - 0.32AE_1 - 0.16BC + 0.18BD - 0.13BE_1 + 0.11CE_1 - 0.14DE_1 - 0.36B^2 - 0.21E_1^2)^2, \% . \]

(5)

Based on Eq. (4) and (5), the surface responses are built \( \hat{t}_{fM(1)} \) and \( \overline{SD}_{fM(1)} \) depending on the variation of the longitudinal feed and the transverse stiffness of the parts (Figure 2).

It has been found that finishing grinding makes it possible to increase \( \hat{t}_{fM(1)} \) by 3-4 times (Figure 2, c, d) with compared to the rough grinding (Figure 2, a, b). In this case, the highest \( \hat{t}_{fM(1)} \) take place at \( A = -1, E_1 = 0 \). The increase in scattering of observations during finishing grinding (Figure 2, g, h) is most likely conditioned upon the decrease in elastic preload between the abrasive tool and workpiece. The noncoincidence of the desired extremums for the reference value \( \hat{t}_{fM(1)} \) and its standard deviation \( \overline{SD}_{fM(1)} \) that causes the need for multivariate optimization of the parts surface topography taking into account the averages and stability of their formation have been determined.

Fig. 2: Effect of the longitudinal feed \( A \) and stiffness \( E_1 \) on \( \hat{t}_{fM(1)} \) and \( \overline{SD}_{fM(1)} \) under different grinding conditions: a, c – \( B = C = D = +1 \); b, f – \( B = C = +1, D = -1 \); c, g – \( B = C = -1, D = +1 \); d, h – \( B = C = D = -1 \)

To achieve high performance, the optimization is more focused on input parameters. Their ranks \( R \), assigned to the goal functions based on their importance in making the decision, are the highest at \( R = 5 \). Degree of the weights function - \( n = [10; 1] \) is for the goal function ‘maximization’ and \( n = [1; 10] \) is for the goal function ‘minimization’. For the rest output parameters \( n \) and \( R \) the programs [1; 1] and 3 respectively are set by default.

During optimization performed by the software Design Expert many solutions meeting the preset conditions has been obtained. Of these, you can choose the optimal solution using the desirability function \( d \), that varies from zero to one. The increase in function \( d \) corresponds to a better optimization of the grinding process.
Table 3 presents the best results of the optimization given the basic surface quality parameters per averages and their SD at rough and finishing stages of the surface grinding of the completely rigid parts under the conditions: 1 - without the process stability control (goal functions for SD are specified ‘within the range’); 2 - taking into account the quality stability control of the parts (goal functions for SD- ‘minimization’). As seen from Table 3, with two variants of optimization, the basic machining time according to (2) turned to be unchanged. However, when grinding in condition 2, the formation stability of the surface topography main parameters increased to 1.66 times. According to the predicted averages, the above said was noted according to accuracy indices by 1.03 - 1.05 times. As for microhardness and \( t_{fM} \), the unfavorable decrease by 1.008 and 1.017 times respectively was noted. Compared with grinding according to the standards [1; 2], the optimal mode of rough grinding made it possible to reduce the basic time on \( k_{q_b} \) by \( 0.22/0.14 = 1.57 \) times.

For finishing grinding with accuracy control in both modes, the optimization results are shown in Table 3. It is seen from it that in condition 2, the basic time \( T_{02(\text{finish})} = 0.53 \) min turned to be 1.1 times more than \( T_{01(\text{finish})} \) taking place during grinding mode 1 with function "within range". When optimizing SD with function ‘minimization’, the decrease of deviations standards to 1.6 times for the most surface topography parameters has been predicted. The said has been violated in two cases: for \( \overline{SD}(EFE_{\max}) \) and \( \overline{SD}(HV) \). For \( \overline{SD}(EFE_{\max}) \) 4.56 \( \mu m \) were predicted at the 1st finishing mode of optimization and 4.54 \( \mu m \) at the 2nd finishing mode respectively, that is almost equal.

### Table 3. The quality expected parameters and their formation stability at optimal conditions for surface grinding of the completely rigid parts from alloy VT22

| Parameter | The expected average during optimization | Parameter | The expected average during optimization |
|-----------|----------------------------------------|-----------|----------------------------------------|
| \( R_{a1} \), \( \mu m \) | 1.29 (1.60) 1.26 (1.60) | \( EFE_{aq} \), \( \mu m \) | 6.52 (TFE6) 6.36 (TFE6) |
| \( \overline{SD}(R_{a1}) \), \( \mu m \) | 0.11 0.086 | \( \overline{SD}(EFE_{aq}) \), \( \mu m \) | 0.83 0.57 |
| \( R_{\max1} \), \( \mu m \) | 7.35 (8.0) 7.36 (8.0) | \( EFE_{aq} \), \( \mu m \) | 7.15 (TFE6) 6.89 (TFE6) |
| \( \overline{SD}(R_{\max1}) \), \( \mu m \) | 0.86 0.80 | \( \overline{SD}(EFE_{aq}) \), \( \mu m \) | 0.98 0.66 |
| \( S_{nt}(2) \), \( \mu m \) | 96.36 (100) 96.36 (100) | \( HV \), MPa | 3,410.92 3,382.43 |
| \( \overline{SD}(S_{nt}(2)) \), \( \mu m \) | 7.41 4.47 | \( \overline{SD}(HV) \), MPa | 173.38 108.26 |
| \( EFE_{\max} \), \( \mu m \) | 11.99 (TFE7) 11.46(TFE7) | \( t_{fM} \), % | 29.74 29.25 |
| \( \overline{SD}(EFE_{\max}) \), \( \mu m \) | 1.69 1.12 | \( \overline{SD}(t_{fM}) \), % | 3.54 3.35 |
**Finishing stage:** \( s_{np} = 8.85 \text{ m/min}; \, s_n = 10.00 \text{ mm/double stroke}; \, t = 0.01 \text{ mm}; \, z = 0.10 \text{ mm} (T_{01} = 0.48 \text{ min}) - d = 0.234; \, **s_{long} = 11.9 \text{ m/min}; \, s_{er} = 10 \text{ mm/double stroke}; \, t = 0.01 \text{ mm}; \, z = 0.15 \text{ mm} (T_{02} = 0.53 \text{ min}) - d = 0.313

| \( R_{a1} \), \( \mu m \) | 0.62 (0.63) | 0.62 (0.63) | \( EFE_{av} \), \( \mu m \) | 2.58 (TFE4) | 2.67 (TFE4) |
|--------------------------|-------------|-------------|----------------|--------------|--------------|
| \( SD(R_{a1}) \), \( \mu m \) | 0.04 | 0.03 | \( SD(EFE_{av}) \), \( \mu m \) | 0.59 | 0.43 |
| \( \bar{R}_{max1} \), \( \mu m \) | 3.53 (4.0) | 3.69 (4.0) | \( EFE_{av} \), \( \mu m \) | 2.86 (TFE4) | 2.94 (TFE4) |
| \( SD(R_{max1}) \), \( \mu m \) | 0.20 | 0.20 | \( SD(EFE_{av}) \), \( \mu m \) | 0.59 | 0.37 |
| \( Sm(2) \), \( \mu m \) | 85.88 (100) | 88.60 (100) | \( HV \), MPa | 3,160.34 | 3,202.61 |
| \( SD(Sm2) \), \( \mu m \) | 14.93 | 12.56 | \( SD(HV) \), MPa | 60.65 | 80.96 |
| \( EFE_{max} \), \( \mu m \) | 4.56 (TFE5) | 4.54 (TFE5) | \( t_{fM} \), % | 37.79 | 44.91 |
| \( SD(EFE_{max}) \), \( \mu m \) | 0.64 | 0.65 | \( SD(t_{fM}) \), % | 5.52 | 4.50 |

Note. In parantheses for roughness, the categorical value according to GOST 2789-73 [X] is indicated; and for flatness deviations, the accuracy degree is indicated according to GOST 24643-81 [IX]. "*" corresponds to the 1st grinding condition; "**" - 2nd grinding condition.

According to results of optimizing the finishing grinding of completely rigid parts from the VT22 alloy the basic transition time (2) has been increased by 1.47 times as compared to the grinding condition recommended according to [XIV; VI]. At the same time, the accuracy of the parts shape per one accuracy degree has been increased (up to TFE5).

It is known that the integral function of desirability \( d \) is a product of the partial (differential) functions of desirability for all parameters of surface topography and grinding conditions. From Figure 3, it can be seen that the integral function of desirability during multi-criteria optimization of the rough grinding of the completely rigid parts according to the 2nd variant turned to be comparably low: \( d = 0.617936 \). The above said is due to the fact that some of the differential functions of desirability for parameters: \( t_{fM} \), \( SD(R_{max1}) \), \( Sm \) are predicted well below the unit.

**Fig. 3:** Functions of desirability when optimizing the rough grinding stage of the completely rigid parts from VT22 alloy

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Below you can see the results of optimizing the surface grinding of parts with different stiffness $j_w$, $w = 1; 2$ given the increase in stability of basic quality parameters (condition 2) formation.

At preliminary assessment it is seen that the arithmetic mean deviation of the profile $R_a(1)$ for such parts turned to be less than for completely rigid parts (Table 3): for parts of the transverse pliability $R_a(1)$ varied within the range $[0.21; 0.87]$ μm; and for parts of longitudinal pliability - $[0.23; 0.94]$ μm. When considering the accuracy of the pliable parts, it can be seen that the maximum deviations from flatness $EFE_{max}$ have been predicted in the interval $[TFE5 - TFE8]$. This allows us to optimize the final stage of grinding under the provision of the following conditions: $R_a(1)w \in [0.32; 0.16]$ μm, $w = 1; 2$, $EFE_{max}$ not more TFE5.

The Table 4 shows the results of optimizing the surface grinding of titanium low-stiff parts. Their stiffness varied in two mutually orthogonal directions $w = 1; 2$ at all stages of machining. In this case, the $SD$ setting was conducted only in condition 2 (Table 3) that revealed the advantages of grinding the completely rigid workpieces from VT22 alloy. The presented results of optimization show that during the preliminary grinding the machining conditions, with variable stiffness in both directions, coincided. They are characterized by the highest $s_{long}^{str}$ at minimum $z$ that has resulted in the increase in the coefficient $k_e$ (3) compared to the normative process almost twofold. The pliability direction of the low-stiff titanium-based workpieces during rough grinding affected only the output parameters of the surface topography, especially the form accuracy that has been increased up to two accuracy degrees for workpieces with longitudinal variable of low stiffness. At the same time, the decrease in the standard deviation $SD(EFE_{max}, EFE_{a}, EFE_{q})$ to 2.5-4.0 times was noted. It should be noted that the parameter $t_{AM2}$ increased favorably by 1.4 times and the stability of its formation increased by 5 times. Averages $(R_{a1}, R_{mat1})w$, $w = 1; 2$ remained unchanged within categorical magnitudes (CM), as well as microhardness. However, their standards of formation decreased by 29.5-30% at small variable stiffness $j_1$.

### Table 4: The quality predicted basic parameters and stability of their formation according to the results of surface grinding optimization of low-stiff parts from alloy VT22

| $w$ | Technology factors | Surface quality parameters | $d$ | $T_\alpha$, min | $k_e$ (3) |
|-----|-------------------|----------------------------|-----|----------------|---------|
|     | Rough grinding    |                            |     |                |         |
| 1   | $s_{np} = 18.00$ m/min; $s_a = 10, 3,00$ mm/double stroke; $t = 0.02$ mm; $z = 0.10$ mm; $j_1 = 380$ N/mm | $\bar{R}_{a11}$ 0.75 (0.80) $\bar{SD}(R_{a11})$ 0.07 | 0.51 | 0.12 | 1.89 |
|     | $\bar{R}_{mat1}$ 4.19 (5.0) $\bar{SD}(R_{mat1})$ 0.43 | $S_{n21}$ 107.93 (125) $\bar{SD}(S_{n21})$ 22.02 | $EFE_{mat1}$ 15.56 (16.00) $\bar{SD}(EFE_{mat1})$ 2.30 | $EFE_{a1}$ 10.91 (11.50) $\bar{SD}(EFE_{a1})$ 2.4 |
| Step | Condition | Value | Standard Error | Value | Standard Error |
|------|-----------|-------|----------------|-------|----------------|
| 1    | \( s_{np} = 18.00 \text{ m/min}; \) \( s_{a} = 10, \) 3.00 mm/ double stroke; \( t = 0.02 \text{ mm}; \) \( z = 0.10 \text{ mm}; \) \( j = 380 \text{ N/mm} \) | \[ \begin{align*} R_{al1} & = 0.58 \text{ (0.63)} \\ R_{max1} & = 3.34 \text{ (4.0)} \\ Sm_{21} & = 107.93 \text{ (125)} \\ EFE_{max1} & = 9.99 \text{ (TFE6)} \\ EFE_{al1} & = 6.96 \text{ (TFE6)} \\ EFE_{al2} & = 7.45 \text{ (TFE6)} \\ HV_{al1} & = 3.316,46 \text{ (SD(HV)1)} \\ t_{al1} & = 34.12 \text{ (SD(tal1))} \end{align*} \] | 0.35 | 0.39 | 2.00 |
| 2    | \( s_{np} = 12.95 \text{ m/min}; \) \( s_{a} = 10.00 \text{ mm/ double stroke}; \) \( t = 0.02 \text{ mm}; \) \( z = 0.10 \text{ mm}; \) \( j = 380 \text{ N/mm} \) | \[ \begin{align*} R_{al2} & = 0.63 \text{ (0.63)} \\ R_{max2} & = 3.52 \text{ (4.0)} \\ Sm_{22} & = 113.82 \text{ (125)} \\ EFE_{max2} & = 5.93 \text{ (TFE5)} \\ EFE_{al2} & = 3.78 \text{ (TFE4)} \\ EFE_{al2} & = 3.99 \text{ (TFE4)} \\ HV_{al2} & = 3.408,06 \text{ (SD(HV)2)} \\ t_{al2} & = 41.72 \text{ (SD(tal2))} \end{align*} \] | 0.46 | 0.16 | 4.87 |
| 1    | No solutions | | | | |
| 2    | \( s_{np} = 5.00 \text{ m/min}; \) \( s_{a} = 6.92 \text{ mm/ double stroke}; \) \( t = 0.01 \text{ mm}; \) \( z = 0.12 \text{ mm}; \) \( j = 380 \text{ N/mm} \) | \[ \begin{align*} R_{al2} & = 0.32 \text{ (0.32)} \\ R_{max2} & = 1.93 \text{ (2.0)} \\ Sm_{22} & = 109.17 \text{ (125)} \\ EFE_{max2} & = 5.26 \text{ (TFE5)} \\ EFE_{al2} & = 4.11 \text{ (TFE5)} \\ EFE_{al2} & = 4.32 \text{ (TFE5)} \\ HV_{al2} & = 3.493,47 \text{ (SD(HV)2)} \\ t_{al2} & = 64.16 \text{ (SD(tal2))} \end{align*} \] | 0.24 | 1.46 | - |

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During finishing grinding of the low-stiff workpieces, the basic transition time reduced by 2 times at the longitudinal low stiffness compared to the orthogonal direction $j_1$. The output parameters of the surface topography retained the trends mentioned above for the rough grinding of titanium workpieces at $j_w = 380$ N/mm, $w = 1$; 2. As for $\bar{SD}_x(R_{a1}, R_{max1})$, $w = 1$; 2 it should be taken into account that the transverse standard deviation is characterized by a large decrease in scattering (up to 40 - 60%) compared to the rough grinding.

During the final grinding stage of workpieces with $j_2 = 380$ N/mm, the further reduction in roughness $R_{a12}$ to 0.32 μm was predicted. All indices of flatness deviations are not beyond the limits of $TFE5$. The contact bearing area has favorably increased to 64.16%. We would like to remind that during rough grinding the latter was 35.56%. However, the similar solution in cases of transverse stiffness of workpieces $j_1 = 380$ N/mm was not found. The foregoing confirms the advisability of the low-stiff workpieces grinding with variation of their pliability in the longitudinal direction. The foregoing is due to the fact, that titanium alloys are characterized by a small elastic modulus (great internal friction) which dampens vibrations of the workpiece and fixture frame on which it is ground. For comparison, when grinding the steel workpieces with a higher modulus of elasticity, in the similar conditions, the best state of the topography is predicted for the transversely pliable workpiece [XX].

With increase in the requirements to the surface quality, the desirability function decreases $d_w = 0.51$, $w = 1$; 2 when grinding the low-stiff parts with their variations in both directions; $d_1 = 0.35$, $d_2 = 0.46$ - during finishing grinding of the low-stiff parts; $d_2 = 0.24$ - during final grinding of the parts with $j_2 = 380$ N/mm (in the orthogonal direction $j_1$ there are no solutions).

The results of the optimization conducted showed that in the case of the rough grinding, the increase in the workpieces stiffness from 380 to 5800 N/mm had virtually no effect on the cutting modes and, therefore, $T_0$, $k_4(3)$ remained at the previous level. However, the desirability function decreased slightly from 0.51 to 0.48. With this, the accuracy of their shape increased by 1-2 accuracy degree in the longitudinal direction and the high-rise indicators of roughness remained within the CM.

During the final grinding, a solution was found only for the longitudinally pliable workpieces. With this, the technological parameters of $s_n$, $t$ ($s_{long} = 10.28$ m/min, $s_n = 2$ mm/double stroke, $t = 0.01$ mm, $z = 0.1$ mm) were significantly reduced that resulted in increasing the basic time up to $T_0= 2.04$ mm. In comparison with finishing grinding, the parameters of the high-rise indicators of roughness were reduced: $R_{a12}$ from 0.63 to 0.32 μm, $R_{max12}$ from 3.54 (4.0) to 1.93 (2.0) μm and the contact area $t_M$ was increased from 39.47 to 66.25%. The flatness deviations indices determining the accuracy of the grinding machine remained at the same level.
Table 5: The quality predicted basic parameters and stability of their formation according to the results of surface grinding optimization of high-stiff parts from alloy VT22

| W   | Technology factors | Surface quality parameters                               | d  | T₀, min | kₑ (3) |
|-----|--------------------|---------------------------------------------------------|----|---------|--------|
|     |                    |                  |    |         |        |
|     | Rough grinding     | averages         | standard deviation |    |         |        |
| 1   | sₚₑ = 17.78 m/min; | Rₐ₁₁ 0.65 (0.80) | SD(Rₐ₁₁) 0.08      | 0.43 | 0.16   | 1.38   |
|     | sₛ = 7.60 mm/double stroke; | Rₐ₄₁₁ 3.73 (4.0) | SD(Rₐ₄₁₁) 0.38     |     |        |        |
|     | t = 0.02 mm;       | Sₘ₁₂ 107.94      | SD(Sₘ₁₂) 24.71     |     |        |        |
|     | z = 0.10 mm;       | EFEₐ₁ 11.32      | SD(EFEₐ₁) 2.03     |     |        |        |
|     | j₁ = 11220 N/mm    | EFEₐ₂ 11.99      | SD(EFEₐ₂) 2.19     |     |        |        |
|     | Finishing grinding  | HV₁ 3.52875      | SD(HV₁) 179.72     |     |        |        |
|     | sₚₑ/sₙ = 18.00 m/min; | Rₐ₁₂ 0.82 (1.0) | SD(Rₐ₁₂) 0.10      | 0.49 | 0.12   | 1.89   |
|     | sₛ/sₙ = 10.00 mm/double stroke; | Rₐ₄₁₂ 4.63 (5.0) | SD(Rₐ₄₁₂) 0.61     |     |        |        |
|     | t = 0.02 mm;       | Sₘ₁₂ 105.57      | SD(Sₘ₁₂) 10.83     |     |        |        |
|     | z = 0.10 mm;       | EFEₐ₁ 6.70       | SD(EFEₐ₁) 1.34     |     |        |        |
|     | j₂ = 11220 N/mm    | EFEₐ₂ 3.94       | SD(EFEₐ₂) 0.73     |     |        |        |
| 2   | sₚₑ = 12.73 m/min; | Rₐ₁₁ 0.34 (0.40) | SD(Rₐ₁₁) 0.034     | 0.26 | 0.59   | 1.32   |
|     | sₛ = 5.64 mm/double stroke; | Rₐ₄₁₁ 1.98 (2.0) | SD(Rₐ₄₁₁) 0.23     |     |        |        |
|     | t = 0.01 mm;       | Sₘ₁₂ 108.71      | SD(Sₘ₁₂) 21.48     |     |        |        |
|     | z = 0.10 mm;       | EFEₐ₁ 9.94       | SD(EFEₐ₁) 2.28     |     |        |        |
|     | j₁ = 11220 N/mm    | EFEₐ₂ 6.03       | SD(EFEₐ₂) 1.07     |     |        |        |
|     | sₚₑ = 12.33 m/min; | HV₁ 3.36564      | SD(HV₁) 86.41      |     |        |        |
|     | sₛ = 9.82 mm/double stroke; | Rₐ₁₂ 0.63 (0.63) | SD(Rₐ₁₂) 0.07      | 0.44 | 0.17   | 4.59   |
|     | t = 0.02 mm;       | Rₐ₄₁₂ 3.54 (4.0) | SD(Rₐ₄₁₂) 0.42     |     |        |        |
|     | z = 0.10 mm;       | Sₘ₁₂ 105.31      | SD(Sₘ₁₂) 11.38     |     |        |        |
|     | EFEₐ₁ 6.34         | SD(EFEₐ₁) 0.86   |                       |     |        |        |
|     | EFEₐ₂ 3.84         | SD(EFEₐ₂) 0.68   |                       |     |        |        |

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According to the Table 5, during surface grinding of high-stiff workpieces the direction of their variation should be based on the priorities of the goal functions. If you want to ensure minimum roughness on the parts surface: CM ($R_{a1w}$) = 0.8 μm, CM ($R_{max1w}$) = 4.0 μm during rough grinding or CM ($R_{a1w}$) = 0.4 μm, CM ($R_{max1w}$) = 2.0 μm at the finishing grinding, then the variable pliability of the workpieces should be combined with the vector $s_{pl}$. In the same direction, their minimum $SD_1$ are located.

If, however, you should ensure the best accuracy and precision on the workpieces shape ($SD$-minimum), the stiffness $j_2 = 11,220$ N/mm should be directed in the orthogonal direction (parallel to the vector $s_{long}$). Additionally, the average maximum $\hat{t}_{FM1}$ and its minimum $SD_1$ is predicted. However, the finishing grinding of the parts with the best roughness grade dramatically reduces the economic performance of the process: $T_0$ - increases, $k_0$ - decreases.

### III. Conclusions

1. To improve the stability of surface formation, the grinding optimization according to the standard deviation should be pursued with the function 'minimization'.

2. The grinding optimization efficiency of the titanium parts with different stiffness has been found at all stages of machining given its stability. With this, the optimum grinding condition reduces the basic operation time to 4.87 times as compared to standard specifications.

3. The parts stiffness and its direction have a significant impact on the quality of the grinding parts with variable stiffness, which are recommended to be ground in the longitudinal direction of the pliability.

4. When grinding the completely rigid workpieces (type of plates) as compared to pliable ones (with stiffness $j = 350-11,220$ N/mm), the elevation of the high-rise indicators of their surface roughness by 1-2 CM and the standard deviation to 2 times is noted. Transversely pliable workpieces, compared with completely rigid ones, allow improving the shape accuracy by one accuracy degree, and for the parts with the longitudinal variable pliability - by (1-2) TF.
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