STUDY OF DYNAMIC PROCESSES DURING THE FINISHING OF SPHERICAL PARTS MADE OF DIFFICULT-TO-MACHINE MATERIALS

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Shaping of surfaces during finish machining using intermittent abrasive tools requires optimized technological systems design and parametrization. To achieve that, theoretical base including equations of motion for discontinuous grinding and calculation of forced vibrations of elastic technological systems is implemented. Approximation of radial component of cutting force provides ability to study the dependence of amplitudes and phases of oscillations of technological system under the action of *k*-th harmonic of disturbing force. Direct correlation between the surface layer shape errors and the parameters of forced oscillations was observed.

KEYWORDS

finishing, intermittent grinding, elastic technological system, forced vibrations, amplitude-frequency characteristics

1 INTRODUCTION

Improvement of technology at present dictates the necessity of increasing the production of high-strength and wear-resistant materials, the machining of which causes serious difficulties. Increasing the share of hard-to-machine materials leads to the need to improve finishing processes, during which the surface layer of the part is formed, which largely determines the operational properties of parts and products [Dombrachev 2004 and 2015, Pokorny 2012, Karpus 2018, Kolesnyk 2022].

The relevance of the presented research is due to the fact that grinding is often used as a finishing operation for high-precision parts. Grinding is a process of high-speed micro-cutting by the smallest cutting edges of abrasive grains fixed on the working surface of the wheel.

The abrasive grains involved undergo periodic force, heat and chemical action as they come into contact with the workpiece. As a result of such impact, abrasion of cutting edges of grains, appearance of wear areas, chipping and tearing out of whole grains from the grinding wheel bond, violation of the correct geometric shape, as well as salting of the working surface of the wheel take place. In grinding practice, there are operations when the wheel does not lose its cutting ability to complete wear in connection with the intensive process of self-sharpening. Such operations include grinding of carbide cutting tools with grinding wheels made of silicon carbide and diamond, some operations of roughing flat grinding, roughing grinding, etc.

As grinding in most cases is a finishing operation, intensive self-sharpening of a wheel is undesirable in connection with the fact that the wheel quickly loses its original correct geometric shape with deterioration of roughness and accuracy of the ground surface. In this case, select such characteristics of grinding wheels and cutting modes, which do not lead to intensive grinding wheel wear. Operation of the wheel occurs with preferential blunting of its cutting edges and salting of the working surface. Thus, sulfation of pores is mainly a consequence of sulfation of abrasive grains and leads to loss of cutting ability of a wheel. The above-mentioned arguments speak to the importance of grinding research.

This phenomenon is often observed when grinding workpieces made of difficult-to-machine materials. For example, when grinding parts from steel EI654 in semi-boring and finishing modes, durability of the wheel, optimal in its characteristics, is 3...5 minutes.

When working at roughing modes the grinding process turns into a process of continuous dressing due to the rapid dressing of the wheel.

Resistance of grinding wheels is associated with changes in the rigidity of the abrasive grain support and with the stability of the grinding process. Studies have shown that as a result of wheel pores clogging by grinding waste, the rigidity of the support of the grain increases, and this, in turn, leads to the appearance of self-oscillation, that is, to the violation of the stability of the grinding process.

Thus, in the process of grinding, under the action of cutting forces and other factors, abrasive grains are torn from the grinding wheel surface without fully using their cutting properties. This violates the correct geometric shape of the wheel and when grinding hard-to-machine steels, the working surface of the wheel is quickly salted, which deteriorates its elastic properties. In order to restore the proper shape of the wheel, as well as cutting properties and characteristics of the elastic support of the grain, it is necessary to dress the wheel, which leads to additional consumption of abrasive and to a decrease in the grinding speed. Inefficient consumption of abrasive should also be attributed to the fact that 1/3 of the wheel goes to waste, i.e. the wheel cannot be used up to the seating hole. In addition, increase in the structure of enterprises in the share of small-scale and individual products and their frequent change leads to increase in the nomenclature and number of grinding wheels, which leads to decrease in efficiency of their use.

The need to improve production efficiency contributes to finding ways of improving the productivity of the grinding process and the most efficient use of abrasive materials.

Ways to influence the non-cutting elements at the stage of tool making are associated with a change in the amount or composition of the bond. In terms of its functional purpose, it must meet contradictory requirements: on the one hand, to firmly bond workable abrasive grains, on the other hand, not to retain blunted, non-cutting grains. However, in addition to its direct functional duties, the bond in the grinding process also plays a role that is not intended for it: it is directly involved in the contact processes of the cutting zone. This role is usually negative, as there is an additional strong friction between the tool and the workpiece. To eliminate this harmful effect of the binder, there are two different ways implemented in the abrasive production process: reducing the amount of binder by creating a single-layer tool or changing the composition and properties of the binder. The latter is achieved by various methods, for example, activation of the binder by treating it with fluorine compounds of titanium, silicon, which improve the mechanical properties of the binder and change its hardness.

The above-mentioned issues are most effectively solved if the abrasive tool is single-layered, that is, the abrasive grains and are fixed on a certain base in a single layer. Manufacturing a tool with a single-layer abrasive coating with a predetermined, and preserved until the full use of the cutting properties of the tool, elastic characteristic of the abrasive grain support will increase productivity and efficiency of the use of abrasive materials.

When manufacturing such a tool, it is possible to carry out the most effective orientation of abrasive grains, as well as to regulate the distance between them, which will increase the number of effectively working cutting edges and in general the cutting properties of the tool. Knowing in advance the characteristic of the elastic support of abrasive grains, it is possible to set the most rational processing modes without violating the stability of the system, i.e. it is possible to extend the stability limits of the grinding process. The absence of pores on the working surface will make it possible to get rid of its salting, thereby keeping the elastic characteristic of the grain support constant.

If a single-layer abrasive tool is used, lower grinding forces and temperatures can be expected, since the bond in this case only secures the abrasive grains on the base and does not participate in the work. If the abrasive is sufficiently firmly anchored to the work surface, which can be ensured by the use of modern bonds, its cutting properties will be fully utilized. Such a single-layer tool can be an abrasive belt.

The belt grinding method is characterized by high productivity, low heat stress, higher quality indicators and significant economic effect in comparison with grinding wheels. It has the following features: safety of work, constant cutting speed, large working surface of the tool, absence of complicated and labor-consuming operations of balancing and dressing, possibility of belt cutting properties control by changing hardness and shape of tool support units, easy maintenance, low cutting forces, as well as wide possibilities of mechanization and automation predetermine the prospects of using this grinding method in mechanical engineering.

Experimental data of tool application with discontinuous working surface and with indirect notches show that tool durability period increases in 2-3 times in relation to usual circles. For circles with discontinuous working surface and with straight notches the results obtained are contradictory, from increase in the period between dressing by 15-20 % in relation to ordinary circles to decrease in the period between dressing due to appearance of forced vibrations with frequency 800-1000 Hz in the elastic technological system. Amplitude of oscillations depends on the spindle speed and can vary up to 30 times from the length of the cavities.

Dependence of radial wheel wear and amplitude of spindle vibrations of discontinuous circles with straight notches depending on the length of circle hollows was established. So, at increase of cavity length from 20 to 100 mm radial wheel wear increases from 25 to 45 µm in the interval of ten minutes grinding time at wheel speed =35 m·s-1 and grinding depth t = 0.03 mm.

Amplitude of oscillations increases significantly with increasing length of the trough. Increase of radial wear is explained by increase of amplitude of vibration, decrease of number of cutting grains and increase of loads on cutting grains.

One of the ways to reduce the magnitude of vibrations is the use of a single-layer tool.

Another way to expand the technological possibilities of grinding is the development of tools on the basis of abrasive belts, where the construction itself creates damping conditions contributing to damping of vibrations.

The dimensional accuracy of intermittent belt grinding, according to Yakimov A.V., varies in the range of 0.01 to 0.1 mm when machining blades at aircraft plants.

As for the combined grinding wheel with a single-layer abrasive tool, the lack of recommendations for the selection of the wheel design and its main parameters taking into account the dynamic properties of the technological system, often a wide dispersion of the belt life and a large interval of dimensional accuracy in external circular discontinuous belt grinding serve as a serious obstacle to wide distribution in production.

From the above analysis of the foundations of belt grinding, it follows that the widespread distribution of materials difficult to process by grinding, increasing demands on the quality and physical - mechanical structure of the surface layer cause the need to improve the processes of abrasive machining. One of these directions is the use of abrasive belts.

Preliminary studies of technological possibilities of the process of grinding with abrasive tape, stretched on the disk, carried out on circular grinding machines, showed that such tool is workable and can be applied for dimensional grinding. As a result of the study of grinding parts made of hard-to-machine materials, it has been established that their machinability corresponds to the classification of S.N. Korchak. As already noted, when grinding similar steels with abrasive wheels, their rapid desalting is observed, when grinding with an abrasive belt stretched on the disk, the specified steels, desalting and visible burns were not observed.

The process of grinding with an abrasive belt is different from grinding with an abrasive wheel, because of the elastic movements in the radial direction of the pliable fabric base of the belt. The elastic movements are commensurate with the depth of penetration of the grain into the metal, which contributes to increasing the contact length of the grain with the workpiece.

The elastic displacements of the grain with the fabric base of the belt have a significant impact on the cutting ability of the abrasive belt and on the roughness of the machined surface.

In the course of preliminary studies, it was also found that at low specific tension, the belt works unstable, with possible runaway of the belt from the periphery of the disk. Consequently, it is necessary to solve the problem of the most rational belt tensioning system on the disc and to establish the optimal tensioning force which provides stable belt operation.

Numerous studies have established that the period of durability of belts of each researcher significantly differs from each other, however, exceeds the period of operation of grinding wheels between their dressing.

Significant expansion of technological capabilities of the grinding process is possible by switching the processing of hard-to-machine materials to discontinuous belt grinding.

A preliminary study of discontinuous belt grinding showed that its use can reduce the temperature in the tool contact zone with the workpiece compared to grinding with a continuous abrasive belt.

Intermittent belt grinding increases the proportion of costs directly to the volume of material and reduces friction costs.

However, insufficient study of thermal processes occurring in the contact zone of the tool with the workpiece, lack of recommendations on the choice of optimal parameters of the tool, taking into account the dynamic properties of the technological system, the unsolved problem of dimensional accuracy of ground parts prevent wide introduction of discontinuous belt grinding.

Analysis of production programmes carried out at various enterprises has revealed a large nomenclature of products manufactured in small batches or in single copies.

A large number of items quickly made in the process of work, but due to the high cost of materials and high labor intensity of their manufacture, undergoing restoration in the form of resurfacing surfaces or by fusing metal on the worn surface with its subsequent grinding was revealed.

The expediency of finishing the above parts with grinding tools with abrasive tape by intermittent grinding, which allows effectively influence the output parameters of manufactured articles with minimum costs, is shown.

Given the wide opportunities to influence the technological parameters, the process of intermittent grinding with abrasive belt is most effective in the conditions of small-scale production with a large nomenclature of manufactured products, in the conditions of repair enterprises with a wide nomenclature of restored products both in shape and size, and in the grade of materials.

Finishing of workpieces with intermittent abrasive tools changes the process of shaping the machined surface. To analyze the formation of cylindrical smooth surfaces during discrete finishing, circular grinding is considered [Dodok 2017, Martinovic 2021]. Studies of the given process showed that the machining error depends on the technological parameters characterized by cutting modes and on the design parameters of the abrasive tool with discontinuous surface [Glazyrin 1998 and 2009, Lamikiz 2005, Vopat 2013, Garrido 2017].

The methods of optimal machining regimes assignment is studied by numerous researchers, e.g. [Michalik 2011, Debnarova 2014, Jakubowski 2014, Nguyen 2020, Parmar 2020, Dharmawardhana 2021]. Four production problems are to be considered [Yakimovich 1994]: finding cutting modes to ensure maximum durability of cutting tools; modes that provide the required parameters of the surface layer quality and operational properties of the part [Krenicky 2020, Zhou 2020]; ranking of tools by serviceability; determining the modes of the minimum cost of the operation [Bezyazychny 2017, Pavlenko 2019 and 2020]. This area is closely linked to the following areas: the interaction of tool parts surfaces, the influence of quality parameters on the physical properties of the contact joints, operating properties, methods of their technological support, etc. The material on the regulation of the quality of the cutting tool parts surfaces is systematized [Kyratsis 2020] and problems of justification of choice and assignment of parameters ensuring operational properties of block-modular tool parts [Vaclav 2007 and 2017a-c], optimization of technological solutions using complex parameters of surface condition are considered [Peterka 2014, Kravtsov 2015, Bozek 2019, Nemeth 2019].

2 MATERIALS AND METHODS

The formation of the surface layer of parts such as bodies of rotation in most cases is carried out by cutting. Cutting is the most precise, versatile and economical method of machining. Abrasive machining is the most economical method for obtaining the accuracy of the parts from 4 to 7 degrees of quality and surface roughness Ra 0,1...0,63. Despite the variety of finish machining methods, grinding is the most widespread.

However, due to the specific microstructure of hard-to-machine materials, abrasive machining of workpieces with conventional abrasive wheels often leads to rapid "soaking" of the tool, which reduces productivity and increases the consumption of abrasive tools. In addition, it contributes to the development of high temperatures in the cutting zone and, as a consequence, the appearance of grinding defects.

One promising method that contributes to the elimination of the aforementioned disadvantages is discontinuous grinding with a belt stretched along the periphery of the wheel. The dynamics of the process of discontinuous grinding differs significantly from the dynamics of grinding with solid circles. Discreteness of the cutting surface of the combined wheel is the source of additional external influence on the elastic technological system, which leads to forced oscillations and inevitably influences on the form errors of the cross-section of the machined product [Kuric 2006, Peterka 2008a,b and 2020a,b]. Scheme of the technological system in intermittent cylindrical grinding is shown in Fig. 1.

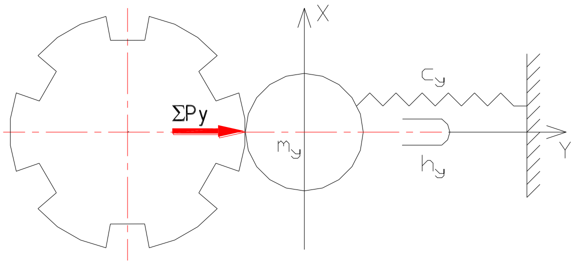

Figure 1. Schematic diagram of the technological system

The equation of motion of the system during intermittent cylindrical grinding can be represented as:

$$m_y \ddot{y} + h_y \dot{y} + c_y y = \sum P_y \qquad (1)$$

where m_y is the mass of the workpiece and mandrel; h_y is the coefficient determining the damping characteristics of the system; c_y is the system stiffness, ΣP_y is total radial component of cutting forces. Then, the force ΣP_y can be represented by a dependence (2):

$$\sum P_y = A_{oy} + \sum_{k=1}^{\infty} A_{ky} \cos\left(k\omega_b t - \alpha_{ky}\right), \qquad (2)$$

where A_{oy} is the constant component of the cutting force, A_{ky} is amplitude of the k-th harmonic, ω_b is frequency of the k-th harmonic, α_{ky} is phase shift of the k-th harmonic, t is time in sec. Consequently, the equation of motion of the system can be written in the form:

$$m_y \ddot{y} + h_y \dot{y} + c_y y = A_{oy} + \sum A_{ky} \cos\left(k\omega_b t - \alpha_{ky}\right). \qquad (3)$$

Since the constant component A_{oy} causes only a static displacement [Peterkova 2018], then:

$$\ddot{y} + c_{oy} \dot{y} + r_y^2 y = \sum B_{ky} \cos\left(k\omega_b t - \alpha_{ky}\right) \qquad (4)$$

where $r^2_y = c_y / m_y$.

The solution of equation (4) with respect to the phase of oscillations φ_k will have the form (5):

$$tg\varphi_k = \frac{c_{oy}(k\omega_b)}{r_y^2 - (k\omega_b)^2} \qquad (5)$$

Solution of equation (4) with respect to the amplitude of forced oscillations:

$$B_k = \frac{B_{ky}}{\sqrt{(r_y^2 - (k\omega_b)^2)^2 + c_{oy}^2 (k\omega_b)^2}} \qquad (6)$$

Formulas (5) and (6) determine the dependence of the phases and amplitudes of oscillations of the system under the action of the k-th harmonic on its forced force [Borkin 2019].

The change of cutting force ΣP_y in relative units is shown in Figure 2.

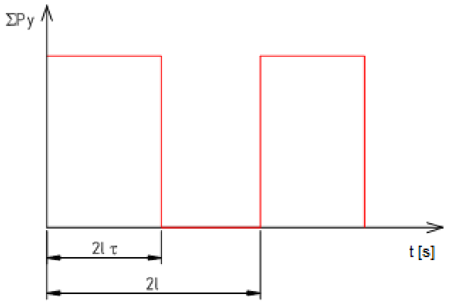

Figure 2. Variation of cutting force during intermittent grinding

The periodic disturbing force for the analysis of forced oscillations can be represented in the form of a Fourier series:

$$f(x) = a_o + \sum\left(a_k \cos\frac{k\pi}{l}x + b_k \sin\frac{k\pi}{l}x\right)$$

or

$$f(x) = A_0 + \sum A_k \cos\left(\frac{K\pi}{l}x - \alpha_k\right)$$

where

$$a_o = \frac{1}{2l}\int_0^{2l} f(x)dx$$

$$a_k = \frac{1}{l}\int_0^{2l} f(x)\cos\frac{\pi \cdot kx}{l}dx$$

$$b_k = \frac{1}{l}\int_0^{2l} f(x)\sin\frac{\pi \cdot kx}{l}dx$$

With the length of the segments equal to the length of the troughs τ = *T*/2 [Slezinger 1955] and the radial component expressed in relative units *H*

$$a_o = H\tau$$

$$\begin{cases} a_k = \dfrac{H}{K\pi}\sin(2K\pi \cdot \tau) \\ b_k = \dfrac{H}{K\pi}(1 - \cos 2K\pi \cdot \tau) \end{cases}$$

Since $A_k = \sqrt{a_k^2 + b_k^2}$ and $tg\alpha_k = \frac{b_k}{a_k}$, then

$$\begin{cases} A_k = \dfrac{2H}{K\pi}\sin(K\pi \cdot \tau) \\ \alpha_k = K\pi \cdot \tau \end{cases}$$

The strength ΣP_y for the first three, the most power-consuming harmonics, will be equal:

$$\sum P_Y = \frac{H}{2} + \frac{2H}{\pi}\sin(\omega_b t) + \frac{2H}{3\pi}\sin(3\omega_b t) \qquad (7)$$

Considering: $\omega_b = \frac{\pi}{l}$ and $l = \frac{\pi}{n}$

Expression (2) for the calculation by three harmonics will be presented in the following form:

$$\sum P_Y = \frac{H}{2} + \frac{2H}{\pi}\sin(n \cdot t) + \frac{2H}{3\pi}\sin(3n \cdot t) \qquad (8)$$

Figure 3 shows the approximation of the radial component of cutting force by three harmonics (the values of radial cutting force and time are given in relative units for the function period equal to *2l*).

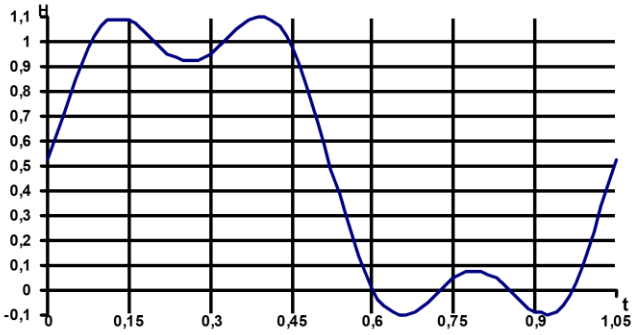

Figure 3. Approximation of the radial component of the cutting force

Formulas (4) and (5) define the dependence of the amplitudes and phases of oscillations of the technological system under the action of the *k*-th harmonic of the disturbing force.

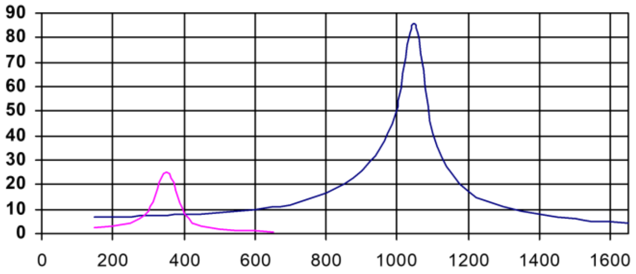

Figure 4. The dependence of the amplitude of forced oscillations on the circular frequency for the 1st and 3rd harmonics

3 EXPERIMENTAL PART

Experimental studies were carried out on a circular grinding machine of model 3B12. The stiffness of the machine in the direction of the force P_y was determined by the experimental load-displacement relation. Dynamic characteristics of the system were determined by oscillograms of natural damped oscillations, caused by pulse loading.

The amplitude-frequency characteristics of the technological system at machining with an intermittent wheel, calculated according to the above method are presented in Fig. 4.

Workpieces of steel 40X with a diameter of 80 mm were processed by intermittent grinding wheel with a diameter of 250 mm with the number of segments 6, with the length of segments equal to the length of the hollows. The belt tension of 40 µm grit was 8 N/mm. Rotation frequency of the workpiece is 100 rpm. Experimental evaluation of forced oscillations for the named conditions was carried out at different circular frequencies [Tyurin 2017]. The values of amplitudes are given in Table 1.

The accuracy of the circular frequency measurement was 5 s^{-1} and the accuracy of the amplitude measurement was 1 µm.

Since in practice, grinding is performed at high speed, so only the 2 highest speeds from Table 1 were used.

Comparison with the values of amplitudes in Fig. 4 shows good convergence of the results (the error does not exceed 12%). There is a direct correlation between the shape errors of the machined workpieces 3 and the parameters of the forced oscillations. As an example, Figure 5 show circular diagrams of machined workpieces at frequencies of 1450 s^{-1} and 1250 s^{-1}, respectively. The form error is 11 µm and 14 µm.

Table 1. Amplitudes of forced oscillations

Frequency [s^{-1}]	Amplitude[µm]
400	21
500	8
725	20
1250	16
1450	9

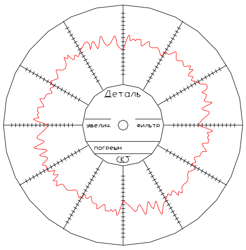

Figure 5. Circle diagram at 1450 s^{-1}

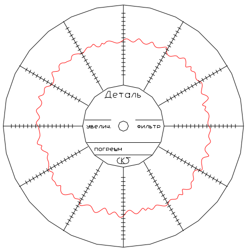

Figure 6. Circle diagram at 1250 s^{-1}

4 CONCLUSION

The presented technique makes it possible to choose the parameters of discontinuous circle, technological modes providing the permissible amplitude of forced oscillations.

A good convergence of the results was observed, where the form error does not exceed 12% with values 11 µm and 14 µm at frequencies 1450 s^{-1} and 1250 s^{-1}, respectively.

There is a direct correlation between the form errors of the processed workpieces and the parameters of forced oscillations.

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