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TOPOGRAPHIC ADAPTABILITY IN THE DIAMOND GRINDING ZONE OF SUPERHARD MATERIALS

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Abstract. *A comprehensive theoretical and experimental analysis of technological topographic adaptability is carried out, based on an idealized description of the topographic parameters of the working surface of the grinding wheel, their changes during its wear and experimental laser scanning of the working surface of the grinding wheel and the processed superhard material (SHM). It has been established that the protrusion height of diamond grains affects the intensity of destruction (removal) of stock through a change in the number of working grains and the actual contact area of the SHM with the working part of the grinding wheel surface. In a controlled grinding process, it is possible to stabilize the working height of the grains in any of the 3 stages of their wear intensity, equating this intensity with the intensity of removal of the intergranular bond. A method has been developed for determining the actual contact area of the working surface of the grinding wheel and changing its technological adaptability. It has been established that in the process of topographic adaptability, the actual contact area can change by several orders of magnitude, respectively, the specific pressure at the contact of diamond grains with the SHM will change, and, consequently, the nature and intensity of their mutual destruction.*
Keywords: *superhard polycrystalline material; diamond grains; working surface of the grinding wheel; microrelief of diamond grains; concentration of diamond grains in the grinding wheel.*

1. INTRODUCTION

The widespread use of superhard materials and the organization of mass production of cutting, smoothing, drawing, drilling and measuring tools from them require the development of highly efficient and precise methods and technology for their processing. The relevance of the problem being solved is dictated by the high labor intensity and low productivity of the SHM grinding process, the high consumption of expensive diamond grains of grinding wheels and, as a consequence, the high cost of processing. It is necessary to improve the reliability and quality of SHM tools, without which it is impossible to use them in automated production.

The process of diamond grinding of superhard materials is characterized by abnormally fast adaptability of the contacting surfaces, which is manifested in changes in their topographic, structural-phase and energy characteristics. All this changes output parameters such as productivity, specific consumption of diamond grains, and the quality of the processed surface. Thus, adaptability as an objective phenomenon determines the efficiency of the SHM diamond grinding process.

2. APPLIED METHODS

Previously, the maximum height of the protrusion of grains from the diamond-retaining bond was taken as the main topographic parameter of the working surface of the grinding wheel (WSGW) [1]. It turns out (and this has been theoretically and experimentally proved) that the height does indirectly determine the value of the actual contact area, but this is a necessary but not a sufficient condition. The analysis showed that, other things being equal (granularity *z*, concentration *K*, grain grade, grinding modes) with the same grain height on different binders (different critical value of grain embedding, h_{cr}),the actual contact area may be different [2, 3]. Thus, the efficiency of the slimming process is determined not only by the working height of the grains on the WSGW, but also by the properties of the bond material, which have a twofold effect on the value of the actual contact area of the SHM with the WSGW [4]. The properties of the bond determine the value of the actual contact area not only due to the degree of diamond retention, but also due to the elastic (and sometimes plastic) pressing of diamond grains into the bond material, which also leads to a change in the actual contact area (further investigated by 3D modeling of the stress-strain state of the "SHM – grain – bond" system).

Previously, it was found that the maximum productivity of the process is achieved at the maximum height of the protrusion of the grains above the bundle, i.e. with a newly threaded grinding wheel [4, 5]. However, the analysis showed that the grinding of SHM does not require a high level of development of the WSGW at the macro level, since it does not determine the productivity due to the depth of grain penetration into the processed material (PM), and the volume of placement of grinding products is negligible. In this regard, the grain height *hp* should be selected only from the conditions of contact or non-contact of the metal bond with the material to be processed [6]. An increase in the working height of the grains inevitably leads to a decrease in the size of their embedding in the bond and, as a result, an increased consumption of diamond grains. A more in-depth study of the effect of grain height on the output of the grinding process found that an increase in h_w affects the processing productivity not due to the depth of grain penetration into the PM and an increase in the cutting parameters or a more favorable placement of grinding products, as in the case of processing other groups of materials, but due to a significant increase in pressure at the points of contact between the SHM and the grain and, as a result, a decrease in the number of cycles before destruction [7, 8].

It has been established that the height of the grain protrusion affects the intensity of destruction (removal) of stock through a change in the number of working grains and the actual contact area of the “SHM – WSGW”. This feature takes place only in the treatment of SHM, when the introduction of grains into the processed material is practically absent, since their hardness is almost the same.

The number of working grains is determined by their concentration in the grinding wheel K and the working height of the grains h_w, i.e. the degree of their protrusion above the bond level:

$$n = f\,(h_w;\, K)$$

It has been established that the determining topographic parameter of the process of adaptability in the process of diamond grinding of SHM is the value of the actual contact area in the "WSGW – SHM" system.

The actual contact area also depends on the degree of wear of the grains Δh, i.e. on the mass nature of the formation of wear points on the grains. In a controlled grinding process, it is possible to stabilize the working height of the grains in any of the 3 stages of their wear intensity V_{worn}, equating this intensity with the intensity of the removal of the bind ($V_b = V_{worn}$) [9, 10]. At the same time, the lower the working height of the grains, the greater their number in contact, and the greater the degree of wear (wear pads) of most working grains. Specific loads per grain are reduced, the critical value of their embedding in the bundle is reduced and, as a result, the utilization rate of diamond grains is significantly increased.

To study the process of topographic adaptability, a comprehensive theoretical and experimental analysis of the 3D parameters of the topography of the working surface of the wheel and the treated surface was carried out, based on the theoretical description of the parameters of the relief of the working surface of the wheel and their change in the process of its wear, and experimental laser scanning of the WSGW and the surface of the SHM. A method has been developed for theoretical and experimental determination of the actual contact area in a system of surfaces that are fundamentally different in relief: discrete (WSGW) and quasi-continuous (SHM) in conditions where diamond grains are not embedded in the processed material.

Having established earlier [1] that the relative value of the actual contact area has a decisive influence on the intensity and nature of the mutual microdestruction of the elements of the "SHM–grain–bond" system, a theoretical analysis of the parameters of the grinding wheel and their changes as the grinding wheel adapts (wears) is carried out. The design model of the 3D grain-bond model is shown in Figure 1.

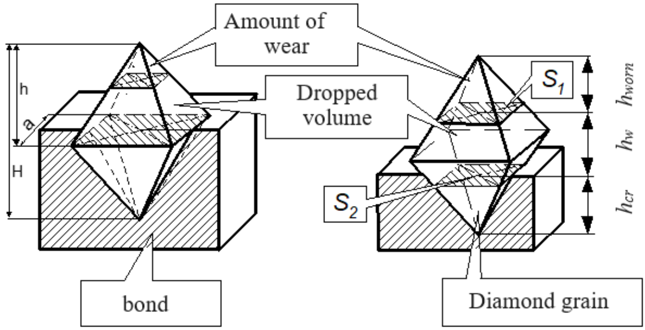


Fig.1. Computational model "Grain–bundle system"

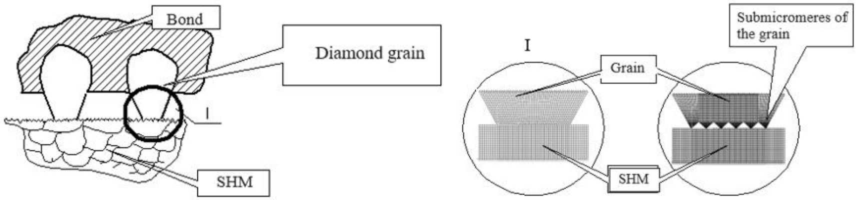
Theoretical dependencies were obtained for calculating and tracking the change in the wear of the grinding wheel of such parameters as the number of grains on the grinding wheel (n) and the relative area of the bearing surface ($t_{rbsa)}$ dependingon the grain size of the wheel (l_{gs}), concentration (K), the properties of the bond material, the degree of wear of the grinding wheel, the working height of the grains (h_w) and the critical value of their integration into the bundle *(*h_{cr}):

$$n = \frac{(l_{gs} - h_{cr})S}{\left(\frac{16}{K}\right)^{\frac{2}{3}} l_{gs} S_{acs}} trbsa = \frac{l_{gs} - h_{cr} - h_w}{\left[\frac{16}{K}\right]^{2/3} 2 l_{gs}}, \quad (1)$$

where: S_{acs} is the average cross-sectional area of the grain.

These dependencies will be used in the development of the theoretical module of the expert system of the SHM grinding process.

It has been established that the relative reference area of the grain relief on the working surface of the wheel (t_{rbsa}) at 100% of the grain concentration in the absence of contact of the binder with the processed material cannot exceed 20.7%. The value of the relative area of the bearing surface of the WSGW, determined by the value of the actual contact area in the “WSGW–SHM” system, depends not only on the height of the protrusion of the grains *(*h_w), but also on the critical value of their embedding in the bundle (h_{cr}*)*. With the same working height of the grains, the value of the actual contact area of the SHM with the WSGW will be different for different bundles.



a) b)
c)

Fig.2 Design diagrams of the contact of the elements "SHM–grain–bundle": a – at the macro level; b, c – at the micro level (finite element mesh of the "grain–SHM" model).

The experimental study of the relief parameters of the WSGW was carried out by laser scanning of the working surface of the wheel. One of the most important advantages of this method is the ability to analyze the dynamics of changes in such an important parameter for the process under study as the relative reference area of the t_{rbsa} profile in a three-dimensional version and in computer mode. A method of theoretical, two-stage determination of the actual contact area of the WSGW with the SHM has been developed, based on the artificial replacement of the discrete surface of the grinding wheel with a solid one and taking into account the elastic deepening (deformation, indentation) of diamond grains into the bond and its change in the process of grinding wheel wear. At the first stage, the actual contact area of "WSGW–SHM" is calculated at the macro level through the relative area of the bearing surface, and then, taking it as the area of the contour, using the modernized method for calculating the parameters of the discrete relative bearing surface of the WSGW (b and γ), the actual contact area is calculated at the micro level "SHM – grain microrelief" according to the known dependencies of N.B. Demkin and I.V. Kragelsky [11] At the same time, as a characteristic the system does not use the modulus of elasticity of the contacting materials, but the modulus of elasticity of the metal bond. The computational models are shown in Figure 2.

A method for theoretical determination of the parameters of the topography of the WSGW (b and V) taking into account its discreteness, based on the artificial replacement of a discrete surface with a solid one. Options b and V The following are defined theoretically:

$$V = \frac{3Kl_{gs}(l_{gs}-h_{cr}-Kh_w)+0.75Kh_w^2}{l_{gs}^2-h_w l_{gs}} \quad (2)$$

$$b = \left[\frac{0.25K(l_{gs}-h_{cr})}{l_{gs}} - \frac{0.25Kh_w}{2l_{gs}}\right]\left[\frac{l_{gs}-h_{cr}}{l_{gs}-h_{cr}-0.5h_w}\right]^V \quad (3)$$

The rounding radius of the vertices of the diamond grains is:

$$r = \frac{\left(0.0125K\left(l_{gs}-h_{cr}\right)\right)^2}{8\left(l_{gs}-h_{cr}-0.95h_w\right)} \quad (4)$$

where the designations correspond to (1).

It has been established that in the process of topographic adaptability, the actual contact area can change by several orders of magnitude, respectively, the specific pressure at the contact of diamond grains with the SHM will change, and, consequently, the nature and intensity of their mutual destruction.

3. RESULTS AND DISCUSSION

Figure 3b shows that the same value of the bearing area of the WSGW t_{rbsa} can be provided with significantly different values of h_w, i.e., by controlling the working height of the diamond grains, it is possible to control the value of tps, and, consequently, the intensity and nature of the destruction of the grains and the SHM.

However, the reduction of the working height of the grains, as noted above, leads to a decrease in the load on one grain, and, consequently, the contact pressures in the "SHM–grain" system also decrease, which, naturally, leads to the transformation of the nature of brittle self-sharpening of diamond grains into the process of their abrasion and a sharp decrease in the intensity of stock removal. An attempt to increase the pressure in the contact of the "SHM-grain" system by increasing the total load in the "SHM–WSGW" system by increasing the transverse feeding of S_{cf} or h_w can lead to the formation of defects on the treated surface of the SHM in the form of a network of microcracks.

Of all the factors that determine the size of the actual contact area, the concentration of diamonds in the grinding wheel remains the most controllable. By reducing the concentration, it is possible to reduce the number of grains in contact, increase the contact pressures in the "SHM–grain" system (without changing the total load on the processed SHM), resume the process of brittle self-sharpening (microcracks) of diamond grains and, as a result, intensify the removal of allowance.

If we analyze the obtained dependencies of the influence of the working height of the grains and the concentration of diamonds in the grinding wheel (Fig. 3a), we can state that the concentration of diamonds in the wheel is the most influential factor in the intensification of stock removal. This is convincingly proved (Fig. 3a) by the possibility of ensuring the same output (Q = 8 mm^3/min) for grinding wheels of 50% concentration and working height of grains h_w= 65 μm, or grinding wheel with 20% concentration and grain working height h_w = 30 μm.

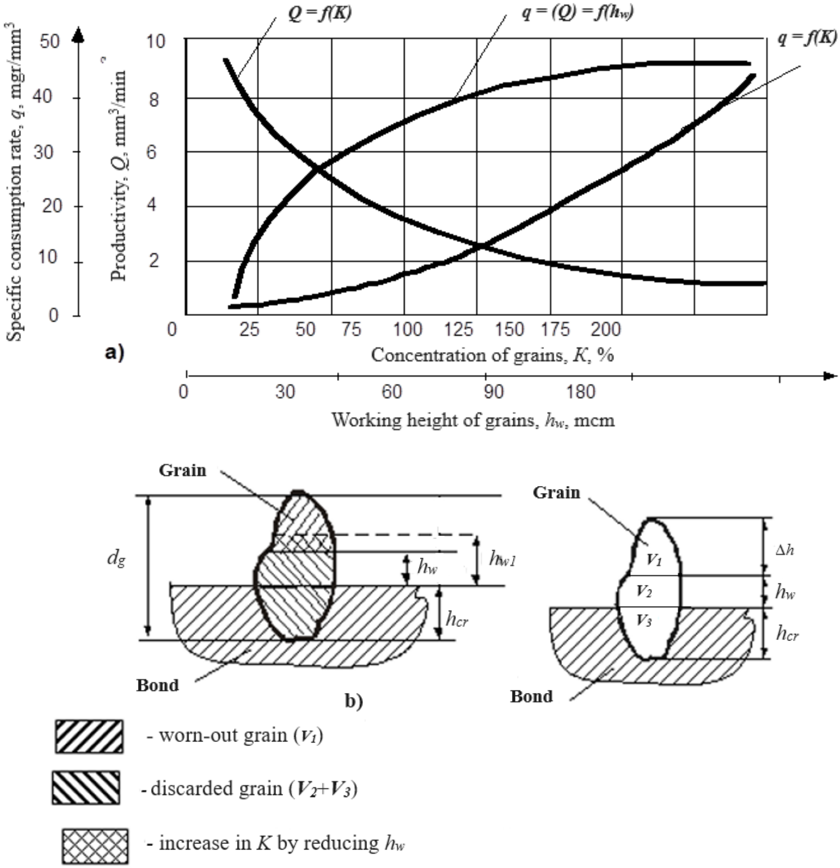


Fig.3. Schematic modeling of control of working height of grains (a) and wear of diamond grains (b)

It can be seen that if we reduce the working height of the grains h_w by half, then this is equivalent (for the value of t_{rbsa}) to an increase in the concentration of the grains by a factor of 2. Thus, if we determine from the dependence $Q = f(h_w)$ that the maximum performance for a 200/160 wheel will be at h_w= 140 μm, then to maintain the same t_{rbsa} at h_w = 20 μm, the height of h_w should be reduced by a factor of 7 or the concentration of diamond grains of the wheel should be no more than K = 14.2%. At the same time, under the same conditions, the specific consumption of diamonds is reduced by a factor of three. A schematic illustration of the analysis of the influence of the working height of grains on the change in the ratio of the worn part of the grains and those that have fallen out of the bundle is shown in Figure 3 b.

Suppose that an increase in the concentration of diamonds in the grinding wheel corresponds to a proportional increase in the number of loading cycles in the “SHM–grain” contact and a similar decrease in pressure in the contact. Calculations have shown that when the load in the contact is doubled, which corresponds to a halving of the concentration of diamonds in the wheel, the number of cycles required to grind the stock with the SHM decreases by 10 times, and the number of cycles caused by the decrease in concentration decreases only by 2 times.

Reducing the concentration of diamonds in the wheel, even taking into account the reduction in the number of loading cycles in the "SHM–grain" contact, can increase the intensity of stock removal by 2–3 times only due to an increase in pressure in the contact.

Thus, it has been theoretically substantiated and experimentally proven that the concentration of diamonds in the wheel, the working height of the grains and the critical depth of their embedding in the bond are interrelated most important factors in the process of diamond grinding of SHM. A decrease in the concentration of diamonds in the wheel to the level of 5 – 20% with a corresponding decrease in the working height of the grains to the level of micro-irregularities of the bond and an increase in the modulus of its elasticity does not lead to a deterioration in the output indicators of the diamond grinding process of the SHM, since the value of the actual contact area of the WSGW with the SHM remains unchanged, but the specific consumption and processing costs are significantly reduced, and the degree of use of diamond grains increases.

When grinding SHM, the concept of coarse-grained and fine-grained wheels acquires a new special understanding, since in the process of microfracture of the allowance with SHM, not all the grain takes part, but only its submicrorelief (Fig. 2 c), since no grain is introduced into the PM. Coarse-grained grains with a well-developed sub-microrelief may be more effective in terms of stock removal than fine, but smooth, or ovalized grains. Therefore, even with a coarse-grained wheel, it is possible to carry out a precise finishing operation for the processing of SHM. Such a process can take place in case of mass formation of wear areas with very fine sub-microrelief on large grains. Such sub-microedges act as a finishing diamond paste with micro-edges rigidly fixed in the diamond grain.

It has also been established that in the case of SHM diamond grinding, the determining topographic parameter is not the macrorelief of the grinding wheel, but the sharpness of the submicroedges on the diamond grains. The protrusion height of the diamond grains from the bond and their concentration in the wheel are interrelated parameters through which the efficiency of the SHM diamond grinding process can be controlled. The value of the actual contact area in the "WSGW–SHM" system depends not only on the working height of the grain protrusion, but also on the critical value of their embedding in the bundle, since at the same working height of the grains, the value of the actual contact area of the SHM with the WSGW will be different for different bundles. It has been theoretically substantiated and experimentally proven that the concentration of diamonds in the wheel, the working height of the grains and the critical depth of their embedding in the bond are the most important factors in the process of diamond grinding of SHM. Reducing the concentration of diamonds in the wheel to the level of 5 – 20% with a corresponding decrease in the working height of the grains to the level of micro-irregularities of the bond and increasing the modulus of its elasticity does not lead to a deterioration in the output indicators of diamond grinding of the SHM, since the value of the actual contact area of the WSGW with the SHM remains unchanged, but significantly reduces the specific consumption and cost of processing, increases the degree of use of diamond grains.

It is possible to control the efficiency of the diamond grinding process both at the pre-production stage, i.e. by selecting the optimal concentration of diamond grains in the wheel, and directly during the processing process – by changing the intensity of targeted dosed removal of the binder and the forced formation of a cutting submicrorelief on diamond grains [12].

It has been theoretically substantiated and experimentally proven that the concentration of diamonds in the wheel, the working height of the grains and the critical depth of their embedding in the bundle are interrelated most important factors in the process of diamond grinding of SHM.

The anisotropy of the physical and mechanical properties of diamond grains, which causes significantly different (up to 10 times) intensity of wear of their different facets, should be taken into account when analyzing changes in the parameters of the working surface of the wheel in the process of its wear, for example, when calculating the number of actually working grains, the value of the actual contact area in the “WSGW–SHM” system, and so on. confirms the correctness of this provision.

Dependencies have been obtained that link the working height of grains, their concentration with the number of grains on the WSGW and in contact with the SHM, the relative support surface area of the WSGW, the values of the actual contact area of the WSGW with the SHM, as well as their changes in the process of adaptability. These dependencies will be used in the theoretical module of the expert system of the SHM diamond grinding process [1].

Thus, a comprehensive theoretical and experimental analysis of the process of topographic adaptability was carried out, based on the theoretical description of the parameters of the topography of the working surface of the grinding wheel, their changes in the process of its wear and experimental laser scanning of the surface of the grinding wheel and SHM.

It has been established that the value of the actual contact area in the "WSGW–SHM" system depends not only on the working height of the protrusion of the grains, but also on the critical value of their embedding in the bundle, since at the same working height of the grains, the value of the actual contact area of the SHM with the WSGW will be different for different bundles. Theoretical dependencies were obtained to determine the number of grains on the WSGW and in contact with the SHM, the relative support surface area and the length of the profile of the WSGW, the value of the actual contact area of the WSGW with the SHM, as well as the dynamics of their change as the wheel wears out and the critical value of the grain embedding in the bundle changes. This makes it possible to theoretically assess the change in the topography parameters of the WSGW during the grinding process.

A method has been developed for determining the actual contact area of the WSGW with the SHM and its change in the process of adaptability, based on the artificial replacement of the discrete surface of WSGW with a continuous one and taking into account the elastic deepening of diamond grains into the binder. A two-stage method of 3D experimental-theoretical determination of the actual contact area of the WSGW with the SHM in the absence of grain penetration into the processed material and the absence of its contact with the bond is proposed, taking into account the sub-microrelief of diamond grains and SHM, the anisotropy of the properties of SHM crystallites and diamond grains, the elastic properties of the grinding wheel bond. At the first stage, the actual contact area "WSGW–SHM" is calculated at the macro level through the relative reference surface area of the wheel, and then, taking it as a contour, using the modernized method for calculating the parameters of the discrete relative support surface of the WSGW (b and γ), the actual contact area is calculated at the micro level "SHM – microrelief of grains" according to the known dependencies of N.B. Demkin and I.V. Kragelsky. The stiffness system uses the modulus of elasticity of the metal bond rather than the contacting materials.

Experimental determination of the actual contact area in the "WSGW–SHM" system can be performed based on the results of laser scanning of their surfaces and computer determination of the value of the relative support area.

4. CONCLUSIONS

It has been established that in the case of diamond grinding of SHM, the determining topographic parameter is not the macrorelief of the wheel, but the sharpness of the submicroedges on the diamond grains. The protrusion height of the diamond grains from the bond and their concentration in the wheel are interrelated parameters through which the efficiency of the SHM diamond grinding process can be controlled.

Theoretical dependencies have been obtained that describe the relationship and change of such parameters as the working height of the grains, the number of grains at the WSGW and in the contact, their concentration in the diffuvial wheel, the relative reference length and the area of the WSGW profile, the actual contact area, and the specific load in the process of wear of the diamond wheel. It has been theoretically substantiated and experimentally proven that the concentration of diamonds in the wheel, the working height of the grains and the critical depth of their embedding in the bond are the most important factors in the process of diamond grinding of SHM. Reducing the concentration of diamonds in the wheel to the level of 5 – 20% with a corresponding decrease in the working height of the grains to the level of micro-irregularities of the bond and increasing the modulus of its elasticity does not lead to a deterioration in the output indicators of diamond grinding of the SHM, since the value of the actual contact area of the WSGW with the SHM remains unchanged, but significantly reduces the specific consumption and cost of processing, increases the degree of use of diamond grains.

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ТОПОГРАФІЧНА АДАПТИВНІСТЬ В ЗОНІ АЛМАЗНОГО ШЛІФУВАННЯ НАДТВЕРДИХ МАТЕРІАЛІВ

Анотація. *Широке застосування надтвердих матеріалів (НТМ) і організація масового виробництва з них ріжучого, шліфувального, волочильного, свердлильного і вимірювального інструменту вимагають розробки високоефективних і точних методів і технології їх обробки. Актуальність розв'язуваної проблеми продиктована високою трудомісткістю і низькою продуктивністю процесу шліфування НТМ, великою витратою дорогих алмазних зерен шліфувальних кругів і, як наслідок, високою вартістю обробки. Проведено комплексний теоретичний та експериментальний аналіз технологічної топографічної адаптивності, заснований на ідеалізованому описі топографічних параметрів робочої поверхні шліфувального круга, їх зміні при його зносі та експериментальному лазерному скануванні робочої поверхні шліфувального круга та оброблюваного надтвердого матеріалу. Встановлено, що висота виступання алмазних зерен впливає на інтенсивність руйнування (видалення) матеріалу заготовки через зміну кількості робочих зерен і фактичної площі контакту оброблюваного НТМ з робочою частиною поверхні шліфувального круга. У процесі контрольованого шліфування можна стабілізувати робочу висоту зерен на будь-якому з 3-х ступенів інтенсивності їх зносу, прирівнявши цю інтенсивність до інтенсивності зношування алмазоносної зв'язки круга. Розроблено методику визначення фактичної площі контакту робочої поверхні шліфувального круга з поверхнею НТМ та зміни її технологічної адаптивності. Встановлено, що в процесі топографічної адаптивності фактична площа контакту може змінюватися на кілька порядків, відповідно, буде змінюватися питомий тиск при контакті алмазних зерен з НТМ, а, отже, характер і інтенсивність їх взаємного руйнування. Отримано теоретичні залежності, що описують взаємозв'язок і зміну таких параметрів, як робоча висота зерен, число зерен на РПШК і в контакті, їх концентрація в алмазоносному шарі круга, відносна опорна довжина і площа профілю РПШК, фактична площа контакту, питоме навантаження в процесі зносу алмазного круга. Теоретично обґрунтовано і експериментально доведено, що концентрація алмазів у крузі, робоча висота зерен і критична глибина їх залягання в зв'язці є найважливішими факторами в процесі алмазного шліфування НТМ. Зниження концентрації алмазів в крузі до рівня 5 – 20% з відповідним зменшенням робочої висоти зерен до рівня мікронерівностей зв'язки і збільшенням модуля її пружності не призводить до погіршення вихідних показників алмазного шліфування НТМ, так як величина фактичної площі контакту РПШК з НТМ залишається незмінною, але значно знижує питомі витрати і вартість обробки, підвищує ступінь використання алмазних зерен.*

Ключові слова: *надтвердий полікристалічний матеріал; алмазні зерна; робоча поверхня шліфувального круга; мікрорельєф алмазних зерен; концентрація алмазних зерен у шліфувальному крузі.*