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A. Grabchenko, V. Fedorovich, I. Pyzhov,
Y. Ostroverkh, N. Kozakova, Kharkiv, Ukraine

3D METHODOLOGY OF RESEARCH OF DIAMOND-ABRASIVE MACHINING PROCESS

Abstract. *Subsystem of computer-generated determination of conditions of manufacturing of defect-free diamond wheels and grinding of superhard materials on the base of 3D simulation of deflected mode of elements of the "SHM crystal grain – metal phase – grain – bond" system at process of diamond wheel sintering and grinding is developed.*
Keywords: *simulation; system "Wheel working surface (WWS)-SHM"; grinding; destruction; system "polycrystal - grain - bond".*

1. INTRODUCTION

Superhard polycrystal materials (SHM) and superhard composites on the diamond base (DC) becomes more and more widely used both as a tool material (especially in precision machining processes) and as constructional materials. Laboriousness of their processing is comparable with natural diamonds processing laboriousness.

Now diamond grinding is the most manufacturable process of SHM machining. However, available processes of diamond grinding by means of wheels on organic and metal bonds do not solve in full measure a problem of low productivity (which in 10000 times below, than when processing, for example, alumina ceramics), significant specific consumption of diamond grains (which sometimes is 30 carats of grains on 1 carat of removed allowance) and essential percent of a spoilage because of occurrence of microcracks grid on machined SHM surface. Development of expert system of manufacturing process of diamond-abrasive tool and grinding process of SHM is made on the following algorithm:

- Three-dimensional (3D) simulation of sintering process of diamond-bearing layer for determination of conditions at which integrity of diamond grains is kept;
- Determination of parameters of 3D topography of SHM surface to be machined;
- Determination of parameters of 3D topography of wheel working surface;
- Determination of the actual area of contact in the system "Wheel working surface (WWS)-SHM";

- Simulation of thermo-force deflected mode (DM) of cutting region when processings by means of single-point tools made of SHM;
- 3D simulation of thermo-force deflected mode (DM) of the system "SHM-grain-bond" (determination of the conditions excluding a spoilage owing to SHM cracking);
- Calculation of process intensity of thermoactivated lapping of SHM surface to be machined.

2. THREE-DIMENSIONAL SIMULATION OF DIAMOND-BEARING LAYER SINTERING PROCESS

The task, solved in the process of 3D simulation of DM of sintering zone of diamond-bearing layer of wheel on metal bond is the determination of optimal combination of strength properties of diamond grains and bond, at which integrity retention of diamond grains is provided during diamond wheel sintering process.

Contrary to available ideas, proposed to consider the model of diamond-bearing layer of wheel as perfect one, we have stated, that the structure of diamond layer of the wheels contains initial defectiveness in the form of damaged diamond grains, which can be quantitatively defined by dimensionless value of a damage rate of diamond grains [1].

It is established in N.V.Novikov's work [1], that the particle-size analysis of synthetic diamond grains AC50 400/315, extracted by recuperation from tvesal sample, has shown that during sintering only about 10-20 % of grains remain undamaged. So it is shown, that diamond grain concentration influences deeply on damaging rate of diamond grains when sintering DC. The increase of concentration from 50 up to 150 % raises damageability of diamond grains during sintering process in 2.8 times.

Since the technology of sintering of diamond-bearing layer of the wheel, for example, on hard-alloy bond such as BK, is practically identical one with the technology of sintering of DC, it is objectively to expect, that some part of grains at sintering of diamond wheels are damaged too.

Authors [2] have shown that during of diamond wheel sintering the percentage of the basic fraction (coarse grains) is diminished by 20-30 %.

Moreover diamond grains of various strength, obviously, will be destroyed during sintering in different ways. There is no doubt that structure of metal bond and therefore technological parameters of sintering of wheels will essentially affect a degree of damageability of diamond grains.

Our experimental investigation of diamond grains carried out by means of electrochemical opening of new diamond wheel is shown, that part of diamond grains destroys as early as diamond wheel sintering (fig. 1).

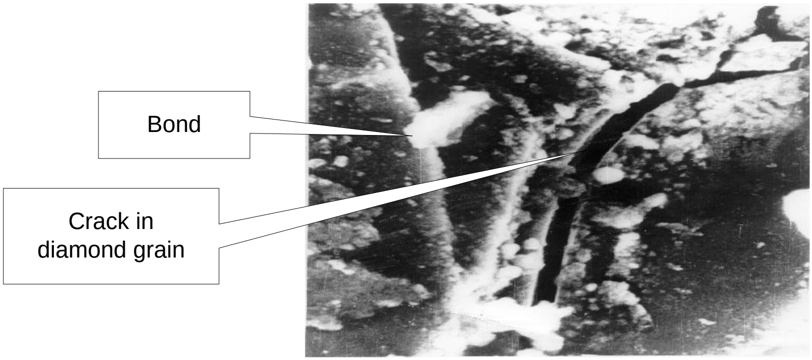

Figure 1 – Diamond grain on the surface of the wheel out of operation

Process of sintering of the diamond grinding wheels was simulated by means of finite element method (FEM) in software package Cosmos-M. At 3D simulation of sintering process the fragment of diamond-bearing layer of wheel was presented as a cube dimensioned 300x300x300 μm, in midpoint of which a diamond grain as an octahedron dimensioned 100x100 μm was placed, that corresponds to 100 % concentration of diamond wheel. At simulation of 50 % diamond grain concentration wheel the size of the cube was redoubled and so on. Metallic phase in diamond grain was simulated as an interlayer of 5-10 μm in thickness and of various form and length. The model was loaded with stress and temperature appropriate to the real process of diamond wheel sintering. It is accepted, that if the reduced stress in diamond grain exceeds ultimate strength it will be considered as destroyed (defective) diamond grain. Sintering process of diamond-bearing layer was simulated for various metal bonds from aluminium up to hard-alloy ones, using diamond grains with various strength from AC2 up to AC160T.

Results of 3D simulation of DM of sintering zone of diamond wheels are presented on fig.2.

Varying combination of diamond grain strength and grain concentration in the wheel for various metal bonds one can determine such their combinations, at which retention of diamond grain integrity was provided i.e. the grains should not be fractured during sintering. It is established, that not all of commercial wheels with usable combination of brand of diamond grains and brand of metal bond can be manufactured with standard concentration of diamond grains without failure of their integrity. So, for example, at sintering of wheel on bond M6-14 with diamond grains of brand AC6 the grain concentration in the wheel should not exceed 7 %, otherwise grains will be fracture as early as wheel sintering. It is shown, that for guaranteed retention of diamond grain integrity practically in all commercial wheels, their concentration should be much less than applied one. Such tendency coordinates well with possibility and necessity of lowering of diamond grain concentration for wheel up to level of 10-15 % at grinding of superhard materials [3, 4, 5].

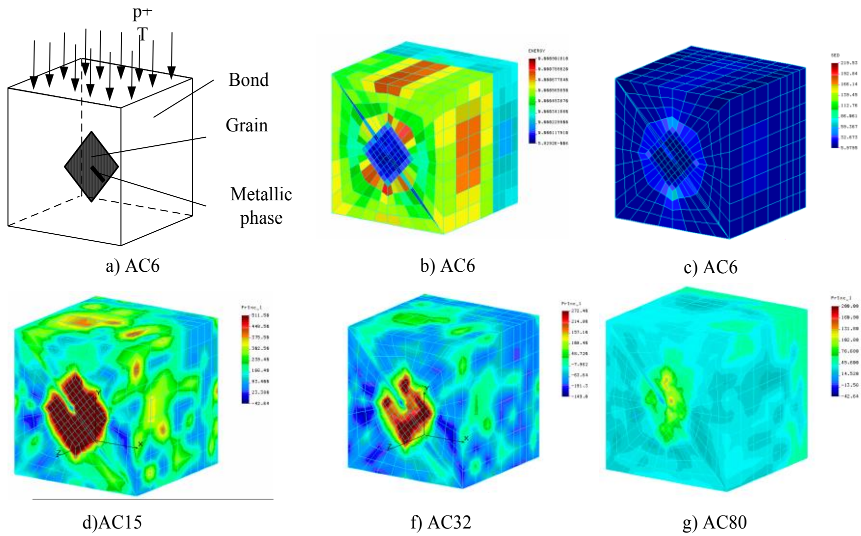

Figure 2 – Influence of grain brand on 3D DM of the system "diamond grain – bond": sintering composition – bond M2-09, graininess 200/160;
a – 3D model of the system "bond – grain – metal phase"; b – energy of deformation;
c,d,f – reduced stress, g – strain energy density

It is established, that for retention of diamond grain integrity during sintering of the wheels one must observe combinations of brand of diamond grains and brand of metal bond. Analysis of theoretical computation allows to determine diamond-metal compositions, which ensure integrity of grains in the wheel during the process of its manufacturing (table 1).

Suggested values of concentration in such wheels are less than ones used in commercial wheels, that is important factor of reducing of cost both the diamond wheels and grinding processes.

Thus, at the first stage of the investigations the optimal combinations of strengths of metal bond and diamond grains with their maximum concentration limit in the wheel providing retention of diamond grain integrity during diamond wheel production are established. Optimal relation of strengths of bond, diamond grains and grain concentration, obtained at this stage, are only limiting parameters and should be determined more precisely for diamond grinding process depending on strength properties of material to be machined.

Table 1 – Diamond-metal compositions suggested for sintering

Grain brand	Coefficient of elasticity of bond, GPa	Graininess, μm	Concentration, %
AC2	40-52	50/40-63/50	5-7
AC4	44-70	50/40-80/63	5-10
AC6	77-95	50/40-100/80	10-16
AC15	86-100	80/63-100/80	15-21
AC32	98-110	80/63-125/100	18-25
AC50	102-119	100/80-160/125	25-28
AC80	143-173	125/100-250/200	25-34
AC100	165-210	125/100-315/250	30-37
AC125	190-260	200/160-315/250	30-40
AC160	210-320	250/200-500/400	35-45

After obtaining of the prescribed limits one should determine optimal combination of strengths of material to be machined, bond, diamond grains and grain concentration in the wheel, which provides maximal efficiency of grinding process. During exploitation optimal combination of strengths of bond, diamond grains and grain concentration is determined depending on strength properties of material to be machined. For this purpose the methodology of 3D simulation of DM, only for grinding zone, will be used too.

3. DETERMINATION OF PARAMETERS OF 3D TOPOGRAPHY OF SHM SURFACE TO BE MACHINED AND WWS

The parameters of 3D topography of WWS were studied by means of laser scanning device "Perthometer S8P" with laser sensor of FOCODYN model, range of vertical resolution of which is ±250 μm, that it is quite enough for measurement of height parameters of WWS for the wheels of graininess up to 630/500. The device allows simultaneously to fix 9 parameters, selected from 86 possible parameters of WWS topography. To estimate topography of diamond grains submicrorelief the scanning pitch of WWS was accepted to be equal 1 μm, i.e. the ray passes some dozens times on each diamond grain [6].

Determination of parameters of 3D topography of SHM surface to be machined was carried out with using the profilograph of "Hammelwerke" corporation, "Turbo Roughness V3.32" model, needle radius is 2 μm.

The examples of 3D topography of SHM and WWS surfaces are shown on fig. 3. The outcomes of study of the parameter of the relative reference area of the profile t_{ps} are used at experimental determination of the actual area of contact in the system "SHM-WWS" [7]. Since at diamond grinding of SHM the hardness of material to be machined is practically equal (without taking into consideration anisotropy of diamond crystallite properties) to hardness of diamond grains and their intrusion in material to be machined infinitesimally small, the measurement of parameter t_{ps} was realized only at level 0.1-1 μm from a line of peaks.

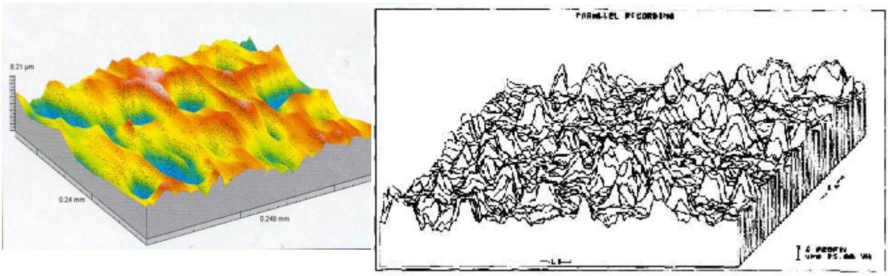

Figure 3 – 3D topography of the surface
a) WWS; b) SHM

Mean value of parameters t_{ps} for WWS and SHM are accepted as actual area of contact (Ar).

$$Ar = \frac{t_{ps}^{\text{ÐÏ Ê}} + t_{ps}^{\text{ÑÒÏ Ì}}}{2}$$

Theoretical computation of actual area of contact in the system "SHM-WWS" is carried out using dependences of N.B.Demkin and I.V.Kragelskiy [5].

4. THREE-DIMENSIONAL SIMULATION OF DEFLECTED MODE OF GRINDING AREA

Having determined actual area of contact, let's go on to simulation of deflected mode (DM) in the system "SHM-grain-bond". As there is an opinion [1], that the cause of SHM destruction can be the essential difference in coefficients of thermal expansion (CTE) of diamond and metal phase of SHM, DM of studied system was investigated. Theoretical analysis of thermo-force DM of system "Crystallites-metal phase-grain-bond" by means of finite element method (FEM) was carried out in software package of bundled software such as "Cosmos" with application of eight nodal elements SOLID (1847 nods, 1640 elements). The package allows to decide the problem in three-dimensional measurement (3D-simulation), that favourably distinguishes the given technique from used one earlier by other authors [8,9]. SHM was simulated as set of crystallites of cubic form of dimensions 0.2x0.2x0.2 mm with the metal phase interlayers of dimensions 20x200x200 μm, arbitrary located in it. Calculation scheme of interaction of the system components simulates the most unfavorable grinding variant with mass formation of wear platforms on diamond grains. Calculation scheme of model and 3D stress in the system "SHM-grain" are shown on fig. 4.

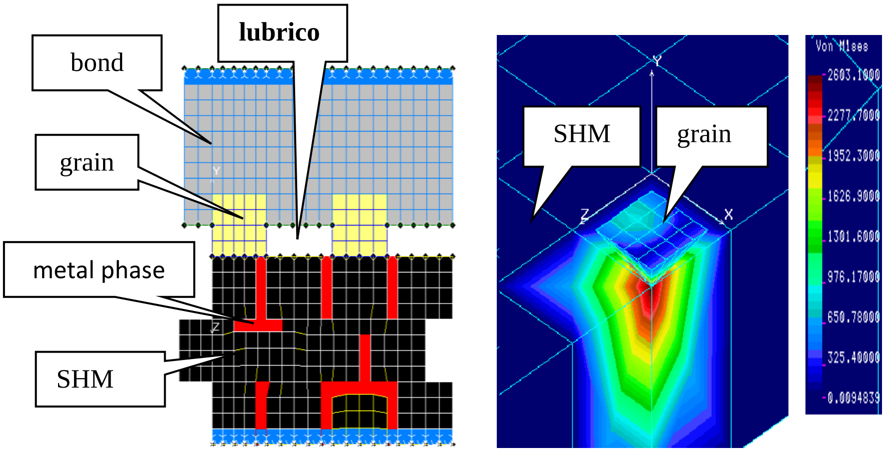

Figure 4 – Finite element calculation scheme of interaction of system "Crystallites-metal phase-grain-bond" (a) and reduced 3D stress in grain and SHM

Advantage of the proposed technique is the possibility in three-dimensional variant (3D-model) to evaluate separately the influence of cross-feed (S_{c-f}), value of normal pressure in contact "WWS-SHM" (P_n), physical-mechanical properties of SHM, diamond grains and bond, temperature in grinding area (in contact "Grain-SHM"), temperature of lubricoolant (or its absence) on temperature fields, value of main and reduced stresses caused by both separately force and thermal factors, and their general effect (thermo-force stress). The package allows also to evaluate strain energy, according to which it is possible, using the Griffith's theory, to determine possibility of formation and development of microcracks both on SHM surface and diamond grains (if they are polycrystallic ones), and development of internal microcracks.

Advantage of the proposed calculation technique is three-dimensional (3D) solution of the problem, obtaining of three-dimensional temperature fields, three-dimensional fields of reduced and main temperature and thermo-force stress in a grain, bond, metal phase and polycrystal.

Possibility of determination of main and reduced thermo-force stress, and also energy of deformation in any point of system " Crystallites SHM-metal phase-grain-bond " allows to use both energy criterion, and force criterion of brittle failure of materials. Using, for example, technique of computer-aided finite element method for prediction of defective layer development at simulation of DM of surface to be machined [9], but, taking into account thus also the thermal factor, is possible to analyze influence of physical-mechanical properties of system components, conditions of grinding and performances of wheels on probability of defect-free machinig of various brands of SHM, including newly created ones.

From the carried out calculations we determine grinding conditions ($S_{c\text{-}f}$, P_n, number of grains in contact, performances of wheel, availability of lubricoolant), at which the probability of formation of defective layer, i.e. reject is eliminated at sharpening the tool made of SHM.

The developed subsystem "Defekt" allows to analyze not only condition of defect-free machining of SHM, but also as the subsystem of the common theoretical expert system allows to optimize process of allowance removal taking account of thermal factor, as it is made, for example, in the work [10], with reference to grinding of glassceramics.

5. CONCLUSIONS

Developed subsystem of theoretical expert system of diamond grinding allows to determine the conditions of defect-free manufacturing of diamond wheels and defect-free machining of SHM at sharpening of tools made of superhard materials.

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Анатолій Грабченко, Володимир Федорович, Іван Пижов,
Євгеній Островерх, Наталія Козакова, Харків, Україна

3D МЕТОДОЛОГІЯ ДОСЛІДЖЕННЯ ПРОЦЕСУ АЛМАЗНО-АБРАЗИВНОЇ ОБРОБКИ

Анотація. *Запропонована 3D методологія комп'ютерного визначення умов виготовлення бездефектних алмазних кругів та шліфування надтвердих матеріалів (НТМ) яка грунтується на основі тривимірного моделювання напружено -деформованого стану елементів системи «оброблений матеріал - металева фаза - зерно - зв'язка». На першому етапі досліджень встановлюються оптимальні поєднання міцності металевої зв'язки і алмазних зерен з межею їх максимальної концентрації в крузі, що забезпечує збереження цілісності алмазних зерен при виготовленні алмазного круга. Оптимальне співвідношення міцності зв'язки, алмазних зерен і концентрації зерен, отримане на цьому етапі, є лише обмежуючими параметрами і повинні бути визначені більш точно для процесу алмазного шліфування залежно від міцності оброблюваного матеріалу. На другому етапі слід визначити оптимальне поєднання міцності оброблюваного матеріалу, зв'язки, алмазних зерен і концентрації зерна в крузі, що забезпечує максимальну ефективність процесу шліфування. В процесі експлуатації визначається оптимальне поєднання міцності зв'язки, алмазних зерен і концентрації зерен в залежності від міцності оброблюваного матеріалу. Параметри тривимірної топографії робочої поверхні круга (РПК) досліджувалися за допомогою лазерного скануючого пристрою «Perthometer S8P» з лазерним датчиком моделі FOCODYN, діапазон розділення по вертикалі якого, становить ± 250 мкм, що цілком достатньо для вимірювання висотних параметрів РПК. Визначення параметрів тривимірної топографії оброблюваної поверхні НТМ виконувалося на профілографі фірми «Hammelwerke» моделі «Turbo Roughness V3.32», з радіусом голки 2 мкм. Розроблена підсистема «Дефект» дозволяє аналізувати не тільки стан бездефектної обробки НТМ, але і бути як підсистема єдиної теоретичної експертної системи, що дозволяє оптимізувати процес зняття припуску з урахуванням теплового фактора. Розроблена підсистема теоретичної експертної системи алмазного шліфування дозволяє визначати умови бездефектного виготовлення алмазних кругів та бездефектної обробки надтвердих матеріалів при заточуванні інструменту з них.*

Ключові слова: *моделювання; система "робоча поверхня круга - НТМ"; шліфування; руйнування; система "полікристал - зерно - зв'язка".*