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Contact Deformation Behavior of an Elastic Silicone/SiC Abrasive in Grinding and Polishing

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Режим контактного деформування пружного силікон/SiC абразиву при шліфуванні і кінцевій обробці

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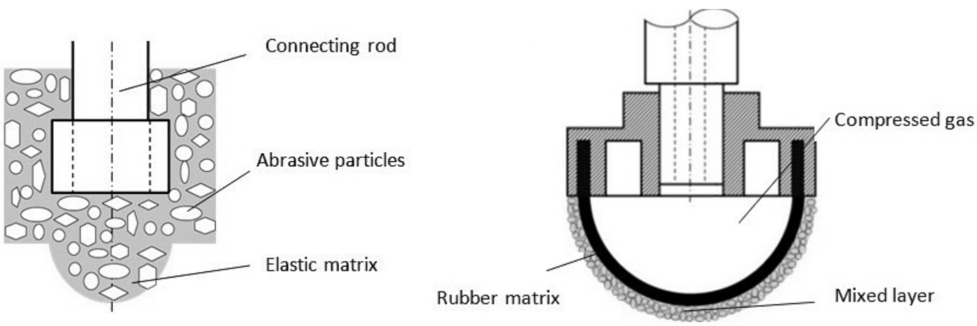
Розроблено пружний абразив нового типу, що дозволяє ефективно регулювати контактний тиск у поєднанні з рівномірним деформуванням. Пружний абразив забезпечує повне ламінування поверхні, збільшує ефективність обробки вигнутої порожнини ливарної форми та дозволяє виконувати тонку обробку поверхні порожнини. Основою цих м'яких пружних абразивних композитів є силікон як матеріал матриці і модифіковані мікрочастинки SiC як армуючий елемент. Вивчено механіку і режими контактного деформування абразивів шляхом аналізу розмірів армуючих частинок та їх вмісту (53,5; 59,3; 65,4%). При механічному стиску композита характерним є показник вигнутої степеневої функції. Аналіз поведінки матеріалу при контактному деформуванні показав, що зв'язність вузлів сітки, яка виникає в результаті зшивання силікону і отвержувача, зростає по об'єму пор кристалічної гратки абразивних частинок при тиску. Пружний розтяг і стиск ланцюжків сітки в композитах гарантує повне ламінування поверхні, що обробляється, а тверді абразивні частинки між ланцюжками доповнюють структуру матеріалу.

Ключові слова: пружний абразив, механічні властивості, силікон/SiC композити, структура.

Introduction. The rough surface contact characteristics, like reliability and safety of the parts, determine the mechanical characteristics of many machines, especially for the high-precision devices, when have a great impact on human life and been widely researched. Furthermore, the overall precision grade of general mechanical and precise machinery equipments, macroscopic mechanical and micro- mechanical equipments is closely related to the precision grade of the various parts [1–6]. High-precision surface processing methods for mechanical parts are mostly manual grinding-polishing, which is low efficient and its accuracy is difficult to meet the requirements [2, 3]. In the process of production, it is difficult to achieve uniform surface roughness, affecting the overall quality of equipment products. In recent years, unshaped abrasives such as the magneto-rheological fluid, abrasive flow and air sac tools have become one of the research hotspots [6–8]. Because of the traces of the irregular shape of the irregular parts left in the rough cutting tool cutting process and EDM, there is a large number of so-called processing dead ends such as trenches, edges, corners, and narrow slits. If the stereotype abrasives are used, processing methods and efficiency are restricted to some extent. Unshaped abrasives have higher requirements in processing equipment [9–13], which increased the of production cost. From hard abrasives, silicon carbide (SiC) is an indispensable material for the industry, in view of its hardness, low thermal expansion coefficient, and high thermal conductivity as well as its hardness against friction [14]. Considering these factors, a deformable soft elastic abrasive tool on the basis of the traditional polishing tool is designed in this research, and the contact deformation characteristic of the composites is discussed. The deformation elastic behavior during the working process is studied. And the elastic abrasives with different deformation variable and its effect on the quality of machined surface are also investigated.

1. **Preparation and Properties of Elastic Abrasives**. The elastic abrasive is made of silica gel as the matrix and modified silicon carbide particle SiC as reinforcing abrasive, toughening agent, coupling agent and other additives to make the elastic abrasive as a whole. The preparation process is as follows. Liquid silica gel and SiC abrasive particles (after treated by coupling agent) were weigh in a certain proportion, and then were poured into the mixing cup, stirred evenly for 15 min by mechanical stirrer. Then the 2% curing agent and toughening agent was added, stirred evenly for 5 min again. The even composite material was poured into the specified mold and compacted, placed into a heating furnace, heated to 100℃ for 2 h, cooled to room temperature. The elastic abrasive samples were removed from the mold and placed in a dry box at room temperature for 48 h.

The designed elastic abrasive specific structure is shown in Fig. 1a. Specifications are $\varnothing 35\times 32$ cylinders, with the end of the hemispherical structure. The composite is composed of silica gel and different content of SiC components (quality content of 53.5, 59.3, and 65.4%) and different particle size of abrasive grains (200, 100, 60, and 40 μm) respectively. And the contact deformation characteristic of these elastic abrasives was studied in this research.



a b

Fig. 1. Structure and air sac structure of elastic abrasive (a) and ballonet tools (b).

The fracture surface morphology was analyzed by Hitachi S-4800 high-resolution field emission scanning electron microscope (Hitachi S-4800, 15kV).

In the working process of abrasives, the end is contacted hemi-spherically and in the compressed state all the time. This structure is different from the air sac polishing structure (Fig. 1b) [2]. The air sac polishing mainly changes the elastic modulus by controlling the air pressure in the rubber base of the air sac and adjusting the thickness of the mixed layer and the abrasive particles, thus to realize the effective contact between the abrasive tool and the machined surface, and to complete the efficient machining of the free-form surface. Depending on elastic deformation characteristics of this structural abrasive tool, according to the relationship between the pre-pressure and the deformation of the abrasive tool, the abrasive tool can effectively contact with the machined surface, finish the high-efficient precision machining of the free-form surface, and achieve the uniform curved surface.

2. **Compression Elasticity of Elastic Abrasives**. The compressive properties of composites reinforced with 200, 100, 60, and 40 μm silicon carbide were tested, respectively. After the specimens are loaded, its integrated compression characteristics are shown in Fig. 2. With the elasticity of each pattern integrated, the function curves (vertical throw) concave and the derivative increases. At the same time, the content of the abrasive grains in the abrasive increases and the vertical throw of the curves increases, that is, the curvature increases gradually and the rigidity of the elastomer is enhanced. It can be seen from the curves that with the same amount of addition, the compressive amount of silicone gel modified by abrasive grains with different sizes increases firstly and then decreases with the abrasive grains size decrease. The compression amount increases nonlinearly with the pressure increasing. Under a certain amount of compression, there is an extreme value, which is the polar derivative of nonlinear curve and increases and then decreases with the particle size decrease. According to the stress–strain diagram of the elastic abrasives with different contents of abrasive grains, the strain function of the abrasive is deduced as Eq. (1):

$$f(x) = a\bar{x}^{b} + \lambda, \tag{1}$$

where $f(x)$ is the compressed distance, x is deformation variable, a and b are constant, $a > 0$, $b > 1$, and λ is the constant coefficient of silica gel.

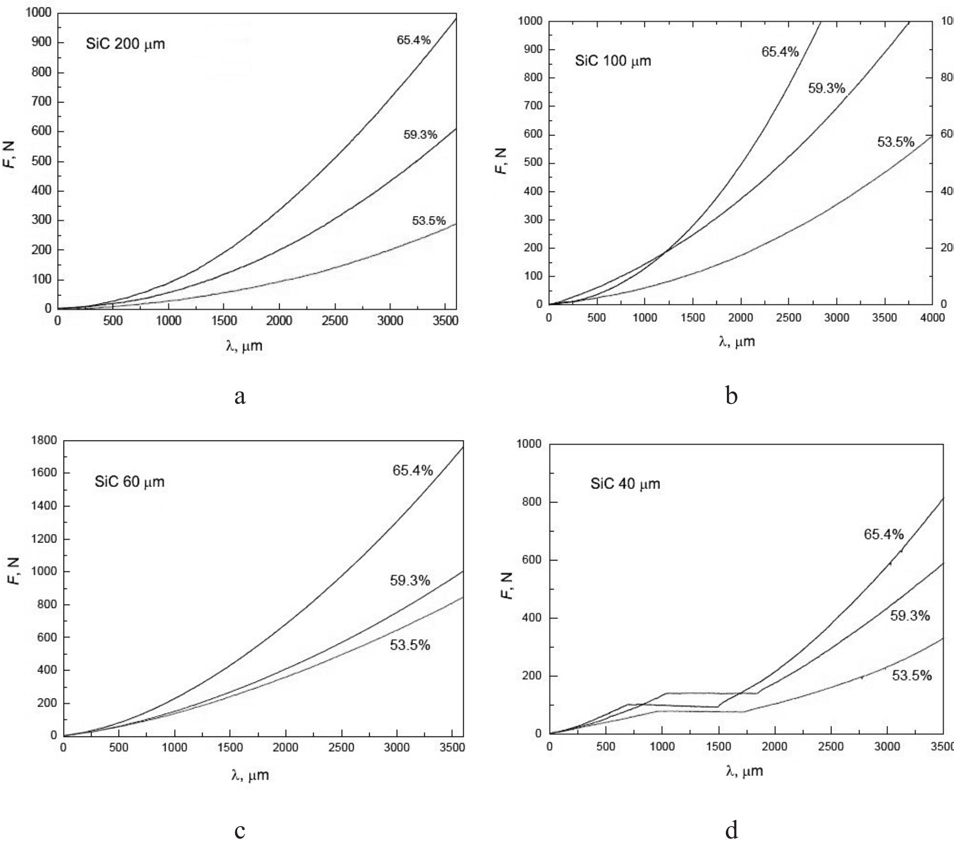
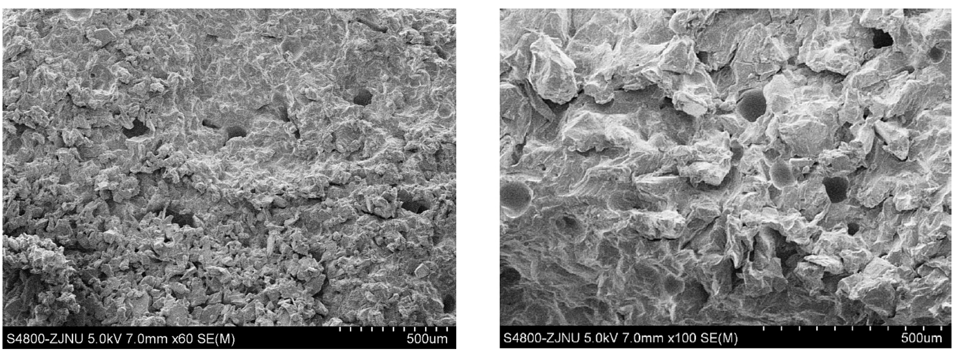


Fig. 2. Compressive performance curves of reinforced composites with different particles.

The curve of the function concaves (vertical throw) and the derivative increases, that is, the curvature increases gradually. There is a power function relationship between the stress and the deformation $\bar{x}$ (displacement), which avoids the elastic modulus change in the process of air sac polishing. This is related to the nature of the elastic matrix itself. When a small stress is applied to the elastic matrix, the elasticity of the material itself can withstand the pressure changes, while the cavitations and porous structure in the material result in a surge in the elastomer itself. When the cavitations are compacted, the elastic matrix itself begins non-line deformation and the abrasive is swelling macroscopically. But the silicone gel is still in a state of elasticity, the irregular hard particles within the composite will start to action, result in enhanced macroeffects of abrasive.

The observed microstructures of the specimens are shown in Fig. 3. It can be seen from the morphologies that there are obvious tearing marks in the matrix. Nonuniform holes are distributed in the matrix. Edges of the enhanced particles become smooth, which cover the matrix into a network-like and interact with each other. At this time, the distribution of particles is relatively uniform. The interfacial phase is torn and connected with the matrix. The abrasive is an effective integral structure, indicating that the composite effect through this preparation process is obvious. The chemical action between the silica gel and the curing agent in the composite retains the porous structure of the silica gel itself. The uniform force of the gas in the mixing process makes the reinforced particles distributed evenly in the matrix, realizing the mosaic-like network link of the abrasive grains and silica matrix with a certain number of "cavitation" structure, which increases the elasticity of the matrix [14–18]. The size of the hole or cavitation is about 100 μm in the composite. When the size of particles changed from about 200 μm to about 40 μm, the smaller the particle size, the stronger the synergistic effect of the reinforcing particles and the silica gel, the greater the possibility of the particles embedded in the gap of silicone hinge (shown in Fig. 2d). When the compressive force reaches a certain value (about 1000 μm), the reinforcing effect of the particles is weakened and the mutual influence increases. The network chain formed through the crosslinking reaction by the silica gel and curing agent penetrates the space of the grain lattice, and surrounds the periphery of the abrasive grains to form a high elastomer body with the natural bonding network chain, which retains the self-porous elastic characteristics. Epoxy resin adhesives are used in the preparation process of abrasives, in order to enhance the combination of abrasive and silica gel.



a b

Fig. 3. Microstructure of silicon carbide soft abrasives: (a) 100 μm; (b) 60 μm.

3. **Compression Contact Deformation Behavior of Elastic Abrasives**. The matrix in the composite has a network-linked structure, its own porous structure (shown in Fig. 3), as well as the mixed cavitations in the preparation process. This structure has high elastic

deformation. Assuming that the hard abrasive grains are random bodies, in the compression process, the mechanical model of the abrasives is shown in Fig. 4. The matrix is characterized by elastic element, the workpiece is rigid body, the abrasive grain has an irregularly shape, covered with the interface phase encapsulated the matrix. When the composite is under pressure, the matrix contact with the surface area of the workpiece at first, and then the interface phase coating in the outer surface of the abrasive is compressed, then to pass to the workpiece surface. The matrix is silicone gel, which is elastoplastic body and shows compression elastic characteristics of spring under the external force. The abrasive grains are hard particles and their elasticity is negligible. There is no deformation of hard abrasive grains under pressure, which interact to extrude into the matrix, showing rigid characteristics. When the compressive capacity reaches a certain level, the compressibility of the matrix reaches its maximum value. Considering of the compression properties of composite under a certain amount of pressure (shown in Fig. 2), the elastic properties of the matrix are enough to meet the working requirements of the composites. Thus, the composite has similar compression properties with the matrix material.

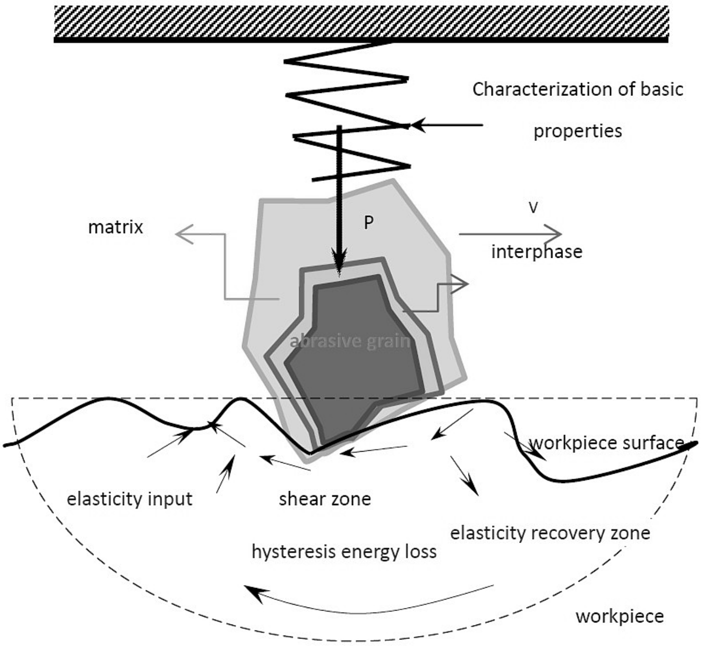


Fig. 4. Sketch of interaction among abrasive particles when polishing.

The working process of elastic abrasives is shown in Fig. 4. Under the pressure, the elastic substrate material stores energy. In the way forward, the workpiece surface will be extruded by the processed abrasives and prone to plastic deformation. The energy of the elastic matrix continues to increase under the reaction of the abrasive grains, which promotes the abrasive to cut the plastic workpiece phase. The action of the abrasive at the tail is small and has a certain plastic effect for cutting surface. At the same time the elastic composite deforms under pressure and shows the viscoelastic behavior for a long time, making the surface smoother. Its load changes with time alternately. In the abrasive working and movement, there are intermittent collisions and cutting between hard particles and the processed surface, the hard particles repeatedly extrude the surface of workpiece until the shape of abrasive is circular or passivated. The passivated abrasive particles work in weak cutting capacity. As a result, the elastomeric matrix will be torn and new abrasive grains will continue to work on the workpiece surface. In the continuous processing, the repeated unloading, extrusion and energy storage-release of the matrix of the abrasives make the matrix more flexible and fall off easily. The peeled abrasive grains will scratch the workpiece surface roughness. The elastic characterization of the abrasive matrix is mainly composed of the three-dimensional chain and network structure of the silica gel and the ordered "hole." Under loading, the chain network stretches and is compressed elastically. The hard particles (abrasive grains) embedded in the gap of mesh play a stereotyped role to ensure that the abrasive fit with the processed surface totally. The "hole" in the structure of abrasives is compacted and extrude. The elastic properties of materials are further strengthened. At the same time, the uneven workpiece surface will promote the effective combination of the two. The matrix will repeatedly work to the workpiece surface like the spring. The composite abrasives will fit with the workpiece surface all the time. After the abrasives work for a certain time, the matrix fails due to fatigue, the abrasive grains are passivated and peeled off, and the composite will be compacted between the abrasives and the matrix. Further, the external load increase will promote the new abrasive particles to act with matrix and then to achieve the precise grinding and polishing.

Conclusions

1. Contact deformation of elastic abrasive is influenced mutually by the chain network structure of silica gel and the hole of this structure. There is a nonlinear relationship between compressed distance and deformation variable of the abrasive. And the amount of compression can be controllable with the function concaves.

2. Composites fail due to the abrasive grains passivated and peeled off with the matrix phase for long-term work. The peeled abrasive grains will scratch the processed surface, which affects the surface quality.

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Резюме

Разработан упругий абразив нового типа, позволяющий эффективно регулировать контактное давление в сочетании с равномерным деформированием. Упругий абразив обеспечивает полное ламинирование поверхности и эффективную обработку изогнутой полости литейной формы, а также позволяет выполнять тонкую отделочную обработку поверхности полости. Основой этих мягких упругих абразивных композитов служат силикон в качестве материала матрицы и модифицированные микрочастицы SiC в качестве армирующего элемента. Изучены механика и режим контактного деформирования абразивов путем анализа размеров армирующих частиц и их содержания (53,5; 59,3; 65,4%). Поведение композита при механическом сжатии характеризуется показателем вогнутой степенной функции. Анализ поведения материала при контактном деформировании показывает, что связкость узлов сетки, возникающая в результате сшивания силикона и отвердителя, растет по объему пор кристаллической решетки абразивных частиц при приложении давления. Упругое растяжение и сжатие цепей сетки в композитах гарантирует полное ламинирование обрабатываемой поверхности, а твердые абразивные частицы, внедренные в промежуток между цепями, дополняют структуру материала.

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