Study on the material-remove mechanism of SiC surface polishing

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As aerospace technology develops rapidly, higher demand for aerospace optic system is brought forward. With its excellent physical qualities, SiC becomes a very promising material for speculums. The material-remove mechanism of SiC surface polishing is studied, that is, the grinding mechanism of ceramic material. Indentation fracture model is also introduced and is used to explain material-remove mechanism of SiC surface polishing, and the model of SiC polishing in ideal condition is analyzed. Finally, the material-remove mechanism of SiC polishing in real state is studied.

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As aerospace optic technology develops rapidly, higher demands for optic system are brought forward. Optic components with high quality in the system are also needed. In order to ensure the stability of the structures of speculums and optic components at work or in the process of manufacturing and testing, and to take into consideration the lightweight requirement for speculums in aerospace optic systems, a series of physical indices are put forward for speculum material: low density, high elasticity modulus, no thermal stress, low coefficient thermal expansion, high thermal conductivity, and mechanical isotropy. Traditional materials can no longer meet these requirements. With such excellent physical qualities such as high elasticity modulus, proper density, comparatively low coefficient thermal expansion, high thermal conductivity, high heat resistance, high specific stiffness, and high stability in size, SiC becomes a promising material for speculums[1–5]. Accordingly, the study on the processing of the optic surface of SiC speculums is widely made at home and abroad. However, the study on the material-remove mechanism of SiC surface polishing still remains untouched.

The polishing of optic surface is affected by many factors, so quantitative control over it is very difficult. For many years, technicians have been exploring the relationships between material removal rate and various affecting factors. Cumbo *et al.* have proposed a successful polishing mechanism of optic glass. They believe polishing is a mechanical–chemical process. During a polishing process, on one hand, machines remove the material to conform to Preston's hypothesis; on the other hand, three chemical reactions occur, namely, 1) the hydration and dissolution of glass material in polishing liquid, 2) the redeposition of debris on the glass surface, and 3) the electric charge exchanges between the surfaces of glass material and polishing material. Due to these chemical reactions, the Preston constant actually measured from glass material is two orders of magnitude lower than the theoretical value of the mechanical process, that is, the inverse of the elasticity modulus of the glass material. To sum up, the chemical processes exert great influence on the polishing of glass material.

SiC material is quite different from glass material and the chemical activity of its components is much lower than that of the components of the glass material. Neither α-SiC nor β-SiC hydrates or dissolves, not to mention the redeposition of the debris. Therefore, in polishing SiC, chemical reactions have no effect.

We believe the polishing of SiC material can be taken as a process of mechanical removal. An ideal SiC material polishing process can be illustrated with indentation fracture model—a similar grinding mechanism of ceramic material Fig. 1.

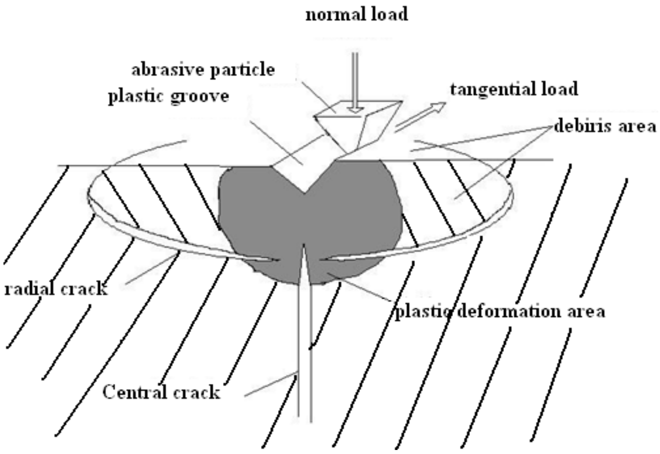

Fig. 1. Indentation fracture model.

Indentation fracture model takes into account the interaction between abrasive particles and workpieces in ceramic material grinding as a small-scale indentation. In this model, a single abrasive particle is considered as an approximate Vickers tetrahedral indenter. As shown in Fig. 1, under the abrasive particle is the plastic deformation area, from which two major fracture processes start: central/radial crack and lateral crack. Central/radial crack usually leads to the lowering of material strength, whereas lateral crack leads to the removing of material. Generally, the condition for central/radial crack is that the normal load P_L exceeds the critical load for central/radial load P_L^*[6,7]:

$$P_L^* = 54.5(a/\eta^2\gamma^4)(K_C^4/H^3), \tag{1}$$

where K_C denotes fracture toughness and H denotes hardness, and a, η, γ are constants (for Vickers indenter $a \approx \pi/2, \eta \approx 1, \gamma \approx 0.2$).

When normal load P_L exceeds critical load P_L^*, the relation between P_L and the central/radial crack C is[6,7]

$$P_L/C^{3/2} = K_C\{\xi(\cot\psi)^{2/3}(E/H)^{1/2}\}, \tag{2}$$

where 2ψ is the included angle between indenter and edge and ψ is a constant.

The condition for lateral crack is the sum P of normal load P_L and tangential load P_r exceeds the critical load for lateral crack P^*,

$$P^* = \xi(K_C^4/H^3)f(E/H), \tag{3}$$

where ξ is a nondimensional constant and $f(E/H)$ is an attenuation function. Here $\xi f(E/H) \approx 2 \times 10^5$.

When P exceeds P^*, the lateral crack C_r is

$$C_r = [\xi_r(\cot\psi)^{5/6}A^{-1/2}(K_C H)^{-1}E^{3/4}]^{1/2}P^{5/8}, \tag{4}$$

where ξ_r and A are constants.

A comparison between P_L^* and the average load of a single abrasive particle will lead to the prediction of whether the grinding process is a lateral fracture process or a plastic removal process. As shown in Fig. 1, lateral cracks exist near the bottom of plastic area and expand laterally on a plane, which is nearly parallel with the surface of the workpieces. The deviation of the lateral crack to the free surface results in the fracture removal of the material and the cutting is conducted. If, by the effect of normal load P_L, the volume of the debris formed by a single abrasive particle is in direct ratio with the size and contact length of the contact L, V_L is[7,8]:

$$V_L = a(P^{5/8}/K_C^{1/2}H^{1/8})(E/H)^{3/8}L, \tag{5}$$

where a is a constant.

SiC polishing process in ideal condition can be taken as a process of fracturing. In ideal condition, every polishing particle, including the ones with the smallest radius, is evenly imbedded into polishing plate under pressure. Only small edges stick out. Every such particle is an approximate Vickers tetrahedral indenter.

When normal load P_L is smaller than the critical load P_L^*, which leads to central/radial cracks, the material removal is plastic and no central/radial cracks are produced. When normal load P_L is larger than the critical load P_L^*, which leads to central/radial cracks, and when P, the sum of normal load P_L and tangential load P_r, is smaller than the critical load P^*, which leads to lateral cracks, material removal is still plastic, but central/radial cracks are produced. According to Eqs. (2) and (3), P_L^* and P^* of SiC are 0.40 and 3.7 Pa, respectively. The values for silicon are still smaller. During polishing process, the normal load is usually $1 \times 10^2 - 4 \times 10^4$ Pa, which is much larger than 3.7 Pa. Therefore, we think the polishing of SiC material in ideal condition is brittle removal, which is accompanied by the appearance of central/radial cracks. In this process, it is debris volume V_L and the defective volume of foreign silicon particles that decides the roughness of the surface. The factors that decide the efficiency of material removal are E, the total energy participating in every rotation of the polishing head and E_2, the energy needed in forming the fracture surface by removing unit volume material. Here

$$E = E_0 = n\bar{E}_1 = VE_2 \rightarrow V = E/E_2 = E_0/E_2, \tag{6}$$

where E_0 is the total energy working on workpiece in every rotation of the polishing head and n is the number of debris pieces in every rotation of the polishing head. $\bar{E}_1$ is the average energy needed in forming a debris and V is the volume of the material removed in every rotation of the polishing head. E_2 is decided by the total area of debris fracture surface.

In virtual polishing, not all the abrasive particles can be completely imbedded in the polishing plate and there is a critical value R_m[9–11]. The particles with radius larger than R_m are imbedded in the polishing plate, while those with smaller radius roll between the polishing plate and the workpiece. R_m is related to the grinding head and the pressure. Therefore, in virtual condition, the polishing process is a combination of the grinding removal of the abrasive particles imbedded and the rolling removal of the unimbedded particles. Those unimbedded particles waste their energy in the interaction with the grinding material particles, in rolling, and even in the removal of the polishing plate. Consequently, the material removal efficiency is lowered. In addition, because the unimbedded particles are much larger than the sticking out parts of the imbedded particles, large debris is produced and thus the roughness of the surface is damaged. Low efficiency and rough surface worsen as the unimbedded particles grow in number and size. At this point, the material removal efficiency is still decided by E, the total energy participating in every rotation of the polishing head, and E_2, the energy needed in forming the fracture surface by removing unit volume material. Here

$$E = (E_0 - J - E_3) = n\overline{E}_1 + m\overline{E}_4 = VE_2 + m\overline{E}_4 \approx VE_2, \quad (7)$$

$$V \approx E/E_2 \approx (E_0 - E_3)/E_2, \quad (8)$$

where J is the heat loss in the polishing process, E_3 is the energy loss in the interaction and rolling of the unimbedded particles during each rotation of the polishing head, m stands for the number of the debris produced by unimbedded particles during each rotation of the polishing head, and $\overline{E}_4$ is the average energy needed for one piece of debris produced by unimbedded particles. Usually, J and mE_4 are much smaller than E_3 and VE_2 and are negligible. Although mE_4 is very small, the large pieces of debris produced by this energy can damage the roughness of the surface. Therefore, there are two factors that decide the roughness of the surface: V_L, the volume of the debris piece produced by the imbedded particles and V_{Rm}, the volume of the debris piece produced by the unimbedded particle, whose radius is R_m. Because $V_{Rm} > V_L$, V_{Rm} is the leading factor.

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