Study on Wear Mechanism of Diamond Particles in the Cutting of Pipeline Steel

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Abstract. The wear of diamond particles is an important factor that limits the working efficiency of diamond wire saws. In this paper, the physical model of diamond particle is established and the mechanical analysis is carried out. ANSYS finite element analysis software was applied to establishing unworn model and worn model for diamond particles. The cone angle of diamond particle, the protrusion height of diamond particle and the depth of the diamond particles press into the cutting face were analysed to study theirs effect on the shear stress extreme value of diamond particles in the process of cutting underwater pipeline. The results shown that the depth of the diamond particles press into the cutting surface and the cone angle of diamond particle have a great influence on the wear of the diamond particles, and the protrusion height of diamond particle is relatively small for the wear of the diamond particles.

1. Introduction

Wear mechanism of diamond particles is an important research field. In the process of cutting the underwater pipeline by the diamond wire saw machine, the diamond particles are subjected to severe impact, scraping and chip erosion of the material. Therefore, most diamond tools are faced with serious wear, and the wear of diamond particles will directly affect the processing efficiency and processing cost. Tönshoff [1] pointed out that the wear mechanism of diamond particles can be divided into four main forms: adhesive wear, friction wear, diffusion wear and abrasive particle breakage. Ersoy [2] studied the wear of diamond abrasive grains from ten different rock materials, and considered cutting power as a key factor which affects wear characteristics. Aydin [3] studied the wear performance of diamond circular saw blades in granite cutting and determined the effect of various operating variables on specific worn rates. Hui [4] studied the material removal mechanism and abrasive wear characteristics of diamond bead rope cutting rock. It is believed that the material removal mechanism is mainly volumetric fracture. Yilmazkaya [5] studied the effect of line speed and cutting speed on the unit wear and tear of a single wire cutter. Su [6] studied the change of diamond wear shape and blade height during the cutting process. Goel [7] used a molecular dynamics simulation method to study the wear mechanism of diamond tools on single crystal silicon during single-point diamond turning.

Research on the wear characteristics of diamond cutting tools has achieved a lot of results. However, due to the complexity of the problem, most of the work focused on the study of the wear type, worn morphology and worn process of diamond particles. In this paper, the process of sawing the pipeline steel by diamond wire saw is analysed, and the diamond particle is modelled and analysed. Through the finite element software, unworn model and worn model for diamond single-particle were established, and the influence of diamond particle parameters on wear was obtained.
2. Force analysis of diamond particle

Figure 1. Force state of diamond particle.

Diamond particles on the bead surface directly act on the workpiece material during cutting. The strength of the diamond particles is much greater than the strength of the workpiece material. Under the action of extrusion, the workpiece material yields to achieve the cutting effect. However, after the diamond particles are worn, the contact area is increased, the cutting effect is lowered, and sometimes the abrasive particles are detached from the binder. In order to analyze the cutting effect of diamond abrasive grains, it is assumed that the diamond particle on the bead surface is regular, diamond-shaped structures with the same particle size and diamond particles uniform adhesion to the surface of the binder material. Figure 1 shows the stress state of a single diamond particle on the bead surface. Where $F_T'$ is the axial pulling force along the sawing rope, $F_B'$ is the cutting surface resistance, $F'$ is the normal pressure of the single diamond particle along the cutting surface, $h_1$ is the average blade protrusion height of the diamond particle, and $h_2$ is the depth of diamond particle press into the cutting surface, $\phi$ is the cone angle of diamond particle.

In the quasi-static state, the depth of the diamond particles press into the cutting surface depends on the normal pressure, so it is necessary to first determine the normal pressure of the single diamond particles. This paper introduces a linear relationship based on the basic theory of nanoindentation testing:

$$F' = HA$$  \hspace{1cm} (1)

Where: $H$ is the indentation hardness of the cutting material, and $A$ is the projected area of the contact surface of the diamond particles and the cutting material.

According to the particle geometry, the specific expression can be obtained as

$$A = \frac{3\sqrt{3}}{4} \tan^2 \left( \frac{\phi}{2} \right) h_2^2$$  \hspace{1cm} (2)

Substituting equation (2) into equation (1), the expression of the pressure of a single diamond particle and its indentation depth can be obtained:

$$F' = \frac{3\sqrt{3}}{4} H \tan^2 \left( \frac{\phi}{2} \right) h_2^2$$  \hspace{1cm} (3)

Although the diamond particles have higher strength, they are more brittle. And impact and shear are prone to cracking, which causes the diamond particles to break or brittle. During the cutting process of the sawing rope, the end of the diamond particle is subjected to the shear stress caused by the frictional resistance. The resistance of a single diamond particle cutting surface is expressed as:
\[ F_3 = \frac{F_3L}{N\pi r w N l_d l_c} \]  

(4)

Where \( F_3 \) is the frictional resistance of the cutting surface, \( N_d \) is the number of diamond particles per unit area of the bead surface, \( N \) is the number of beads that are simultaneously cut, \( L \) is the total length of the saw rope, \( r_w \) is the outer radius of the bead, and \( L_d \) is the axial length of the diamond bead.

The average shear stress expression is:

\[ \tau = \frac{F_n}{A} \]  

(5)

According to the equation, \( h_2 \) and \( \varphi \) have a great influence on the shear stress.

### 3. Finite element model

Based on Fig. 1, the finite element model of the problem is established by ANSYS and the finite element analysis is carried out to obtain the influence of different parameters on the force and wear of diamond particles. This paper analyzes and discusses the situation based on unworn and worn.

The parametric APDL language is used to draw the geometric model of the problem. The definition of \( h_1 \) is the average protrusion height of the diamond particles, \( h_2 \) is the depth of the diamond particles press into the cutting surface, \( h_3 \) is the height of worn, and \( \varphi \) is the cone angle of diamond particle. The above four parameters are the parameters to be discussed in the finite element analysis.

The geometric model is meshed with a finer cell size. Based on the Saint-Venant principle, displacement constraints are applied to the side and bottom edges of the steel tube section to statically set the model. At the same time, according to the direction of the tension of the saw rope and the direction of the cutting pressure, the corresponding uniform load is added on the side line and the upper line of the adhesive part, and the mesh and the constraint are as shown in figure 2.

![Figure 2. Constraint and load.](image)

### 4. Results

#### 4.1. Result of unworn diamond

**4.1.1 Effect in the particle cone angle \( \varphi \)**

Taking \( h_1=0.4\text{mm}, \ h_2=0.04\text{mm}, \ 0.05\text{mm}, \ 0.06\text{mm}, \ 0.07\text{mm}, \ 0.08\text{mm}; \ \varphi=60^\circ, \ 75^\circ, \ 90^\circ, \ 105^\circ, \ 120^\circ. \)

The calculated internal shear stress extreme value of the diamond is shown in Figure 3.

It can be seen from the calculation results that the extreme value of shear stress in diamond decreases with the \( \varphi \) increase. This is mainly due to the increase in the inclination angle of the contact
surface between the diamond and the steel pipe. The shear stress extreme point is at the tip position, as is shown in Figure 4. It can be seen that the larger $\phi$ plays a significant role in reducing the wear of the diamond.

However, if the value of $\phi$ is large, the equivalent stress at the cutting point will be reduced, thereby reducing the cutting effect. Therefore, the proper angle $\phi$ plays an important role in both the wear resistance and the cutting effect.

In addition, it can be seen from the calculation results that the shear stress extreme value in diamond also decreases with the increase of $h_2$. This is due to the increased contact area between the diamond and the steel tube.

4.1.2 Effect in the average protrusion height $h_1$

Taking $h_2=0.04\text{mm}$, $h_1=0.30\text{mm}$, 0.35mm, 0.40mm, 0.45mm, 0.50mm; $\phi=60^\circ$, 75$^\circ$, 90$^\circ$, 105$^\circ$, 120$^\circ$. The diamond internal shear stress extreme value is shown in the figure 5.

It can be seen from the calculation results that the shear stress extreme value in diamond gradually increases with the increase of $h_1$, but the increase is relatively small. The shear stress extreme point is at the tip position. Therefore, adjusting the size of $h_1$ has little effect on the wear of diamond.
4.2. Result of worn diamond

4.2.1 Effect in the particle cone angle $\phi$
Taking $h_1=0.4\text{mm}$, $h_2=0.04\text{mm}$, $\phi=60^\circ$, 75°, 90°, 105°, 120°; $h_3=0.04\text{mm}$, 0.06mm, 0.08mm, 0.10mm, 0.12mm. The calculated internal shear stress extreme value of the diamond is shown in Figure. 6.

4.2.2 Effect in the depth of the diamond particles press into the cutting surface $h_1$
Taking $h_1=0.4\text{mm}$, $\phi=120^\circ$, $h_2=0.04\text{mm}$, 0.05mm, 0.06mm, 0.07mm, 0.08mm; $h_3=0.04\text{mm}$, 0.06mm, 0.08mm, 0.10mm, 0.12mm. The calculated internal shear stress extreme value of the diamond is shown in Figure. 7.

It can be seen from the calculation results that the shear stress extreme value in diamond decreases with the $\phi$ increase. This is mainly caused by the increase in the inclination angle of the contact surface between the diamond and the steel pipe. In addition, the shear stress extremes are greater when worn under the same conditions than when there is unworn. It is shown that the wear resistance of the worn diamond will decrease.

It can be seen from the calculation results that the shear stress extreme value in diamond decreases with the increase of $h_2$. This is mainly caused by the increased contact area between diamond and steel pipe. When $h_2=0.04\text{mm}$, the shear stress extreme point is located on the shallow surface of the diamond near the end of the contact surface. In other cases, the shear stress extreme point is located at the lower end of the contact surface. It can be seen that increasing $h_2$ can play a certain role in reducing the wear of diamond.
4.2.3 Effect in the average protrusion height $h_1$
Taking $h_2=0.4\text{mm}$, $\varphi=120^\circ$, $h_1=0.30\text{mm}$, 0.35mm, 0.40mm, 0.45mm, 0.50mm; $h_3=0.04\text{mm}$, 0.06mm, 0.08mm, 0.10mm, 0.12mm. The calculated internal shear stress extreme value of the diamond is shown in Figure. 8.

Figure 8. Location of shear stress extreme ($\varphi=120^\circ$).

It can be seen from the calculation results that the shear stress extreme value in diamond increases with the increase of $h_1$, but the increase is small. The shear stress extreme points are located on the shallow surface of the diamond near the end of the contact surface. It can be seen that adjusting $h_1$ has little effect on the wear of diamond.

5. Conclusion
In this paper, based on the worn and unworn conditions of diamond particles, the effect of the average protrusion height of the diamond particles $h_1$, the depth of the diamond particles press into the cutting surface $h_2$, the wear height $h_3$, and the cone angle of the particles $\varphi$ were analysed to study the shear stress extreme values of the diamond particles, that is, the impact on the wear of the diamond wire saw.

(1) The extreme value of shear stress in diamond shows an obvious downward trend with the increase of the depth of the diamond particles press into the cutting surface $h_2$.

(2) The shear stress in diamond increases with the increase of the average protrusion height $h_1$, but the increase is small.

(3) The extreme value of shear stress in diamond decreases with the increase of the cone angle of the particles $\varphi$. The larger $\varphi$ plays a significant role in reducing the wear of diamond.

(4) The shear stress extreme value is greater when there is worn under the same conditions than when there is unworn. It indicates that the wear resistance of the worn diamond will decrease.
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