Development of Aramid Fiber Reinforced Tool for Pneumatic Wheel Finishing

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Abstract. Aramid fibers are selected as a filler in polymer which can keep the outer abrasive particles more stable in high-speed machining process to irregular surface. Elastic modulus prediction model of fiber reinforced polymer has been established and confirmed by tensile test. Rules of stress and strain of pneumatic wheel with different volume ratios of fiber are given by simulation. Machining experimental results show it improves materials removal rate.

Introduction

Pneumatic wheel tool means that a kind of finishing tool whose inner elastic rubber layer drives outer abrasive particles for finishing high hardness freeform surface[1-2]. In this case, abrasive particles possess more cutting power than free abrasive particles. Moreover, its softness make pneumatic wheels can match with irregular freeform surface. Combined with robot technique, pneumatic wheel tool plays an important role in finishing process especially to laser hardening mold’s surface[3-6].

However, in order to improve efficiency and roughness of surface, contact process between pneumatic wheel and surface always happen at a situation with high speed rotation and deformation of wheel. It seems that partial inner elastic rubber cannot always keep strong enough to hold abrasive particles up. For this reason, distribution of force become inhomogeneous and working particles are inserted into surface at a deep depth. That results in scratches left on the surface need to be controlled[7].

To this problem, scholars focus on controlling contact force to keep scratches away in machining process as follows. Song et al aim at polishing efficiency and experimental results show that the order of main factors of contact force is: bonnet deformation > cutting velocity >ratio of working abrasives[8]. Cheung et al conclude the relationship between cutting force and feeding depth and confirm materials removal model[9]. Gong et al do researches on polishing parameters to optical spherical surface such as inner air pressure, feeding depth, cutting velocity et al. Reasonable bonnet polishing parameters ranges are given[10]. However, these researches listed above mainly choose to improve machining parameters to achieve optimization. But in ultra-precision machining process for higher accuracy and efficiency, a key point which should not be ignored is inner rubber layer whether can always prop outer abrasives up stably or not in the high speed rotation process[11-12]. So the problem comes that how inner rubber make a stable support for abrasives. Some scholars have done correlative researches as follows. Lu et al have done a structural design of a carbon fiber-reinforced polymer wheel for ultra-high speed grinding[13]. Jeon et al do researches on dynamic properties of carbon fiber reinforced polymer[14]. Singh et al figure out stress and deformation of fiber reinforced polymer composites[15]. All above researches focus on the rigid fiber reinforced polymer and it does not match the situation of softness pneumatic wheel. Zhu et al present effects of strain rate and temperature on mechanical properties of Kevlar 49 aramid fabric reinforced[16-17]. Zhege et al shows effect of cyclic loading on the mechanical properties carbon fiber reinforced polymer[18]. And Ji et al present mechanical performance of Lyocell short fiber reinforced polymer[19]. Although these researches shows the characteristic of softness fiber reinforced polymer, performance of wheel still
has not been good enough to fit for irregular freeform surface especially in the situation of high speed rotation and deformation of pneumatic wheel.

To these problems, this paper presents an adaptive pneumatic wheel tool based on aramid fiber reinforced method. Aramid fiber is used for achieving multi-dimension nets distribution in wheel’s polymer matrix. In this case, it can keep uniform performance of wheel in high speed rotation and drive abrasive particles stably for machining.

2 Design of pneumatic wheel based on aramid fiber reinforced method

During inner rubber of wheel vulcanization process, difference of regional distributions of polymer lead to difference of stress on the surface. Therefore, aramid fiber reinforced method is used to achieve multi-dimension nets distribution polymer of wheel for uniform performance of wheel as shown in Fig. 1.

![Fig.1 Fiber reinforced effects](image)

After fiber reinforced into initial polymer, it is expected to form multi-dimension net distribution types. Thereby, it can keep stable performance for driving abrasive particles with uniform stress in high speed rotation as shown in Fig. 2.

(a) Abrasives particles supported by unreinforced polymer

![Fig. 2 Contact effects of abrasive particles with workpiece](image)

(b) Abrasives particles supported by aramid fiber reinforced polymer

As shown in Fig.2, unreinforced polymer appears stress regional difference in contact process. It results in two problems. 1) Machining stress of abrasive particles on workpiece surface is difference and outer abrasives are over pushed with scratch damages left; 2) Inhomogeneous stress of abrasives particles anti-work on polymer. In high speed rotation, pneumatic wheel will become damaged seriously for short time. However, aramid fiber reinforced method is selected to help wheel form a uniform body for supporting particles and overcome regional difference of cutting stress to decrease scratch damages. It also can prolong life-span of wheel.

Aramid fiber was adopted to reinforce initial urethanes polymer with density of 1.41g/mm$^3$ and ratio of length to diameter of 1:80. Due to the high amino ratio of aramid fiber, it possessed good agreeableness with copolymer in mix process. HAP type of PPTA-pulp was used as dispersing solvent for mixing in advance, whose fiber volume ratio was 33.3%. Average length of main fiber was 1 mm and the ratio of superficial area to quality was 14m$^2$/g.

Mixed refining process of aramid fiber was operated by open mill machine and Roll nip was adjusted properly. And then the flow of cooling water was controlled. After that, PPTA-pulp
dispersing solvent was added into mixing process firstly. Then copolymer and compounding material were mixed into polymer. The mixture was filled into mold, and then the shape of wheel with fiber reinforced polymer was formed by pressed and heated process by vulcanizing machine. The fracture surface of polymer at 500 times of magnification were taken by SEM as shown in Fig.3.

(a) Initial rubber        (b) Fiber reinforced polymer

Fig.3 SEM photography of fiber reinforced pneumatic wheel

In microscopic view, fiber had been mixed with polymer at a form of chain type with directivity. It made up for deficiencies of initial polymer.

Modulus prediction of aramid fiber reinforced polymer plays an important role in pneumatic wheel’s characteristic analysis. The initial model based on Halpin-Tsai formula is given as[20]:

\[
E_z E_n^{-1} = \left(1 + \eta \xi \nu_f \right) \left(1 - \eta \nu_f \right)^{-1}
\]

(1)

Where,

\[
\eta = \left( E_z E_n^{-1} - 1 \right) \left( E_z E_n^{-1} + \xi \right)^{-1}
\]

(2)

Reinforced fibers shows appearance of breakage, length difference and distribution difference. Thereby, correction coefficient \( \zeta \) combined with average length is brought into for prediction modulus model. When orientation coefficient of fiber \( f \) changes, its reinforcement ability and \( \zeta \) decreases. Therefore, the equation can be given as :

\[
\zeta = 2 L d^{-1} \cos^2 \psi
\]

(3)

Orientation coefficient of fiber \( f \) is given as :

\[
f = 2 F(\psi) - 1
\]

(4)

Where

\[
F(\psi) = \int_0^{\pi/2} n(\psi) \cos \psi d\psi
\]

(5)

\( n(\psi) \) is function of fiber distribution whose expression is given as :

\[
\int_0^{\pi/2} n(\psi) d\psi = 1
\]

(6)

In this case, it can be concluded as:

\[
E_{z,o} = \left[1 + \eta L d^{-1} \nu_f \left(f + 1\right) \left(1 - \eta \nu_f \right)^{-1}\right] E_n
\]

(7)

Where, \( E_{L,O} \) is vertical modulus combined with fiber distribution.

\[
\eta = \left( E_z E_n^{-1} - 1 \right) \left[ E_z E_n^{-1} + L d^{-1} (f + 1) \right]^{-1}
\]

(8)

It can be obtained that \( \zeta \) and \( E_{L,O} \) increases with the growth of \( f \). According to equation 8 above, vertical modulus prediction formula can be combined with \( f \) conveniently. As for horizontal modulus, \( \zeta \) can be regarded as 2 in Halpin-Tsai formula[21]. Then it can be concluded as:

\[
E_x E_n^{-1} = \left(1 + 2 \eta \nu_f \right) \left(1 - \eta \nu_f \right)^{-1}
\]

(9)

Where,

\[
\eta = \left( E_z E_n^{-1} - 1 \right) \left( E_z E_n^{-1} + 2 \right)^{-1}
\]

(10)
$E_f$ is far more than $E_m$. So equation 8 above can be changed as:

$$E_v E_a^{-1} = (1 + 2\nu_f)(1 - \eta\nu_f)^{-1}$$

(11)

Due to the inhomogeneous fiber orientation, horizontal and vertical fibers form special angle as a whole. $E_T$ is affected by $\nu_f$. Therefore, effects that $\nu_f$ works on $E_T$ still need to be considered. When fiber orientation is inhomogeneous, $\zeta$ cannot be set as 2. $\nu_f$ can effectively compensate for errors. Where, $\zeta = 2 + K_f \nu_f$. $K_f$ is a constant related with volume effect, which is decided by factors such as fiber orientation, modulus of matrix and fiber. The equation. 10 can be concluded as:

$$E_v = \left[1 + (2 + K_f \nu_f)\nu_f\right](1 - \nu_f)^{-1} E_a$$

(12)

Fibers cannot always appear as straight and rigid form in polymer. Therefore, the orientation deviations of fiber will come out. According to these method above, vertical and horizontal modulus of fiber reinforced polymer are predicted to explain the relationship between strain and stress of pneumatic wheel. It establishes basis in theory for further machining analysis.

3. Simulation and Experiments

3.1 Simulation of fiber reinforced pneumatic wheel

Machining contact process of fiber reinforced pneumatic wheel with workpiece had been simulated by ANSYS. The parameters of model are listed as Table. 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of wheel $D_w$ (mm)</td>
<td>40</td>
</tr>
<tr>
<td>Thickness $\delta_w$ (mm)</td>
<td>2</td>
</tr>
<tr>
<td>Angle $\theta_w$ (°)</td>
<td>20</td>
</tr>
<tr>
<td>Length of workpiece $L_w$ (mm)</td>
<td>100</td>
</tr>
<tr>
<td>Width of workpiece $W_w$ (mm)</td>
<td>100</td>
</tr>
<tr>
<td>Poisson ratio $\mu$ (-)</td>
<td>0.47</td>
</tr>
<tr>
<td>Feeding depth $d_w$ (mm)</td>
<td>2</td>
</tr>
</tbody>
</table>

Simulation parameters were set according to experimental parameters. As a composite polymer reinforced by fiber, property of wheel has relationship with initial polymer and fiber, whose parameters are listed as Table.2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus of fiber $E_f$ (MPa)</td>
<td>3123</td>
</tr>
<tr>
<td>Elastic modulus of initial polymer $E_m$ (MPa)</td>
<td>3.012</td>
</tr>
<tr>
<td>Average length of fiber $L_f$ (mm)</td>
<td>2</td>
</tr>
<tr>
<td>Average diameter of fiber $d_f$ (mm)</td>
<td>0.25</td>
</tr>
<tr>
<td>Angle of fiber distribution $\Psi$ (°)</td>
<td>0-\pi</td>
</tr>
</tbody>
</table>

Based on theoretical analysis above, the elastic modulus of composite polymer of wheel can be concluded with the parameters in Table.2. In ideal situation, fibers are reinforced at uniform angles in wheel’s body as a whole. Therefore, fiber reinforced angle from 0 to $\pi$ should be brought in for calculation and description of multi-dimension net distribution. Combined with theoretical calculation, predictive modulus results are shown as Table.3 respectively at fiber volume ratio of 2.5%、3% and 5%.

<table>
<thead>
<tr>
<th>Group</th>
<th>Vertical modulus $E_{L-O}$ (MPa)</th>
<th>Horizontal modulus $E_T$ (MPa)</th>
<th>Volume ratio $v_f$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>5.809</td>
<td>5.532</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Fiber volume ratio needed to be controlled within 5% to keep orientation characteristics of fiber distribution. Thereby, regional accumulation situation of fiber could decrease. According to parameters in Table.1, simulation deformation results of wheel are shown in Fig.4.

![Fig. 4 Deformation of wheel](image)

(a) \( v_f = 0\% \)  
(b) \( v_f = 2.5\% \)  
(c) \( v_f = 3.3\% \)  
(d) \( v_f = 5.0\% \)

Fig. 4 Deformation of wheel\((E_m=3.012\text{MPa})\)

Deformation of pneumatic wheel without fiber is shown in Fig.4a. In the case, the deformation of wheel in contact process was inhomogeneous and has regional difference. When the fiber distribution volume ratio was 2.5% in Fig.4b, deformation area of composite polymer of wheel had changed obviously. However, it still was asymmetric deformation and not stable enough for high speed machining. When fiber distribution volume ratios were 3.3% and 5% respectively, deformation area of composite polymer was well-distributed regionally in Fig.4c and Fig.4d. It proved that fiber reinforced method could improve the strain of wheel for machining. Meantime, outer abrasive particles would not be pushed by wheel too much in deformation but obtained homogeneous stress from wheel. Stress of wheel is shown in Fig.5.

![Fig. 5 Contact stress of wheel](image)

(a) \( v_f = 0\% \)  
(b) \( v_f = 2.5\% \)  
(c) \( v_f = 3.3\% \)  
(d) \( v_f = 5.0\% \)

Fig. 5 Contact stress of wheel

As shown in Fig.5a, probability of stress peak like red area of wheel was the highest in the core contact area. And regional stress difference was obviously. In the case, inhomogeneous machining stress of abrasive particles would appear easily. When fiber volume ratio became 2.5% as shows in Fig. 5b, core contact area of wheel increased and distribution area of stress peak became narrow. When fiber volume ratio was 3.3%, core contact area spread uniformly and low stress distribution area like yellow area of wheel had been strengthened as shows in Fig. 5c. When fiber volume ratio became 5%, core contact area further spread in Fig. 5d. However, compared with Fig. 5c, stress distribution area showed little difference. Furthermore, when fiber volume ratio was ranged from 2.5% to 5%, contact stress of wheel increased with the growth of fiber volume ratio. It increased fast at fiber volume ratio ranged from 2.5% to 3.3% but further increased slow at fiber volume ratio ranged from 3.3% to 5%.

Based on the simulation analysis, it can be proved out that fiber reinforced pneumatic wheel rubber matrix can deal with the contact deformation problem of pneumatic wheel, which can spread core contact area and control stress balance to keep the outer abrasive particles uniformly for machining. Besides, overall contact stress of fiber reinforced wheel increases and it is benefit to promote processing efficiency oriented to workpiece with high hardmess.

### 3.2 Test of fiber reinforced pneumatic wheel
For obtaining elastic modulus of composite polymer with fiber, the tests had been operated by INSTRON machine. Under parameters of Table 2, the test groups had been marked as A1, A2 and A3 (different colors) respectively with different drawing directions under \( v_f \) of 2.5%, 3.3% and 5.0%. The test results are shown in Fig. 6.

![Graphs showing stress-strain curves for different drawing percentages](image)

**Fig. 6 Drawing data of fiber reinforced wheel**

Strain and stress curve of fiber reinforced wheel had been shown in Fig. 6. In machining process, abrasive particles were adhered on softness wheel’s surface. For this reason, strain of wheel needed to be controlled with 25%. Therefore, in calculation of elastic modulus, stress of polymer were recorded from strain \( \varepsilon \) of 2% to \( \varepsilon \) of 21%. In Fig 6a, there were difference among three groups with \( v_f \) of 2.5%. Stress of group one was higher than other two groups’. That means stress has important relationship with drawing direction and multi-dimension nets distribution of polymer is not formed stably. When \( v_f \) became 3.3%, drawing stress was higher than that of \( v_f \) of 2.5%. And difference of drawing stress among three groups decreased as shown in Fig. 6b. When \( v_f \) became 5.0%, the drawing stress showed very close results and it demonstrated distribution of fibers had formed a stable state in polymer which could bear drawing stress in different direction. It could accord with design standard of wheel. And ratio of \( E_L \) to \( E_m \) have been shown in Table 4 respectively in theory and in experiment.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>A0</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed depth ( d ) (mm)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Machining angle ( \theta ) (°)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Velocity ( n ) (r/min)</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Diameter ( D_p ) (μm)</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Ratio ( v_f ) (%)</td>
<td>0</td>
<td>2.5</td>
<td>3.3</td>
<td>5</td>
</tr>
<tr>
<td>Time ( t ) (min)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Laser hardening mold with hardness of 532HV and average roughness \( R_a \) of 1.5μm was selected as workpiece. The initial surface were taken by ZYGO as shown in Fig. 7.
Comparison tests between $A_0$ and $A_3$ were carried on under the parameters in Table. 5. The results are shown in Fig.8.

It was obtained from Fig.8a that performance of workpiece surface was promoted at a certain extent by pneumatic wheel of group $A_0$. But it was not still ideal result enough due to the obvious scratch damages on workpiece surface. When it was machined by pneumatic wheel of group $A_3$, performance of workpiece surface was improved observably and the scratch damages on surface were under the control. It proves that the fiber reinforced pneumatic wheel shows better machining ability than ordinary pneumatic wheel’s.

According to the machining parameters in Table. 5, machining results of pneumatic wheel from group $A_0$, $A_1$, $A_2$ and $A_3$ were recorded as listed in Table. 6.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$A_0$</th>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average roughness $R_a$ ($\mu m$)</td>
<td>0.157</td>
<td>0.135</td>
<td>0.073</td>
<td>0.069</td>
</tr>
<tr>
<td>Materials removal rate $R'$ (mg/min)</td>
<td>0.5</td>
<td>0.6</td>
<td>1.5</td>
<td>2.1</td>
</tr>
</tbody>
</table>

From Table.6, machining results of aramid fiber reinforced pneumatic wheels from three groups were different. Due to distribution defect of fiber in group $A_1$, situations of both inadequate contact or over load contact would happen between abrasives and workpiece. It lead to high average roughness and low material removal rate. Wheels from $A_2$ and $A_3$ achieved similar average roughness. However, stress of $A_3$ was more higher than that of $A_2$, which lead to high machining ability. Above all, fiber reinforced method indeed helps pneumatic wheel promote materials removal rate and meantime improves average roughness of surface.

4. Conclusion
This paper research on machining properties of adaptive pneumatic wheel based on aramid fiber reinforced method. It commits to form multi-dimension net distribution of fiber in composite polymer of wheel to achieve high efficient machining and decrease scratch damages.

1. Based on Halpin-Tsai formula, fiber orientation coefficient is introduced and modulus prediction model of fiber reinforced pneumatic wheel is established. Then relationship between strain and stress of fiber reinforced pneumatic wheel is established in dynamic contact process.

2. Machining process of fiber reinforced pneumatic wheel is simulated by ANSYS. Strain and stress of wheel with different volume ratios of fiber are shown, which confirm that fiber reinforced method can deal with the contact deformation problem of pneumatic wheel. It also can balance stress of core contact area and control machining stress.

3. The aramid fiber reinforced wheel is made by mixed refining and modeling process. Multi-dimension nets distribution of fiber is observed by SEM in composite polymer. And elastic modulus prediction model is proved out by drawing test. It is obtained that when fiber volume ratio are 2.5% and 3.3%, wheels present anisotropic characteristic in drawing processes under different directions. And fiber volume ratio of 5.0% is confirmed as the best parameter of wheel to form stable net distribution of fiber in polymer.

4. Laser hardening mould is machined by fiber reinforced pneumatic wheel. Materials removal rate has been promoted from 0.5mg/min to 2.1mg/min and average roughness is improved from 0.157 μm to 0.069 μm. It is confirmed that fiber reinforced pneumatic wheel could improve the quality of workpiece surface and control the scratch damages.

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