Experimental study and prediction on impact scratching of single abrasive for K9 glass

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Abstract: The orthogonal test $L_{16}(4^3)$ was designed, and the impact scratching experiment for K9 glass was carried out by using Vickers diamond indenter on the DMG ULTRASONIC 70-5 linear. The three-dimensional morphology of the surface for glass was observed by scanning electron microscope (SEM), which was compared with that in the quasi static state. The strain rate of the grinding process was obtained by choosing the contact zone length as the impact contact length, which was the evaluation index of impact. The relationships between strain rate and the depth of radial crack, strain rate and the depth of transverse crack, strain rate and normal scratching force were first analysed. The results showed that the depth of radial crack, the depth of transversal crack and normal scratching force decreased with the increase of strain rate. The two-layer BP neural network was established, which took the strain rate as input variables. The depth of radial crack, the depth of transversal crack and normal scratching force were predicted and the errors were within 10%, which indicated that the prediction results of BP neural network were reliable.

Keywords: impact scratching; K9 glass; strain rate; depth of crack; BP neural network.


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1 Introduction

Hard brittle materials such as optical glass and engineering ceramics, interest in grinding of advanced ceramics over last two decades, which are widely used in aerospace, petrochemical industry, electrical and electronic engineering, automobile and manufacturing with their low density, chemical stability, high hardness and high strength (Chen et al., 2015; Ma et al., 2014; Gu et al., 2011a, 2011b). On the contrary, they are typical difficult-to-machine materials owing to its great hardness and low fracture toughness. Therefore, it is important to research the removal mechanism and surface formation mechanism of hard brittle materials, which can improve the efficiency and the accuracy.

Although great progress of researching for hard brittle materials has been made, the removal mechanism and surface deformation characteristic of hard brittle materials are still in the exploratory stage. Jiang et al. (2011) observed a sharp ductile-to-brittle transition (DBT), and proposed the shear transformation zone volume to quantitatively characterise the DBT behaviour in fracture of metallic glasses. Esmaeilzare et al. (2014) carried the grinding experiment for Zerodur® glass ceramics, and researched the surface roughness and sub-surface damage. The prediction model was established, and the results showed that the prediction model was reliable. Single grain scratching is an effective means, which can research the material removal mechanism and the surface deformation characteristic. Many scholars conducted experimental study for hard brittle materials by single grain scratching. Meng et al. (2015) carried the nano-scratching test for 6H-SiC by using a Berkovich diamond indenter, the results indicated that phase transformation has not occurred during the nano-scratching process of this material. Gu et al. (2011a) carried the quasi-static scratching test of single grit for optical glass BK7, and researched the surface morphology for coupling scratching of double grits.

In the process of grinding, the abrasives have strong impact because of the high grinding speed and the low removal rate (Xiu et al., 2014). The quasi-static scratching is difficult to characterise the impact effect between abrasive and workpiece in grinding.
process because of the low scratching speed. Therefore, carrying out the impact scratching of single grit for hard brittle material plays an important role in researching surface and sub-surface damage in grinding process. Strain rate, the first derivative of strain, can characterise the materials deformation speed, which can be used as an evaluation index for impact effect of impact scratching process. Artificial neural network has very strong memory, nonlinear mapping and self-learning ability, and the prediction accuracy is high in the range of the given training samples. Yang et al. (2011) proposed an identification method for the key thermal stiffness of a machine tool based on the thermal error neural network prediction model. Application of the method on a viaduct gantry machining centre for its key thermal stiffness identification showed that the identification results are consistent with the verification test results. Hao et al. (2006) improved BP neural network by genetic algorithm, and the SPRT cutting experiment was carried out. The SPRT cutting force was predicted by GA-BP neural network, the results showed that the GA-BP neural network was reliable.

In this paper, the orthogonal test L_{16} (4^4) was designed, and the impact scratching experiment for K9 glass was carried out by using Vickers diamond indenter on the DMG ULTRASONIC 70-5 linear. In order to explore the influence on depth of crack and the normal scratching force, the strain rate of impact scratching was obtained by theoretical derivation. And the two layer BP neural network was established with the strain rate as the input, by which the depth of crack and the normal force are predicted.

2 Experiment device and condition

The size of workpiece is 20 mm × 20 mm × 20 mm. In order to remove the glass damage layer, the surface of the workpiece is traditionally polished (the polishing powder is cerium oxide). The surface roughness of the polished workpiece is detected by atomic force microscopy (70 μm × 70 μm), the value of which is Ra = 2 nm [Figure 1(a)]. The length chisel edge for diamond Vickers indenter is less than 1 μm, and the angle is 136° (±15°).

Figure 1  (a) Surface topography of polished workpiece (b) Experiment device (see online version for colours)
Experiment device is shown in Figure 1(b). Two Vickers indenters, one of which with a diamond grit and another with no diamond grit, are placed symmetrically on the sides of the cutter bar, which can ensure the stability in impact process. The rotation radius is 20 mm. The impact scratching experiment for K9 glass was carried out on the DMG ULTRASONIC 70-5 linear, and the scratching force was measured by the three dimensional Kistler 9257B dynamometer. The experiment of quasi-static scratch is also conducted on DMG ULTRASONIC 70-5. And the rotation speed of spindle is 0, the feed speed is 100 mm/min. The workpiece coordinate was established by using the three point levelling system of machine tool. There was no fluid cooling in impact scratching because of the small scratching depth and short time.

In order to research the influence of various parameters for the surface and sub-surface damage, three orthogonal test L₁₆ (₄³) was designed (as shown in Table 1).

### Table 1 The factors and levels of orthogonal test

| Level |  
|-------|-------|-------|-------|-------|
|       |  
| Factor | n₀  r/min | v₀  mm/min | a₀  μm |  
| 1     | 2,000     | 100     | 4   |  
| 2     | 4,000     | 200     | 6   |  
| 3     | 6,000     | 300     | 8   |  
| 4     | 8,000     | 400     | 10  | 

### 3 Results and discussion

#### 3.1 Analysis of sub-surface and surface morphology in impact scratching

The three-dimensional morphology of the surface for glass was observed by Hitachi SU8010 scanning electron microscope (SEM). The workpiece was tumbled by spray-gold before observing by SEM because the K9 glass is insulator. The sub-surface of workpiece was polished by the traditional cross-section polishing. After the polishing process, the sub-surface was ultrasonically cleaned and tumbled by spray-gold. Then the SEM was used to observe the morphology of the sub-surface.

As shown in Figure 2, there were typical radial crack expressed as $h_1$ and transverse crack expressed as $h_2$ in the sub-surface.

The process and the surface morphology of impact scratching for K9 glass were different of that in quasi-static scratching because of the high speed and the impact effect. The surface morphology of impact scratching is shown in Figure 3(a) and the surface morphology of quasi-static scratching is shown in Figure 3(b). There were more micro cracks [dotted ellipse in Figure 3(a)] in the groove surface for impact scratching. There was obvious impact-spalling and shell-shape fracture in scratching surface [dotted line in Figure 3(a)]. While, the size of surface crack for quasi-static scratching was bigger than that in impact scratching [dot dash line ellipse in Figure 3(b)], and the quantity of surface crack is less. The material removing was through the extension of large crack. And there were many larger cracks extending to the surface of workpiece [full line ellipse in Figure 3(b)].
Figure 2 Sub-surface crack

Figure 3 Comparison of the impact scratching and the quasi-static scratching for surface groove morphology (see online version for colours)
Figure 4(a) is the sub-surface morphology of impact scratching and Figure 4(b) is the sub-surface morphology of quasi-static scratching. There were more small collapse and sub-surface crack in the groove section for impact scratching, while there were more large edge-breaking in the groove section for quasi-static scratching.

Figure 4  Comparison of the impact scratching and quasi-static scratching for sub-surface morphology (see online version for colours)

3.2 The influence of strain rate on crack depth and normal scratching force

3.2.1 Derivation of strain rate in impact scratching for single grit

As shown in Figure 5 (Stephen, 2008), in the process of grinding, the abrasives have strong impact, which plays an important role in researching surface and sub-surface damage. Spindle speed, feed rate and depth of scratching are the main factors which influence the process of impact scratching. And the strain rate which is related to impact scratching parameters can characterise the impact effect.

In order to analyse the strain rate of the impact scratching process, the cutting process can be regarded as a single diamond grit scratching the surface of workpiece. As shown in Figure 5, the abrasive began to contact with the workpiece surface from $F'$. And the cutting path $F'B'C'A'$ is a cycloid which is synthesised by scratching speed $v_s$ and feed speed $v_w$. The shaded part $AF'A'$ is the undeformed shape of chip in grinding. $B'$ is the origin of coordinate system X-Y. When the rotation angle of grinding wheel is $\theta'$, the trajectory of abrasive is as the follow:

\[
\begin{align*}
    x &= \frac{d_s}{2} \sin \theta' \pm \frac{d_s}{2} \frac{v_w}{v_s} \theta' \\
    y &= \frac{d_s}{2} (1 - \cos \theta')
\end{align*}
\]  

(1)

where $v_w$ is feed speed; $v_s$ is linearspeed; $d_s$ is diameter of cutter bar; $\theta'$ is rotation angle of indenter.
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Figure 5 The scratching path of single grit

Because the rotation angle $\theta'$ ($0^\circ < \theta'$) is very small, equation (1) can be simplified as:

\[
\begin{align*}
  x &= \left(1 \pm \frac{v_w}{v_s}\right) \frac{d_s}{2} \theta' \\
  y &= \frac{d_s \theta'^2}{4}
\end{align*}
\]

(2)

So, the scratching path of abrasive is:

\[
y = \frac{x^2}{d_i \left(1 \pm \frac{v_w}{v_s}\right)^2}
\]

(3)

The scratching path of abrasive is $F'B'A'$, the length $F'B'$ can be represented as the half of translation $s$ of time interval for two successive scratching, the length of scratching path $F'B'A'$ is:

\[
l_k = \int_0^\theta d_k \frac{s}{2}
\]

(4)

where, $s$ is the translation of time interval for two successive scratching, $d_k$ is the integral of scratching path.

$d_k$ is substituted in equation (4), and the following result is gotten:

\[
l_k = \left(1 \pm \frac{v_w}{v_s}\right) \frac{d_k \theta}{2} + \frac{\theta^3}{6 \left(1 \pm \frac{v_w}{v_s}\right)} + \frac{s}{2}
\]

(5)

The $\theta$ is very small, the high order quantity of which can be neglected. So the arc length $AB$ can be equivalent to the chord length. $s/2$ is too short compared with the length of scratching path to be neglected. So, equation (5) can be simplified as:

\[
l_k \approx \left(1 \pm \frac{v_w}{v_s}\right) l_k
\]

(6)
where $l_c$ is contact length, $l_c = (a_p d_s)^{1/2}$, $a_p$ is the scratch depth.

Therefore, the action time of single diamond grit in the contact zone can be represented as:

$$t = \frac{l_c}{v} = \frac{1 \pm \frac{v_s}{v_s}}{(a_p d_s)^{1/2}}$$

(7)

where in down-grinding is ‘−’, in up-grinding is ‘+’.

The length of contact arc is very short, and average strain rate of contact layer can be represented as scratching speed divided by the contact length, namely:

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{1}{l_k} \frac{dl_k}{dt} = \frac{1}{l_k} \frac{v}{t} = \frac{v_s}{(a_p d_s)^{1/2}}$$

(8)

In impact scratching experiment, the strain rate changes with the change of impact scratching parameters for single diamond grit. As shown in Figure 6(a) and Figure 6(b), the depth of radial of crack and the depth of transversal crack decreased with the increase of strain rate. With the increase of strain rate, more micro cracks will be generated due to the impact wave and the cracks will bear the stronger impact. As is shown in Figure 6(c), the normal scratching force decreased with the increase of strain rate. This is because that the strength of glass material enhanced with the increase of strain rate. So, the crack extends more difficulty. The chip was removed when the size of crack is small, and the normal scratching force decreases.

3.2.2 The principle of BP neural network

BP neural network (back-propagation network), which applied error back-propagation arithmetic to train network. Guiding ideology of BP neural network was that modified network weights and threshold value were along the decline direction of expression function.

$$x_{k+1} = x_k - a_k g_k$$

(9)

where $x_k$ was the current weight and threshold value matrix, $g_k$ was the gradient of current expression function, $a_k$ was learning rate.

Option activation function was expressed as:

$$\varphi(v) = \frac{1}{1 + \exp(-\alpha v)}$$

(10)

$s$ represented a certain known specimen, $O_i^s$ represented relevant output state, $H^s_i$ was implicit strata cell, $I^s_i$ was output cell, $w_{ij}$ was from the weight of interlayer to that of
output layer, \( w_{ij} \) was from the weight of input layer to that of output layer. The output of implicit cell for specimen was expressed as:

\[
\overline{h_j^i} = \sum_{k=1}^{j} \overline{w_{jk}} I_k^i
\]

(11)

The relevant output state was listed as:

\[
H_j^i = \varphi \left( \overline{h_j^i} \right) = \varphi \left( \sum_{k=1}^{j} \overline{w_{jk}} I_k^i \right)
\]

(12)

Final output of network was expressed as:

\[
O_j^i = \varphi \left( \sum_{j=1}^{i} w_{ij} \varphi \left( \sum_{k=1}^{j} \overline{w_{jk}} I_k^i \right) \right)
\]

(13)

The error was expressed as:

\[
E(W) = \frac{1}{2} \sum_{i,j} \left[ T_j^i - \varphi \left( \sum_{j=1}^{i} w_{ij} \varphi \left( \sum_{k=1}^{j} \overline{w_{jk}} I_k^i \right) \right) \right]^2
\]

(14)

Every step correction was expressed as:

\[
\Delta w_{ij} = -\eta \frac{\partial E}{\partial w_{ij}} = \eta \sum_s \left[ T_j^i - O_j^i \right] \varphi' \left( h_j^i \right) H_j^i = \eta \sum_s \delta_j^i H_j^i
\]

(15)

All modified weight was as follow:

\[
\Delta w_{pq} = \eta \sum_s \delta_j^i v_q^s
\]

(16)

3.2.3 The prediction of crack depth and normal scratching force

The two layer BP neural network was established, the number of hidden layer neuron was assumed as follow, namely, the number of radial crack depth, transverse crack depth, and the normal force were respectively 100, 60 and 50. The numbers 1, 2, 4, 5, 6, 8, 9, 10, 12, 13, 15, 16 group of data are training data, and the numbers 3, 7, 11 and 14 group of data are training verification data. The implicit training function is ‘tansig’, the training function of output layer is ‘purelin’, the learning function of the weight and threshold value for back-propagation network is ‘learngdm’, the training function of back-propagation network is ‘traingdx’. The maximum training algebra is 10,000, training speed is 0.05, training error is 0.01. The prediction results of BP neural network are shown in Figure 6. The predicted value is consistent with the test value, which indicated that the prediction results of BP neural network were reliable.
Figure 6  Prediction results and the relationship between strain rate and, (a) radial crack depth (b) transverse crack depth (c) normal scratching fore (see online version for colours)
4 Conclusions

There were more micro cracks in the groove surface for impact scratching, and there was obvious impact-spalling and shell-shape fracture in scratching surface. While, the size of surface crack for quasi-static scratching was bigger than that in impact scratching. The material removing was through the extension of large crack. And there were much larger crack extending to the surface of workpiece in quasi-static scratching.

The relationships between strain rate and the depth of radial crack, strain rate and the depth of transverse crack, strain rate and normal scratching force were first analysed. The results showed that the depth of radial of crack, the depth of transversal crack and the normal scratching force decreased with the increase of strain rate.

The two layer BP neural network was established, which took the strain rate as input variables. The depth of radial crack, the depth of transversal crack and normal scratching force were predicted and the errors were within 10%, which indicated that the prediction results of BP neural network were reliable.

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