Analysis of flow field of hydrodynamic suspension polishing disk based on multi-fractal method

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Abstract: Amorphous film is an important amorphous material, which has a wide application prospect in the aspects of electronics, mechanics, chemical industry, national defence and so on. The quality of amorphous film substrate has a significant impact in the amorphous film performance. Hydrodynamic suspension polishing is a super-smooth and non-damage polishing method, which is suitable for the processing of amorphous film substrate. The characteristic of disk’s flow field is the key factor for influencing the quality of polishing. The movement and distribution of abrasives in flow field is analysed in this paper by high speed photography technology. The distribution of bubbles and abrasives is extracted by MATLAB in the dynamic flow field of hydrodynamic suspension polishing based on fractal and multi-fractal theory. The multi-fractal spectrum is calculated and the association of multi-fractal spectra is analysed. The results show that when buoyancy meets the requirement, the lower the polishing disk rotational speed, the more uniform abrasive distribution. Polishing effect will be better with well continuity of polishing slurry.

Keywords: multi-fractal; flow field; multi-fractal spectra; suspension polishing.


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1 Introduction

Amorphous material is a new widely studied field in material science and a new important material which is rapidly developing. Amorphous film is an important amorphous material. Compared with crystalline film, amorphous film commonly has higher micro-hardness, better wear resistance and corrosion resistance. Some amorphous film also has a good catalytic activity and magnetic property. Amorphous film has a widely application prospect in the aspects of electronics, mechanics, chemical industry, national defence because of its excellent property in physics, chemistry, mechanics and anticorrosion.

As one of important flow polishing methods, the main characteristic of hydrodynamic polishing technology is using dynamic-pressure of liquid to realise high-precision polishing. Due to the high rotational speed of cutting tool and hydrodynamic effect of wedge interaction between cutting tool and workpiece, film is formed between cutting tool and workpiece. And abrasive flow entered into the film flow field which will be received by field shear stress, which can drives abrasive flow to machining workpiece surface. Hydrodynamic polishing technology includes dynamic-pressure suspension polishing, suspension polishing, flow suspension processing and so on and the requirement of high quality surface and reproducibility can be meet (Wang et al., 2011; Zhan et al., 2010; Zhang et al., 2007; Ji et al., 2012; Hung et al., 2012, 2011; Chi and Suo, 2010). The research of hydrodynamic polishing is constantly developing, Y.T. Su and his colleague have taken a deep research on hydrodynamic polishing. (Su and Sheen, 1999; Su et al., 1996, 2003).

In 1975, Benoit B. Mandelbrot first creatively proposed the word ‘fractal’ and used it to describe the things whose topological dimension was less than its Hausdorff dimension. He published famous book Fractals: Form, Chance and Dimension in which he elaborated ‘fractal’ further that marked the naissance of fractal theory. As a method which used to deal with complex problem, fractal theory has been widely applied in mechanical science, tribology, physical chemistry, material science, computer graphics, biology, economics, astronomy, informatics, linguistics and other science fields.

The movement and distribution of abrasives in the flow field with the working condition is analysed in this paper by high speed photography, based on which we have done several works below. The results show that:

1. By controlling the rotational speed of polishing disk, the suspension height of hydrodynamic suspension polishing disk can be quantitatively controlled and the processing quality can be guaranteed.
In order to get a better processing quality and ensure the disk’s suspension height, the rotational speed of polishing disk should be controlled within 50 r/min and be as small as possible.

2 Experiment scheme

2.1 General scheme

The suspension height of disk and the rotational speed of disk are proportional. After analysing the influence of rotational speed on multi-fractal spectra which reflect the characteristics of flow field, the characteristics of flow field can be controlled by controlling rotational speed. The flow field of hydrodynamic suspension polishing disk is a film field whose thickness is between several microns and several tens of microns. So it’s difficult to intuitively observe the movement of fluid in flow field and analyse its characteristics by particle image velocimetry (PIV).

Figure 1 Fractal experiment platform (see online version for colours)


In view of the difficulty to directly observe the characteristics of flow field, a method based on multi-fractal theory which can be used to study the flow characteristics of hydrodynamic suspension polishing is proposed in this paper. The key of this method is
designing a reasonable experiment scheme and establishing effective ways of fractal experiment, which can provide the basis of multi-fractal theory for analysing characteristics of flow field.

Fractal experiment platform is showed in Figure 1. The experiment platform includes observation system and polishing system. Wedge polishing each structured surfaces of the base plate consists of a slope and a plane, the length in the circumferential direction is B, the width of the radius is L, B * L is 20 mm * 32 mm. The size will affect film flow field and then change the polishing effect. The observation system consists of high speed camera and multi-function bracket. The polishing system mainly consists of NANOMAX polishing machine, transparent hydrodynamic suspension polishing disk and trimming ring.

Trimming ring will rotate driven by the friction function of polishing pad, but the retaining ring and friction ring will limit it and keep it rotating in a position. Thus the movement transparent hydrodynamic suspension polishing disk in the trimming ring is limited in a settled area. The experiment platform is designed as the requirement of realising the analysis of multi-fractal theory which can overcome the difficulties of direct observation and many kinds of required data and image can be obtained.

2.2  Shooting the flow characteristics of polishing disk

In working condition, the suspension height of polishing disk is about tens of microns, so high speed camera is used to shoot the changing characteristics of bubble distribution in flow field of hydrodynamic suspension polishing with different rotational speed of polishing disk. The rotational speeds of NANOMAX polishing machine are 10 r/min, 20 r/min, 30 r/min, 40 r/min, 50 r/min and 60 r/min.

For clearly shooting effect during the experiment, two steps and two points should be noted. The followings are two main steps:

a  The setting of high speed camera, mainly includes shooting speed, amplification, shutter speed and resolution. In figure 2, the shooting speed is 250pfs. The shutter speed is 1/2000 second. The resolution is 640 * 480. The amplification will be taken respectively as 5, 10, 20, 30, 40 and 50.

b  Focal length setting, after the high speed camera is been set as above, in order to obtain clearest shooting effect, the focal length can be adjusted by adjusting multi-function bracket and fixed bracket.

Figure 2  Parameter setting of high speed camera (see online version for colours)
The following are two points:

a. Focal length needs to be adjusted after every change of amplification.

b. After every change of NANOMAX grinding and polishing machine’s rotational speed, test shooting need to be taken. If we can’t obtain clear dynamic images with current shutter speed, the speed needs to be adjusted. Typically the shutter speed needs to increase while the rotational speed of NANOMAX grinding and polishing machine increase.

3 Multi-fractal spectra of suspension polishing disk

The images we obtain by high speed photography technology in fractal experiment are colourful. According to the feature and requirement of box-counting method theory, images need to be processed in binarisation so that we can get threshold images. The key of binarisation process is to select a threshold which will be a dividing point. The one larger than threshold will be 1 and the one less than threshold will be 0. Thus colourful images have been converted to threshold images which are called black and white images and only have the value of 1 and 0. Different colourful images have different peak value distributions. So it can select different binarisation thresholds with the requirement of fractal feature. There are available library functions in MATLAB software to offer the threshold selection of different fractal images.

Under 40 times lens, the bubble distribution characteristics with different rotational speed in flow field are shown in Figure 3.

Figure 3 Flow bubble distribution characteristics with different rotational speed under 40 times lens, (a) 10 r/min (b) 20 r/min

At speed between 10 r/min and 60 r/min, the left parts of the images are the colourful images shot by high speed camera. The right parts are the corresponding threshold
images. The selected binarisation threshold values show in Table 1. The black parts of threshold images express blue ink part while the white parts are the air in liquid.

Table 1  Selected binarisation threshold values of fractal images with different rotational speeds

<table>
<thead>
<tr>
<th>Rotational speed (r/min)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold values</td>
<td>0.7412</td>
<td>0.7824</td>
<td>0.7882</td>
<td>0.8059</td>
<td>0.8510</td>
<td>0.8490</td>
</tr>
</tbody>
</table>

4  Box-dimension analysis of flow field

From box-dimension fitting curves of fractal images with different rotational speeds, the fractal dimension of flow bubble distribution can be calculated by fractal geometry theory. The box-dimension values are the slopes and the sizes are shown in Table 2. The size of fractal dimension expresses the bubble’s density degree. The higher bubble’s density degree is the larger fractal dimension will be. But the uniformity of bubble distribution is not acquired from simple fractal dimension. So it needs to calculate multi-fractal spectra for analysis.

Table 2  Box-dimension values of fractal images with different rotational speeds

<table>
<thead>
<tr>
<th>Rotational speed (r/min)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractal dimension value</td>
<td>1.812</td>
<td>1.830</td>
<td>1.961</td>
<td>1.969</td>
<td>1.981</td>
<td>1.993</td>
</tr>
</tbody>
</table>

5  Results of multi-fractal spectra test and analysis

After the above research, we know that the rotational speed of polishing disk has close association with the buoyancy, bubble density, bubble distribution and abrasive distribution of flow field of hydrodynamic suspension polishing disk. The rotational speed of polishing disk is the tie between multi-fractal spectra and bubble distribution and also is the tie among above parameters. So we will first analyse the association between multi-fractal spectra and the rotational speed of polishing disk.

Programming based on the algorithm given above and selecting q between –5 and 5, we integrate multi-fractal spectra of fractal images with different six speeds and make a comparison which is shown in Figure 4 (Zhou et al., 2000a, 2000b). From Figure 4, we can see that every fractal spectrum has a tangent point with linear \( f(\alpha) = \alpha \) and the shape of \( f(\alpha) \) looks like a left hook, of which characteristics are consistent with the judging criterions of multi-fractal spectra. The left hook shapes of multi-fractal spectra show that large probability distribution occupies the dominant position in fractal images studied with different rotational speed.

The polishing speed has close associations with multi-fractal spectra. The shapes and positions of multi-fractal spectra have more or less changes with different rotational speeds. From the figure we can see that when the rotational speed of polishing disk increases, the shapes of multi-fractal spectra become wider and the value of \( f(\alpha) \) also becomes bigger.
6 Conclusions

This paper analyses the abrasive movements and distribution based on the shooting experiment of flow field. The calculation of multi-fractal spectra is realised by the relevant algorithm. The mass index obtained from calculation is analysed, which has been verified that the dynamic flow fields of hydrodynamic suspension polishing disk has multi-fractal characteristics. The association between multi-fractal spectra and rotational speed of polishing disk and the association between multi-fractal spectra and bubble distributions in flow field is analysed in detail. The results show that the higher rotational speed of polishing disk is, the wider fractal spectrum is and the more non-uniform bubble distribution is. Meanwhile, the increasing of \( f(D)_{\text{max}} \) expresses that the percentage of bubbles in whole image increases. On the contrary, the lower rotational speed of polishing disk is, the narrower fractal spectrum is and the more uniform bubble distribution is. Meanwhile, the value of \( f(D)_{\text{max}} \) decreases while the percentage of bubbles decreases and the continuity of polishing slurry increases. The final conclusion is:

1. The suspension height of hydrodynamic suspension polishing disk can be controlled quantitatively and the quality can be ensured by controlling the rotational speed of polishing disk.

2. In order to get better processing quality and ensure the disk’s suspension height, the rotational speed of polishing disk should be controlled within 50r/min and selected value should be as small as possible.
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References


