Mechanical scribing test analysis of lateral ridges law on aluminum

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Abstract. In order to study the rule of lateral uplift of pure aluminum (purity is 99.999%) during mechanical scribing, based on the mechanical scribing test device, the tool tip angles are 80 °, 85 °, 90 °, 95 °, 100 °. The diamond cone cutter is used to perform mechanical scoring test on pure aluminum with a depth range of 5μm-25μm. Through the bump height detection analysis, lateral ridge height and groove depth - mathematical statistical relationship knife sharp corners, through the known parameters such as groove depth, groove on the bump height is pre-sentence, thereby pre-Groove play an important role in the control.

1. Introduction
Mid-step gratings, prism sheets, etc. are optical elements with a V-groove structure. According to different functions, the theoretical groove depth of the middle step grating is 5.06μm, and the groove depth of the prism sheet is generally 10-25μm, and the deepest can reach 50μm. By processing the metal surface into a master with a V-groove structure, replication and mass production can be achieved. The processing quality of the master groove will directly determine the quality of a large number of replicas. Taking a mid-step grating as an example, in order to improve the plastic forming ability of the groove shape and prolong the service life of the diamond tool, the aluminum plate substrate[1] is usually mechanically scribed into grooves to make a master. However, for large-depth V-shaped grooves, the material mechanical and physical properties of larger-thickness aluminum coatings are difficult to ensure uniformity, which affects the quality of the scribed grooves[2]. Therefore, using the target of vapor-deposited aluminum film-pure aluminum with a purity of 99.999% as the scribe master material is a good experimental choice.

During the scoring process, the diamond cutter extrudes the metal into grooves and produces plastic bumps on both sides. With the change of the negative rake angle and the depth of the engraving knife, three scribe forming methods will appear. When the scoring depth is greater than the height of the shunt point on the blunt circle of the blade tip, when the working negative rake angle is large, a scoring method combining scoring and ploughing is generated to squeeze into a groove. This process does not generate chips and groove. The surface quality is good; as the working negative rake angle decreases, the processing method gradually changes from plow cutting to cutting and generates chips. The phenomenon of peeling and tearing on the surface of the material will also affect the surface quality of the groove. When the scoring depth is less than the height of the diverting point on the blunt circle of the blade tip, only plow cutting occurs, but it does not have functional groove characteristics[3-5]. In addition, different diamond tool forms and different processed material properties will have different effects on the machining quality of the groove. In view of the current nano-scoring tests and experiments, geometrically symmetric diamond scribes are used as scoring tools, such as conical scribes. Therefore,
this paper uses a diamond cone knife to carry out the relevant analysis of mechanical scratch test of pure aluminum. The mechanical scratch test of pure aluminum material with a depth of 5 μm-25 μm was performed by five conical engraving blades with a tip angle of 80°, 85°, 90°, 95°, and 100°, and the calculation and analysis of the test data were performed. To study the relationship between the depth of scribing—the tip angle and the height of the lateral bulge of the material, in order to predict the quality of the groove of the mechanical scribing.

2. Analysis of uplift height

In the process of mechanical scoring, as the tool is fed on the surface of the sample and its blade is pressed into the surface of the sample to a certain depth, the material at the front of the tool will be sheared to flow to both sides. This forms a groove with lateral ridges[7]. The mechanical scribing process is essentially a three-dimensional process, but when considering three-dimensional scribing, due to the inherent geometric complexity of plastic mechanics, I want to establish a fully analytical solution that can simultaneously satisfy the equilibrium equation, coordination equation, and plastic flow criteria. The model is very difficult, so simplifying the three-dimensional scoring model into a two-dimensional simplification model has become the main method for analyzing the scoring problem[11].

Figure 1 Schematic diagram of bulge formation

A simplified cross-section of a trough is constructed. Since the conical indenter is a regular indenter, its left and right topographical features are consistent, so one side is taken for analysis. Where h is the depth of the groove, h' is the height of the lateral bulge, and θ is half of the blade angle. According to the principle of constant volume, there are:

$$S1 = S2 + S3$$

Figure 2 Slotted cross section

During the formation of the bulge, the BC surface is not constrained by the tool extrusion, and the surface has no pressure. The shape of this surface is not easy to control. Therefore, the bulge profile formed by the plastic flow of the material is not easy to quantitatively analyze, and the bulge height is difficult to obtain through the theoretical model control. However, the AB surface is pressed by the tool, the surface is pressed, and the surface is deformed into a plane strain. The relationship between the ridge height and the groove depth can be analyzed from this surface. As shown in the Figure 2:

$$γ = β, \text{ so } ∆AOP \sim ∆ABD; \text{ we can get } h'/h = K$$
By experimentally obtaining the K value, the functional relationship between the groove depth and the uplift can be known.

3. Test materials, equipment and methods

3.1. Preparation of test materials
The sample is a round pure aluminum sheet with a diameter of 5cm (purity is 99.999%), and is polished by a polishing machine to make its surface roughness less than 200 nm. Hot paraffin was used to fix the sample on the mechanical scoring process test device, and it was left to stand for 24 hours. After it was cooled, mechanical scoring was performed.

3.2. Test equipment
The test equipment uses a mechanical scoring process test device. Rigid tool holder with quantifiable adjustment of the installation angle of the cutter is used to achieve tool setting and falling through a combination of coarse adjustment and fine adjustment. Close-loop control of the electric linear slide table and the movement of the workpiece surface relative to the slide table are achieved using a high-precision contact displacement sensor. Detecting the inclination of the direction; adopting a two-dimensional tilt adjusting table to achieve precise adjustment of the workpiece surface inclination, and adopting a high-power video optical microscope to realize visual in-situ monitoring of the tool setting, falling and scoring processes. It has the characteristics of multiple degrees of freedom, visualization, precision, openness and ease of operation[6].

Figure 3 Mechanical scoring process test device

3.3. Test method
The test was performed at room temperature. In order to eliminate the influence of the azimuth angle on the test results, the mechanical scribe test was performed on the samples with diamond cone cutters with regular tip angles of 80°, 85°, 90°, 95°, and 100°, respectively. In order to reduce the error caused by the screw clearance when the scoring direction is changed, the test is carried out with a gradient feed. For every 0.3cm feed, the scoring depth increases by 2μm, and the total length is 3cm. The groove depth ranges from 2 μm to 25 μm. In order to avoid interference between the grooves, the distance between each two grooves is not less than 1mm. Repeat the scoring 3 times for each knife to get the best value. The Keyence super depth of field 3D analysis system VHX-1000 was used to detect the groove shape.

Figure 4 Groove morphology under Keyence super depth of field microscope

4. Test results and discussion

4.1. Test results
The groove depth and the height of the bulge were tested separately. Due to the heterogeneity of the material structure, the height of the bulge on both sides was slightly different. The value of the bulge
height was taken as the average of the height of the bulge on both sides of the groove. The results are shown in Table 1:

Table 1 Measured values of groove depth and hump height at different tool tip angles

| Blade angle (2θ) | 80° | 85° | 90° | 95° | 100° |
|------------------|-----|-----|-----|-----|------|
| h                |     |     |     |     |      |
| h'               |     |     |     |     |      |
| 1                | 4.659 | 2.1855 | 4.283 | 3.082 | 1.067 |
| 2                | 8.333 | 4.4965 | 7.7 | 5.013 | 7.433 |
| 3                | 12.69 | 6.092 | 10.6 | 5.88295 | 7.703 |
| 4                | 17.9 | 8.1005 | 12.33 | 5.882 | 7.433 |
| 5                | 20.98 | 11.0325 | 15.87 | 7.4045 | 20.53 |
| 6                | 21.23 | 9.5025 | 18.11 | 10.312 | 22.77 |
| 7                | 22.03 | 11.3085 | 19.81 | 14.63 | 22.77 |
| 8                | 23.8 | 11.29 | 21.21 | 13.971 | 25.27 |

Use the correlation coefficient to calculate the formula[7]:

\[ r = \frac{\sum x y - \bar{x} \sum y}{\sqrt{(\sum x^2 - \bar{x}^2)(\sum y^2 - \bar{y}^2)}} \]  \hspace{1cm} (1)

Calculate the linear correlation coefficients \( r \) for \( h \) and \( h' \), where \( X = h \), \( Y = h' \), and \( N \) is the number of samples. The calculation results are shown in the following table:

Table 2 Correlation coefficient \( r \) of experimental data of different tools

| Blade angle (2θ) | 80° | 85° | 90° | 95° | 100° |
|------------------|-----|-----|-----|-----|------|
| Correlation coefficient \( (r) \) | 0.98567 | 0.9776 | 0.97093 | 0.96098 | 0.95687 |

It can be seen that \( h \) and \( h' \) conform to the linear correlation characteristic.

The data in Table 1 was imported into the excel mathematical analysis software. The groove depth was taken as the abscissa and the bulge height was taken as the ordinate. Each point was traced, and a function curve was fitted according to \( h = kh' \).

4.2. Analysis of test results

Mark the data in Table 1 and perform curve fitting, as shown in Figure 5. It can be seen from the fitting curve graph that when the cutting edge angle is 80°, the ridge height decreases due to obvious chips generated during the scoring process, which causes the ratio of the ridge height to the groove depth to
decrease, and the curve slope is the smallest; the cutting edge angle is greater than 85°. At, the slope decreases as the tip angle increases. When the blade angles are 95° and 100°, the slopes are almost equal, and the curves are almost coincident.

The curve formulas of the fitted curve are:

\[
\begin{align*}
    h_1 &= 0.48544h_1' \\
    h_2 &= 0.69743h_2' \\
    h_3 &= 0.64343h_3' \\
    h_4 &= 0.59594h_4' \\
    h_5 &= 0.59443h_5'
\end{align*}
\]

\(h\) and \(h'\) are in a proportional relationship. Therefore, to find the geometric relationship between the value of \(K\) and the half-angle \(\theta\) of the tool tip, the height of the bulge can be predicted from the depth of the groove and the half-angle \(\theta\) of the tool tip, so as to know the shape of the groove. When the tip angle is 80°, chips are generated during the scoring process. When chipping occurs, the surface of the material breaks, resulting in poor groove surface roughness, so it is not considered. When the tip angle is 95° and 100°, the K value is in the range of 0.595 ± 0.001, so only the K value curves of 85°, 90°, and 95° are considered.

Establish a two-dimensional coordinate system with K as the ordinate and tangent \(\tan \theta\) of the half-angle of the tool tip as the abscissa:

![Fig. 6 Fitting relationship between the tangent value of the tool tip angle and the K value](image)

By fitting the curve once, the following fitting function is obtained:

\[K = -0.5427X + 1.1907\] (2)

Where \(x = \tan \theta\), combined with \(h' = Kh\), the shape of the groove can be obtained from the angle of the blade and the depth of the groove.

This model has a blade tip angle ranging from 85° to 95°. When it is larger than 95°, the ratio of the ridge height to the groove depth tends to be fixed, and the value is about 0.6.

The calculation of the above model is based on the mechanical scoring test of pure aluminum with a diamond cone cutter. Through the established mathematical model of the ridge height, the ridge height can be calculated in advance to predict the shape of the groove.

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