The Study on Grinding Ratio in Form Grinding with White Fused Alumina (WA) Grinding Wheels

Wang Junming¹, Wang Jiong², Lou Deyuan¹

¹School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China
²School of Mechatronics Engineering, Harbin Institute of Technology, Harbin, China

Abstract. The study is carried out based on an experiment of form grinding spur rack with white fused alumina (WA) grinding wheels. In the experiment, SOV-3020A type tri-axial image mapper is utilized to measure the profile of the tooth space in the rack, and the curve equations between the sectional area of the tooth space and the tooth sequence under different grinding depths are established by nonlinear curve regres using software of origin8.0. Then, it deduces the prediction equations for current grinding ratio and cumulative grinding ratio under different grinding depths. The result shows that the grinding ratio is exponential decline relationship with the increase of the number of the tooth to be ground under the same grinding depth, and the decline speed is fast in the initial stage. With the increase of grinding depth, the grinding ratio increases gradually. The cumulative grinding ratio is about twice as high as the current grinding ratio. Thus, large grinding depth is generally used in rough grinding to improve grinding efficiency.

1. Introduction

Grinding ratio is defined as the volume of material removed from the work per unit volume of wheel wear. It is related with Young's modulus, the elastic failure energy and the visco-elastic properties of bond.

It is obvious that the large grinding ratio can obtain high grinding efficiency, so many researchers have done many works about how to enhance the grinding ratio.

In 2011, Shi et al. suggested that the improvement of the heat resistance of the modified resin binders could enhance their adhesive force to diamond grits, thereby the grinding ratio of the grinding wheels was enhanced. And Duan et al. (2015) suggested resin abrasive with diamond coated corundum had a relatively high grinding ratio, reaching to 4.074, higher than Tig by 17.7%. But Liu et al. (2016) found that the metal bonded diamond wheel could achieve the same level dimensional accuracy consistency and higher grinding ratio in 2016, compared with resin bonded diamond wheel.

Actually, the change of the grinding ratio in a grinding cycle was confirmed experimentally, and the grinding ratios seem to vary widely (Izumi and Ochi, 2006).

In a word, there are many achievements for grinding ratio, but a few research findings involved form grinding in previous studies. Additionally, most people only researched the grinding ratio based on grinding performance loss because of grinding wheel wear, without considering the changes of grinding ratio during grinding process. Actually, the changes play a very important role in form grinding. To some extent, grinding ratio changes reflect the changes of grinding wheel wear, which affects the form grinding precision largely.
2. Form Grinding Experiment Design

The main equipment of the form grinding experiment is NC rack grinding machine produced by HuaZhong University of Science and Technology. The parameters of which are as follow: The spindle motor: Y132M-4 type three-phase asynchronous motor produced by Simo; Power: 7.5KW; Rated speed: 1440r/min. The parameters of the form grinding wheel are as follow: WA/F120K type white fused alumina (WA) grinding wheel manufactured by Qingdao Sisha Taiyi Abrasion Corporation limited; Diameter : 350mm; The maximum lineal speed: 25m/s.

This subject is mainly a single-factor experiment, which aims to measure the sectional area of tooth space under different grinding depth, and to explore the grinding ratio and the cross-sectional shape error of grinding racks. Table 1 shows the design of the grinding experiment.

### Table 1. The grinding experiment design.

| Component                  | Specification                                                                 |
|----------------------------|-------------------------------------------------------------------------------|
| NC rack grinding machine   | Precision: 6 grade; Maximum grinding length: 1000mm; Maximum lineal speed: 25m/s |
| Form grinding wheel        | Type: WA/F120K; Diameter: 350mm; Dressed according to the module about the test rack (m=2mm) |
| Workpiece                  | Steel 45 (HRC52), 350mm×50mm×50mm                                             |
| Rack parameters            | Module: m=2mm; Pressure angle: 20 degree; Tooth width: B=50mm                      |
| Grinding depth             | \(a_p = 60\mu m\), \(a_q = 50\mu m\), \(a_r = 40\mu m\)                       |
| Grinding fluid             | Dry grinding                                                                  |
| Wheel dressing parameters  | Diamond truing pen, lineal speed: 25m/s, Feed speed: 0.25m/min; Per dressing amount: 5 ~ 20 \(\mu m\)       |
| Measure equipment          | SOV-3020A type image mapper                                                   |

In the experiment design, tri-axial image mapper SOV-3020A is used to measure any geometry dimension on the plane. It can output real-time image based on the figure of real work-piece shape to engineering drawings in AutoCAD. The grating ruler resolution can reach 0.0005mm.

A schematic diagram of the experimental setup is shown in figure 1, and the experiment is conducted as follows:

1. Test rack blanks are placed on the workbench, its sectional area is projected by mapper through LED light source.
2. The profile of projection is depicted by MV8 measurement software and then is processed into CAD drawings.
3. The sectional area of tooth space is calculated by the enquiry area function of CAD.

![Figure 1. Measuring diagram.](image)
3. The Experimental Data Analysis

Figure 2 is a picture of three test specimen ground. Each of them is unslotted for ease of measurement and analysis, and the cross-sectional shape is tested one time at five-tooth intervals. The grinding experimental data is presented in table 2.

![Figure 2. A picture of the grinding test specimen.](image)

| tooth sequence (i) | sectional area measurement data (mm²) |
|--------------------|---------------------------------------|
|                    | $a_p = 60\mu m$ | $a_p = 50\mu m$ | $a_p = 40\mu m$ |
| 1                  | 0.0796 | 0.0672 | 0.053 |
| 6                  | 0.0781 | 0.0663 | 0.0521 |
| 11                 | 0.078  | 0.066  | 0.0508 |
| 16                 | 0.0777 | Singular point | 0.0506 |
| 21                 | Singular point | 0.065 | 0.0493 |
| 26                 | 0.077  | 0.0646 | 0.0483 |
| 31                 | 0.0756 | 0.0636 | 0.0479 |
| 36                 | 0.0746 | | 0.0457 |
| 41                 | 0.0739 | | Singular point |
| 46                 | 0.0734 | | 0.0436 |
| 51                 | Singular point | | 0.0435 |

As is shown in table 2, it has deleted some singular points. Then the curve equations between the sectional area of the tooth space and the tooth sequence under different grinding depths are established by nonlinear curve regress using software of origin8.0. Three curve equations are as the following:

\[
A_{a_p=60\mu m} = 0.0851 - 0.0058e^{i/64.5} \\
A_{a_p=50\mu m} = 0.07509 - 0.00799e^{i/88.49486} \\
A_{a_p=40\mu m} = 0.0929 - 0.03973e^{i/224.43095}
\]

From above equations, it is concluded that these two factors distribute exponentially, and the maximum relative error among three fitting curves is less than 1%.

After the equations above are partly adjusted, the unified equation of removal sectional area is concluded as follow:

\[
A_{r} = (0.442 + 5 \times 10^3 a_p - 14.3 a_p^2 + 139.1 a_p^3) - (0.462 - 16.472 a_p - 147.75 a_p^2)e^{i/(1057-6907 a_p - 559706 a_p^2)}(4)
\]
In the equation (1)-(4), \( a_p \) is the grinding depth, \( i \) is the tooth sequence and \( i=1, 2, 3 \ldots \).

4. Research on the Grinding Ratio in Form Grinding

In form grinding rack, the changes of the cross-sectional shape reflect the changes of the wear loss of the grinding wheel at the same grinding depth to some extent. After the experimental data processed by CAD, it is found that the first tooth space image is overlapped by the thirty-sixth tooth space image, as is shown in figure 3. It is clear that the area of the latter one is smaller than that of the former one because wheel has been wear after grinding many times. The shadow is the sectional shape error of the thirty-sixth tooth space to be ground in figure 3.

![Figure 3. The sectional shape error of the tooth space.](image)

Based on the grinding process of the rack, a series of calculation formulas would be obtained as follow:

- **Current volume of grinding wheel wear:**
  \[
  V_{Si} = (A_{w1} - A_{wi})\pi D \quad (i = 1,2,3,\ldots,n)
  \]
  (5)

- **Cumulative volume of grinding wheel wear:**
  \[
  V_S = \sum_{i=1}^{i=n} (A_{w1} - A_{wi})\pi D \quad (i = 1,2,3,\ldots,n)
  \]
  (6)

- **Current volume of the removal material of the work-piece:**
  \[
  V_{wi} = BA_{wi} \quad (i = 1,2,3,\ldots,n)
  \]
  (7)

- **Cumulative volume of the removal material of the work-piece:**
  \[
  V_W = \sum_{i=1}^{i=n} BA_{wi} \quad (i = 1,2,3,\ldots,n)
  \]
  (8)

- **Current grinding ratio:**
  \[
  G_i = \frac{V_{wi}}{V_{Si}} \quad (i = 1,2,3,\ldots,n)
  \]
  (9)

- **Cumulative grinding ratio:**
  \[
  G = \frac{V_W}{V_S} = \frac{\sum_{i=1}^{i=n} BA_{wi}}{\sum_{i=1}^{i=n} (A_{w1} - A_{wi})\pi D} \quad (i = 1,2,3,\ldots,n)
  \]
  (10)

The definition for the symbols in above equations as follow:

- \( A_{w1} \): current sectional area of the \( i^{th} \) tooth space to be ground
- \( A_{wi} \): the sectional area of the first tooth space to be ground
D: the diameter of grinding wheel  
B: the width of the rack blank

According to the equation (4), (9) and (10), the predicting formulas of the current grinding ratio and the cumulative grinding ratio under different grinding depth would be obtained. Figure 4 and figure 5 are the predicting charts for the current grinding ratio and the cumulative grinding ratio respectively.

According to figure 4 and figure 5, it is clear that the grinding ratio is exponential decline relationship with the increase of tooth number, and the decline speed is fast in the initial stage. With the increase of the grinding depth, the grinding ratio increases gradually. The cumulative ratio is about twice as high as the current grinding ratio. Therefore, it concludes that large grinding depth is generally used in rough grinding to improve grinding efficiency.

**Figure 4.** The simulation diagram of the current grinding ratio.

**Figure 5.** The simulation diagram of the cumulative grinding ratio.
5. Conclusion
1. The study is carried out based on an experiment of form grinding spur rack with white fused alumina (WA) grinding wheels. And the paper deduces the predicting equations of the current grinding ratio and the cumulative grinding ratio under different grinding depths.

2. The results show that the grinding ratio is exponential decline relationship with the increase of tooth sequence, and the decline speed is fast in the initial stage. With the increase of grinding depth, the grinding ratio increases gradually. The cumulative ratio is about twice as high as the current grinding ratio. Therefore it concludes that large grinding depth is generally used in rough grinding to improve grinding efficiency.

Reference
[1] Shi D L, Li K H, Zhao Y J, Liu Q W, Ding Y L, Ding C S 2011 *Diamond Abras. Eng.* **31**(185) 56-9.
[2] Duan W Y, Yin Y H, Xue Q H, Li Y L 2015 *Bull. Chinese Ceram. Soc.* **34**(3) 808-12.
[3] Liu W Y, Xie H, Zhang Y X, Gong J F 2016 *Cem. Carbl.* **33**(1) 38-41.
[4] Izumi M, Ochi O 2006 *Japan Soc. Abras. Tech.* **50**(8) 471-6.