INVESTIGATION OF SINGLE-POINT DRESSING OVERLAP RATIO AND DIAMOND-ROLL DRESSING INTERFERENCE ANGLE ON SURFACE ROUGHNESS IN GRINDING

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ABSTRACT
This paper investigates the effect of both single-point and diamond-roll dressing techniques on the workpiece surface roughness in grinding. Two empirical surface roughness models are studied – one that incorporates single-point dressing parameters, and another that incorporates diamond-roll dressing parameters. For the experimental conditions used in this research, the corresponding empirical model coefficients are found to have a linear relationship with the inverse of the overlap ratio for single-point dressing and the interference angle for diamond-roll dressing. The resulting workpiece surface roughness models are then experimentally validated for different depths of cut, workpiece speeds and dressing conditions. In addition, the models are used to derive a relationship between overlap ratio for single-point dressing, and interference angle for diamond-roll dressing such that both dressing techniques produce a similar surface finish for a given material removal rate.

Keywords: grinding; surface roughness; dressing.

ÉTUDE DU RAPPORT DE RECOUVREMENT LORS DU DRESSAGE À POINTE SIMPLE ET DE L'ANGLE D'INTERFÉRENCE LORS DU DRESSAGE PAR MOLETTE DIAMANTÉE SUR LA RUGOSITÉ DE SURFACE LORS DU MEULAGE

RÉSUMÉ
Cet article présente une étude sur l’effet du dressage à pointe simple et par molette diamantée sur la rugosité de surface de la pièce de fabrication lors du meulage. Deux modèles de rugosité de surface empiriques sont étudiés – un incorporant des paramètres du dressage par pointe simple, et l’autre, des paramètres du dressage par molette diamantée. Pour les conditions expérimentales utilisées dans cette recherche, il est trouvé que les coefficients des modèles empiriques correspondants ont une relation linéaire avec l’inverse du rapport de recouvrement pour le dressage à pointe simple et l’angle d’interférence pour le dressage à molette diamantée. Les modèles de rugosité de surface de la pièce de fabrication résultante sont par la suite validés expérimentalement pour différentes profondeur de coupe, vitesses de la pièce de fabrication et conditions de dressage. De plus, les modèles sont utilisés pour dériver une relation entre le rapport de recouvrement pour le dressage à pointe simple et l’angle d’interférence pour le dressage à molette diamantée afin que chaque technique de dressage produise un fini de surface similaire pour un taux de dépose de matériau donné.

Mots-clés : meulage; rugosité de surface; dressage.
1. INTRODUCTION

Creep-feed grinding has the ability to produce desirable surface finishes at higher material removal rates than conventional surface grinding. To quantify the quality of the resulting surface topography, one can measure the arithmetic mean surface roughness $R_a$. This parameter, referred to as surface roughness throughout this paper, can be defined as the average of the absolute values of the deviations of the surface profile height from the mean line within the sampling length of the ground surface.

To help predict the surface roughness in grinding, several empirical models have been developed in the literature as described by Tönshoff et al. [1] and, more recently, by Choi et al. [2] for cylindrical grinding and Di Ilio et al. [3] for surface grinding. Hecker and Liang [4] point out that these types of models require the adjustment of the corresponding empirical parameters for every workpiece material, cutting fluid and wheel type. The grinding wheel dressing process has a significant influence on the grinding process including, as discussed by Verkerk and Pekelharing [5] and Salje and Mackensen [6], the resulting workpiece surface roughness. In particular, the work of Snoeys et al. [7] showed that, for a given dressing condition, the surface roughness can be related through empirical constants $R_f$ and $x$ to the equivalent uncut chip thickness $h_{eq}$ as follows:

$$R_a = R_1(h_{eq})^x$$

(1)

The equivalent uncut chip thickness $h_{eq}$ can be defined as:

$$h_{eq} = \frac{v_w a}{v_s}$$

(2)

where $a$ is the grinding depth of cut, $v_w$ is the workpiece speed, and $v_s$ is the circumferential grinding wheel speed.

In the case of single-point dressing, Malkin [8] showed how the coefficient $R_f$ in Eq. (1) could be replaced with dressing lead $S_d$, dressing depth $a_d$, and a new empirical constant $R_2$ as follows:

$$R_a = R_2 S_d^{0.5} a_d^{0.25} \left( \frac{v_w a}{v_s} \right)^x$$

(3)

This equation can be re-written in terms of the dressing overlap ratio $U$ as follows:

$$R_a = R_2 \left( \frac{b_d}{U} \right)^{0.5} a_d^{0.25} \left( \frac{v_w a}{v_s} \right)^x$$

(4)

where the overlap ratio is the ratio of the active width $b_d$ of the single-point diamond tip to the dressing lead $S_d$.

Malkin [8] also showed that, in the case of diamond-roll dressing, the coefficient $R_f$ in Eq. (1) could be replaced with the interference angle $\delta$ and a new empirical constant $R_3$ as follows:

$$R_a = R_3 \delta^{0.33} \left( \frac{v_w a}{v_s} \right)^x$$

(5)
The interference angle $\delta$ can be defined as:

$$\delta = \arctan \left( \frac{v_f}{|v_d - v_s|} \right)$$  \hspace{1cm} (6)
where \( v_i \) is the dressing infeed speed, \( v_d \) is the diamond-roll dresser speed and \( v_s \) is the grinding wheel speed. The interference angle can be changed, according to Eq. (6), by adjusting the infeed speed, or by adjusting the wheel speed and diamond roll speed (dressing ratio).

This paper builds upon the previous work by establishing a relationship between the empirical constant \( R_2 \) in Eq. (4) and the overlap ratio, in the case of single-point dressing, as well as a relationship between the empirical constant \( R_3 \) in Eq. (5) and the interference angle, in the case of diamond-roll dressing. The resulting surface roughness models are then experimentally validated for different depths of cut, workpiece speeds and dressing conditions when creep-feed grinding with aluminum oxide wheels. A relationship is then derived for single-point and diamond-roll dressing such that both dressing techniques produce a similar surface finish for a given constant material removal rate.

2. EXPERIMENTAL SETUP

Creep-feed grinding experiments were performed on a Blohm Planomat 408 grinding machine with AISI 1018 steel workpieces of dimensions 150 mm × 6.35 mm × 50 mm and a Radiac Abrasives’ vitrified “ruby and pink” (RPA) aluminum oxide grinding wheel (RPA 801 G+800 VOS). Cutting fluid was supplied to the grinding zone as shown in Fig. 1 using a coherent jet, as described by Steffen et al. [9], at a flowrate of 20 (liters/min) and a pressure of 1 MPa. In addition to a coherent jet, a separate high-pressure 8 MPa wheel-cleaning system was implemented, as described by Cameron et al. [10]. Both the coherent-jet coolant-delivery system and the wheel-cleaning system used the same cutting-fluid concentration of 95% water and 5%...
CIMTECH® 310 Synthetic Metalworking Fluid manufactured and distributed by CIMCOOL Global Industrial Fluids and Milacron Canada. Each experiment consisted of truing the workpiece, dressing the grinding wheel, taking a single grinding pass, and then measuring the resulting workpiece surface roughness. In all experiments, the dressing depth of cut and diamond-roll dresser peripheral speed were held constant at 0.15 mm and 28.7 m/s, respectively. Although the grinding wheel diameter was initially at 40.64 cm in diameter and changed slightly each time the wheel was dressed, the grinding wheel peripheral speed was held constant at 22.4 m/s throughout all of the experiments. The reverse-plated Norton RPC 9512 J033721 diamond-roll dresser had a diameter of 152 mm and dressed the grinding wheel in the “down” mode. In the case of single-point dressing, the active width of the diamond tip was determined to be 1.23 mm using optical microscopy. The resulting surface roughness of the workpiece $R_a$ was measured across the grinding direction at six equally-spaced locations along the grinding direction using a Mahr Federal Pocket Surf with a resolution of 0.01 μm and a cutoff length of 0.8 mm. Note that if workpiece burn was observed near the end of the workpiece, the roughness measurements were taken up to the point at which burn occurred. The corresponding roughness values were then averaged to obtain the overall surface roughness, and every grinding experiment was carried out three times to establish the repeatability of the results.

Fig. 4. Error between measured and predicted surface roughness as a function of exponent $x$ (single-point dressing).
3. EXPERIMENTAL RESULTS

A series of grinding experiments were conducted to identify and validate the empirical constant $x$ in Eqs. (4) and (5). In the first set of experiments, the workpiece speed and grinding depth of cut were held constant at 2.0 mm/s and 1.0 mm, respectively. Workpiece surface roughness was measured for single-point overlap ratios $U$ of 6, 3, 1.7, 1.2, and 1, and diamond-roll interference angles $\delta$ of $1.73 \times 10^{-6}$, $1.66 \times 10^{-5}$, $2.99 \times 10^{-5}$, $4.23 \times 10^{-5}$, $6.64 \times 10^{-5}$, and $8.5 \times 10^{-5}$ rad. These interference angles were achieved by varying the dressing infeed speed from 0.54 to 0.011 mm/s. The empirical constants $R_2$ in Eq. (4) and $R_3$ in Eq. (5) were then plotted as a function of $1/U$ and $\delta$ for a range of exponents $x$. Samples of these plots are shown in Figs. 2 and 3 for the case when the exponent $x$ was set to 0.56. For each $1/U$ and $\delta$ dressing parameter tested, the plotted points in Figs. 2 and 3 show the variations and corresponding average observed for the $R_2$ and $R_3$ parameters from the three repeatability experiments. Instead of empirical parameters $R_2$ and $R_3$ being constant values, the authors discovered that, for the grinding conditions used in this research, the relationships between $R_2$ and $1/U$, and $R_3$ and $\delta$ exhibit a high degree of linearity for exponents $x$ ranging from 0.25 to 0.90.

The resulting linear relationships derived from this first set of experiments were used in Eqs. (4) and (5) to predict the workpiece surface roughness for workpiece speeds of 1.0, 1.5 and
2.5 mm/s, while keeping the grinding depth of cut constant at 1.0 mm. Different values for the exponent \( x \) were assumed in these equations, with values ranging from 0.25 to 0.85. A second set of grinding experiments were then carried out for these new workpiece speeds (keeping depth of cut constant at 1.0 mm) using both single-point and diamond-roll dressing, and the corresponding workpiece surface roughness was measured. The predicted and measured workpiece surface roughness values were then compared and the resulting error was plotted as a function of exponent \( x \) as shown in Figs. 4 and 5. As shown in Fig. 4, single-point overlap ratios of 1.0, 1.64 and 6.0 were tested and the lowest roughness prediction errors observed correspond to exponents ranging from 0.4 to 0.6, which is consistent with the 0.2 to 0.6 range reported by Chiu and Malkin [11]. Similarly, as shown in Fig. 5, diamond-roll interference angles of \( 1.33 \times 10^{-5} \), \( 1.72 \times 10^{-5} \), \( 4.23 \times 10^{-5} \), and \( 8.5 \times 10^{-5} \) rad were tested and exponents ranging from 0.45 to 0.7 were observed to yield the lowest roughness prediction errors. Based on these experimental results an overall average value of \( x = 0.56 \) was calculated and, substituting the corresponding identified linear relationships for \( R_2 \) in Eq. (4) and \( R_3 \) in Eq. (5), yielded the following surface roughness models:

\[
R_a = \left( \frac{0.45 + 0.22U}{U^{1.5}} \right) a_d^{0.25} \left( \frac{v_w}{v_s} \right)^{0.56} \]  

(7)

Fig. 6. Predicted and experimental \( R_a \) for grinding depth of cut \( a = 1 \) mm (single-point dressing).
where $\text{Eq. (7)}$ represents the surface roughness in the case of single-point diamond dressing, and $\text{Eq. (8)}$ corresponds to the surface roughness for diamond roll dressing.

These new empirical models were compared to the existing models shown in Eqs. (4) and (5) with empirical parameters $R_2$ and $R_3$ set to constant values. To determine these empirical constants, the same value of $x=0.56$ was used in Eqs. (4) and (5). For the dressing and grinding conditions used in the first set of experiments described earlier, values for $R_2$ and $R_3$ were then calculated and averaged resulting in $R_2 = 0.44 \text{ mm}^{-0.31}$ and $R_3 = 12.20 \text{ mm}^{-0.44/\text{rad}^{0.33}}$ for single-point and diamond-roll dressing, respectively.

In order to validate and compare the existing models shown in Eqs. (4) and (5) with the new models shown in Eqs. (7) and (8), the corresponding predicted surface roughness values were plotted with measured values for the 1.0 mm depth of cut experiments described previously, as well as for a new set of 2.0 mm depth of cut experiments. Figs. 6 and 7 plot the surface roughness as a function of $1/U$ for depths of cut $a = 1.0$ and 2.0 mm, respectively. Similarly, Figs. 8 and 9 plot the surface roughness as a function of diamond-roll interference angle for depths of cut $a = 1.0$ and 2.0 mm, respectively. In these figures, the existing and new model results are shown as curves, while the experimental data are superimposed as points. For the experimental conditions used in this research, the new models provide an improvement in surface roughness prediction over the existing
models. Any experimental error bars associated with these figures were found to lie within the diameter of the plotted points, showing good agreement between the predicted roughness values from the new model and the measured roughness values.

It can be also seen in Figs. 6 and 7 that, in the case of single-point dressing, the workpiece surface roughness appears to continuously increase as the overlap ratio decreases. This observation is likely due to how cutting edges are generated in single-point dressing. The wheel surface generated under coarse dressing conditions with an overlap ratio of 1 ($S_d=1.23$ mm) was investigated using a Scanning Electron Microscope (SEM). Fig. 10 shows the resulting SEM image of the wheel surface in the direction of the single-point dresser. The thread profile observed in this figure has a profile similar in shape to the single-point diamond tip and the thread pitch is equal to the 1.23 mm active width $b_d$ of the single-point dressing tool.

Assuming a circular profile for the single-point diamond tip, the following equation geometrically relates the cusp height $h$ on the wheel to the overlap ratio $U$:

$$h = r - \sqrt{r^2 - (b_d/U)^2}/4$$  \hspace{1cm} (9)

where $r$ is the radius of the diamond tip.

Fig. 8. Predicted and experimental $R_a$ for grinding depth of cut $a=1$ mm (diamond-roll dressing).
Equation (9) shows that the cusp height on the wheel continuously increases with $1/U$ following the general trend of the corresponding workpiece surface roughness observed by the present authors in Figs. 6 and 7.

In the case of diamond-roll dressing, as shown in Figs. 8 and 9, the generated workpiece surface roughness appears to increase as the interference angle increases up to approximately $4.23 \times 10^{-5}$ rad, beyond which increases in interference angle do not appear to have a significant effect on the workpiece surface roughness. One possible explanation for this observation is that, for small interference angles (which correspond to small dressing infeed speeds), the resulting dressing forces are small and lead to a smooth grinding wheel and workpiece surface. As interference angles increase and corresponding dressing infeed speeds increase, the dressing forces become larger, the bonds along the wheel surface begin to fracture, the wheel becomes rougher, and the resulting workpiece surface becomes rougher. At some interference angle, however, most of the bonds around the periphery of the wheel will be broken exposing new sharp grains below. Increasing the interference angle beyond this point, while breaking bonds deeper in the wheel, will ultimately expose new sharp grains that have similar surface topologies which will produce workpieces with similar surface roughness values.

Fig. 9. Predicted and experimental $R_a$ for grinding depth of cut $a=2$ mm (diamond-roll dressing).
4. EQUIVALENT DRESSING PARAMETERS

If one were to set the new surface roughness model for single-point dressing represented by Eq. (7) equal to the new surface roughness model for diamond-roll dressing represented by Eq. (8), then the following relationship between the overlap ratio and interference angle can be established that provides the same material removal rate per workpiece width $Q_w$ and generates a similar workpiece surface roughness:

$$M U^{1.5} - 0.22U - 0.45 = 0 \tag{10}$$

where $M = (11.43 - 0.35 \times 10^5 \delta) \delta^{0.33} / \delta a_d^{0.25}$.  

Figure 11 shows this equivalent dressing parameter relationship by plotting $1/U$ for single-point dressing as a function of the interference angle for diamond-roll dressing for the experimental conditions used in this research. This relationship can then be used as a guide for selecting diamond-roll dressing parameters that give an equivalent surface roughness as that achieved with single-point dressing.

A new set of experiments were carried out to experimentally validate the equivalent dressing parameter relationship shown in Fig. 11 for the dressing and grinding parameters listed in Table 1 and a material removal rate per workpiece width $Q_w$ of 3.0 mm$^2$/s. Note that the combination of these grinding and dressing conditions was not used to identify the original models on which Fig. 11 is based.

The predicted and experimental results are summarized in Fig. 12 which is a multi-axis figure having two horizontal and vertical axes corresponding to single-point and diamond-roll
dressing. The dashed curve represents the model-predicted roughness with single-point dressing, while the solid curve shows the roughness predicted with diamond-roll dressing. Desired roughness values of 0.7, 1.3, 2.0 and 2.5 μm were selected as indicated by the dotted horizontal lines in Fig. 12. For each of these roughness values, the corresponding overlap ratio and diamond-roll interference angle were selected and tested. The resulting measured surface roughness was then superimposed as different markers on Fig. 12 for two different grinding conditions (a=1.5 mm, v_w=2.0 mm/s) and (a=3.0, v_w=1.0 mm/s). The results show good agreement between the experimentally-measured roughness and the roughness predicted by the

Table 1. Validation of equivalent dressing parameters.

<table>
<thead>
<tr>
<th>a (mm)</th>
<th>v_w (mm/s)</th>
<th>S_d (mm)</th>
<th>U</th>
<th>v_i (mm/s)</th>
<th>δ (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50</td>
<td>2.00</td>
<td>0.30</td>
<td>4.10</td>
<td>0.005</td>
<td>7.40 × 10^{-07}</td>
</tr>
<tr>
<td>1.50</td>
<td>2.00</td>
<td>0.60</td>
<td>2.05</td>
<td>0.032</td>
<td>5.02 × 10^{-06}</td>
</tr>
<tr>
<td>1.50</td>
<td>2.00</td>
<td>0.90</td>
<td>1.37</td>
<td>0.132</td>
<td>2.07 × 10^{-05}</td>
</tr>
<tr>
<td>1.50</td>
<td>2.00</td>
<td>1.10</td>
<td>1.12</td>
<td>0.400</td>
<td>6.32 × 10^{-05}</td>
</tr>
<tr>
<td>3.00</td>
<td>1.00</td>
<td>0.30</td>
<td>4.10</td>
<td>0.005</td>
<td>7.40 × 10^{-07}</td>
</tr>
<tr>
<td>3.00</td>
<td>1.00</td>
<td>0.60</td>
<td>2.05</td>
<td>0.032</td>
<td>5.02 × 10^{-06}</td>
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<td>3.00</td>
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<td>0.132</td>
<td>2.07 × 10^{-05}</td>
</tr>
<tr>
<td>3.00</td>
<td>1.00</td>
<td>1.10</td>
<td>1.12</td>
<td>0.400</td>
<td>6.32 × 10^{-05}</td>
</tr>
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Fig. 11. Equivalent dressing parameters.
new models, and demonstrate that the equivalent dressing parameters relationship described by Eq. (10) can be effectively used to achieve a desired roughness.

5. CONCLUSION

In this research, two empirical workpiece surface roughness models that incorporate the effects of different grinding and dressing conditions were examined. The empirical parameters of both models were found to have a linear relationship with the inverse of the overlap ratio for single-point dressing and interference angle for diamond-roll dressing. The resulting new models were experimentally validated over a wide range of grinding and dressing conditions.

In addition, these surface roughness models were used to derive a relationship between overlap ratio and dressing interference angle that produces the same surface roughness for given constant material removal rate. The identified relationship was validated experimentally and, for the grinding conditions used in this research, the resulting relationship can be used as a reference guide from which appropriate dressing techniques and parameters can be selected to produce a desired roughness.

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