Computer-aided Simulation of Rotary Diamond Dressing Based on Kinematic Analysis*

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Abstract

Rotary diamond dressers are one of the most widely used dressers for the dressing of vitrified grinding wheels. In this study, we develop a relatively comprehensive dressing mechanism for the rotary diamond dresser that takes into consideration the relationship between the dressing conditions and the dressing trajectories of diamond grits formed on the working surface of a grinding wheel. The dressing mechanism can be used to determine the dressing performance, i.e., whether or not the diamond grits come in contact with the entire circumferential surface of the grinding wheel, known as complete dressing. A computer-aided simulation of the dressing process is developed to visualize the dressing trajectories formed on the working surface of the grinding wheel for a given set of dressing conditions, i.e., the velocity ratio of the rotary diamond dresser to the grinding wheel, up-cut or down-cut dressing, and single-pass or multipass dressing. Using the simulation process, the maximum feed speed of the rotary diamond dresser in single-pass dressing and the minimum number of passes in multipass dressing required to realize complete dressing are examined.

Key words: Dressing, Rotary Diamond Dresser, Grinding Wheel, Dressing Performance, Optimal Dressing Conditions

1. Introduction

Grinding is one of the most important material removal processes for manufacturing precision parts. When the material removal efficiency of a grinding wheel decreases, the grinding wheel requires dressing^(1,2). Dressing restores the performance of the grinding wheel by sharpening and protruding the abrasive cutting edges on its working surface. Note that there are different types of dressing such as mechanical dressing, dressing based on beam-aided machining, dressing based on electrochemical machining and hybrid dressing⁽³⁾. Among these different types of dressing, mechanical dressing is the most widely used and the rotary diamond dresser (RDD) is one of the most useful dressers, particularly for the dressing of vitrified superabrasive grinding wheels, owing to its high wear resistance.

The grinding wheel surface topography resulting from dressing affects the performance of the subsequent grinding; therefore, the evolution of the grinding wheel surface during dressing is an important research topic, and many authors have studied this issue from different perspectives. Focusing on the dressing methods, Kubo and Tamaki⁽⁴⁾ developed a solid-type RDD consisting of a chemical vapor deposition (CVD) diamond disc and demonstrated that such an RDD results in a lower grinding force and a larger surface roughness than those of conventional RDDs. Tawakoli and Daneshi⁽⁵⁾ developed a specially designed electroplated RDD called a T-dresser, which markedly reduces the grinding force

*Received 4 Mar., 2013 (No. 13-0113)
[DOI: 10.1299/jamdsm.7.506]

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and results in almost the same ground surface roughness as that produced by a grinding wheel dressed with a conventional electroplated RDD. Mochida et al.⁽⁶⁾ developed a single-point diamond dresser with a specific back rake angle and found that the back rake angle strongly affects the grinding wheel surface topography and the grinding performance. Focusing on the performance of rotary dressers, Huang⁽⁷⁾ considered the resultant force acting on an individual grit of a vitrified diamond grinding wheel to evaluate the dressing efficiency of two types of rotary dresser: a SiC roll and a steel roll. Yamauchi et al.⁽⁸⁾ investigated the dressing performance of two types of RDD, a metal-bonded RDD and a prismatic monocrystalline RDD⁽⁹⁾, by conducting the internal grinding of a small bore. Mochida et al.⁽¹⁰⁾ examined the performance of two types of dresser, a single-point diamond dresser and an RDD, in terms of the relationship between the dressing force and grinding performance.

The mechanical dressing of a vitrified grinding wheel can be considered as a type of cutting process in which a composite of abrasive grits and vitrified bonds is cut by a diamond tool, and the transferability of the cutting path markedly affects the topography of the working surface of the grinding wheel. Especially, RDDs create highly complex patterns on the working surface of the grinding wheel. Therefore, it is important to simulate the grinding wheel topography after dressing. Simulation assists decision making when optimizing dressing and also when designing new dressers. Doman et al.⁽¹¹⁾ reviewed topography models of the grinding wheel surface that have been developed over half a century starting from the 1950s and proposed the important components and framework for a 3D topography model of a grinding wheel surface. Klocke and Linke⁽¹²⁾ developed a finite element model of a grinding wheel surface dressed with a single-point dresser and showed how the wheel wear is affected by the dressing parameters. Baseri et al.⁽¹³⁾ developed a 2D topography model of a grinding wheel surface dressed with a rotary dresser that was based on a stochastic approach. This model can predict the number and angle of abrasive cutting edges generated on the grinding wheel surface. Bzymek et al.⁽¹⁴⁾ developed a 3D topography model in which the effect of vibration generated from the RDD driving apparatus is considered. Moritomo et al.⁽¹⁵⁾ introduced a stochastic model of an RDD on whose surface the diamond grits are placed at random, and derived the dressing ratio, i.e., the ratio of the dressed area to the whole surface of the grinding wheel. Yokogawa and Furukawa⁽¹⁶⁾ developed a 3D topography model of a grinding wheel surface dressed with an RDD on whose surface the diamond grits are arranged at regular intervals.

To achieve effective dressing using an RDD, the diamond grits of the dresser should come in contact with the entire working surface of the grinding wheel. In traverse dressing using an RDD, the dressing of the entire working surface of the grinding wheel, i.e., complete dressing, can be realized by single-pass dressing with a reasonably low traverse speed or by multipass dressing, in which the depth of cut is given for each pass. One of the drawbacks of single-pass dressing is that the same area may be dressed several times. This is undesirable because the already dressed abrasive grits might lose their sharpness owing to abrasion with the dresser. Another issue is the time required for both single-pass and multipass dressing. The dressing time should be minimized to reduce the cost of dressing and grinding.

There have been no systematic studies that deal with the above-mentioned performance issues of dressing. In this study, the authors have addressed these issues in a systematic manner from the perspective of an RDD. For the sake of better understanding, the first half of this article deals with the dressing mechanism on the basis of kinematic analysis and the other half deals with the evaluation of dressing performance by computer-aided simulation.

The simulated topographies of the grinding wheel surface are expected to be used as a benchmark to understand the actual mechanism of dressing, in which cutting as well as the abrasion and fracture of abrasive grits and vitrified bonds occur.

Nomenclature

D_g	: Diameter of grinding wheel
W	: Width of grinding wheel
V_g	: Peripheral speed of grinding wheel
N_g	: Rotational speed of grinding wheel
D_d	: Diameter of rotary diamond dresser
V_d	: Peripheral speed of rotary diamond dresser
n	: Number of diamond grits on rotary diamond dresser
m	: Length of diamond grits on rotary diamond dresser
D_b	: Width of diamond grits on rotary diamond dresser
t	: Depth of cut
t_c	: Critical depth of cut in dressing
VR	: Velocity ratio of rotary diamond dresser to grinding wheel (V_d / V_g)
f_d	: Feed speed of rotary diamond dresser
L_d	: Dressing lead (f_d / N_g)
θ	: Lead angle of dressing
FR	: Feed rate of rotary diamond dresser (L_d / D_b)
N_D	: Number of passes in dressing
l_a	: Length of dressing trajectory
P	: Pitch of dressing trajectory
D_r	: Dressing ratio

2. Kinematic Analysis of Rotary Diamond Dressing

It is important to understand the dressing mechanism of an RDD before developing a simulation-based approach to evaluate the dressing performance. This section deals with the dressing mechanism. The functionality of the RDD depends on the number, shape and arrangement of diamond grits on its surface. In this study, we focus on a prismatic monocrystalline RDD⁽⁹⁾.

Figure 1 shows a photograph and optical image of a prismatic monocrystalline RDD (SDR50L, Noritake Co., Ltd.), wherein equally sized monocrystalline diamond logs cut in a given crystal orientation are embedded onto the circumferential surface of the rotary dresser at regular intervals with a constant protrusion height h . The cross section of the diamond grits has the form of a square of side $m = D_b$. In the case of the RDD shown in Fig.1, h and m measure 0.1 mm and 0.2 mm, respectively. This type of RDD is subjected to less wear and therefore has been widely used in the dressing of grinding wheels for precision grinding. Using this type of RDD, we can carefully examine the dressing mechanism and the dressing performance, from which the geometrical uncertainty of the RDD is eliminated.

Fig. 1 Prismatic monocrystalline RDD (SDR50L, Noritake Co., Ltd.)

2.1 Process of grinding wheel surface generation in rotary diamond dressing

While performing dressing using an RDD, a depth of cut t is created between the grinding wheel and RDD. At the same time, there is relative motion between the RDD and grinding wheel. This creates a set of trajectories of the diamond grits on the circumferential surface of the grinding wheel, as schematically illustrated in Fig. 2. In the figure, the x -axis corresponds to the width direction of the grinding wheel and the lines at $x = 0$ and $x = W$ are the side edges of the grinding wheel. The y -axis corresponds to the circumferential direction of the grinding wheel and the lines at $y = 0$ and $y = \pi D_g$ are the same lines on the circumferential surface of the grinding wheel. The RDD moves parallel to the x -axis in the left or right direction at a feed speed of f_d and forms a series of dressing trajectories with a dressing lead L_d .

The form and size of each dressing trajectory are determined by the length l_a , the width D_b and the angle of the dressing lead θ . The arrangement of the dressing trajectories, i.e., the dressing pattern formed on the circumferential surface of the grinding wheel, is determined by the pitch of two consecutive dressing trajectories P , the dressing lead L_d and the start points of a series of dressing trajectories, A and B, which are arbitrarily given at each dressing pass, whose x -coordinate is within a range of L_d and whose y -coordinate is within a range of P . Note that an offset part of the dressing trajectory of length l_a and an offset part of the undressed part given by a gap g , both of which are located on the exterior of the x - y plane, are folded back at $y = \pi D_g$ to move them to the position $y = 0$, at which the next series of dressing trajectories starts.

In the case of multipass dressing, a depth of cut is formed on both sides of the grinding wheel, for example, in the i th pass and $(i+1)$ th pass shown in Fig. 2; therefore, the total depth of cut increases, resulting in the elongation of the dressing trajectory of length l_a .

Table 1 lists the specifications of the grinding wheel and RDD and the dressing conditions used in the following theoretical analysis.

Fig. 2 Dressing trajectories formed on the grinding wheel surface

Table 1 Dressing conditions

Grinding wheel diameter	$D_g = 140$ mm
Grinding wheel velocity	$V_g = 36.7$ m/s (5000 rpm)
Rotary dresser	Monocrystalline diamond logs
Diameter of dresser	$D_d = 50$ mm
Number of diamond grits	$n = 120$
Length of diamond grits	$m = 0.2, 0.4, 1.0$ mm
Width of diamond grits	$D_b = 0.2$ mm
Depth of cut	$t = 2, 4, 6, 8$ μ m
Velocity ratio	$VR = V_d / V_g = 0 - \pm 2.0$ (+:Up-cut, -:Down-cut)
Feed speed of dresser	$f_d = 1 - 5000$ mm/min
Dressing lead	$L_d = 0.2 - 1000$ μ m/rev
Feed rate of dresser	$FR = 0.001 - 5.0$
Number of passes in dressing	$N_D = 1 - 20$

2.2 Length of dressing trajectory

Mechanical dressing is a type of cutting process for hard and brittle materials; therefore, kinematic analysis is an effective means of understanding the underlying dressing mechanism. As mentioned in the introduction, Yokogawa and Furukawa⁽¹⁶⁾ have reported the kinematic analysis of a prismatic monocrystalline RDD in the case of single-pass dressing. They rigorously analyzed the locus of a diamond grit formed on the surface of a grinding wheel, that is, they derived the actual contact length between a diamond grit and the grinding wheel by integrating the sectional profile of the locus, which consists of two trochoid curves and a straight line segment. Therefore, their analysis provides complex relationships among the dressing parameters and is difficult to apply to the development of a computer-aided dressing simulation. The authors have revisited the dressing mechanism of the RDD and developed a relatively simple but comprehensive model of the dressing mechanism. In the proposed model, the length of the dressing trajectory of a diamond grit is analyzed, then the sectional profile of the dressing trajectory is analyzed using an approximate solution.

Fig. 3 Dressing mechanism of RDD

Figure 3 shows a schematic diagram of the interaction between the RDD and the grinding wheel. A grinding wheel of diameter D_g rotates at a peripheral speed of V_g and an RDD of diameter D_d rotates at a peripheral speed of V_d . Down-cut dressing is realized when the rotational direction of the grinding wheel is the same as that of the RDD, and up-cut dressing is realized when the rotational directions are opposite. In both cases, the depth of

cut is given by t . A given number of diamond grits of length m are embedded on the surface of the RDD, and one diamond grit is shown in the figure as an example. Other diamond grits have the same interaction and will be considered when determining the length of the dressing trajectory.

The front end of the diamond grit first comes in contact with the grinding wheel at point s and terminates its contact at point e .

The length l_d measured from point s to point e along the circumference of the RDD is given as

$$l_d = 2\sqrt{D_{eg}t}, \quad (1)$$

where D_{eg} is the equivalent diameter of the RDD given by

$$D_{eg} = \frac{D_g D_d}{D_g + D_d}. \quad (2)$$

This yields the following expression for the contact period T :

$$T = \frac{l_d}{V_d} = \frac{2\sqrt{D_{eg}t}}{V_d}. \quad (3)$$

During the contact period, point s on the outermost surface of the grinding wheel moves by a distance l_g along the circumference of the grinding wheel to another point.

l_g is given as

$$l_g = TV_g = 2\sqrt{D_{eg}t} \frac{V_g}{V_d}. \quad (4)$$

When the depth of cut t is very small compared with D_g and D_d , the length l_d measured along the circumference of the RDD is almost equal to the length of the circular arc $s-e$ measured along the circumference of the grinding wheel. Therefore, the length of the dressing trajectory of the front end of a diamond grit l'_a , which is measured along the circumference of the grinding wheel, is given as

$$l'_a = l_d \pm l_g = \left| (2\sqrt{D_{eg}t}) \pm \frac{V_g}{V_d} (2\sqrt{D_{eg}t}) \right| = \left| 1 \pm \frac{V_g}{V_d} \right| (2\sqrt{D_{eg}t}). \quad (5)$$

In Eq. (5), the plus sign is applied in the case of up-cut dressing and the minus sign is applied in the case of down-cut dressing.

Since the length of the diamond grit is m , its rear end will come in contact with the grinding wheel after a period T_m given as

$$T_m = \frac{m}{V_d}. \quad (6)$$

In time T_m , the grinding wheel also travels the circumferential distance

$$l_m = T_m V_g = \frac{V_g}{V_d} m. \quad (7)$$

Thus, the length of the dressing trajectory of a diamond grit l_a , which is measured along the circumference of the grinding wheel, is given as

$$l_a = l'_a + l_m = 2 \left| 1 \pm \frac{V_g}{V_d} \right| \sqrt{D_{eg} t} + \frac{V_g}{V_d} m. \quad (8)$$

The relative positions of the dressing trajectories of the front end and rear end of a diamond grit on the grinding wheel are illustrated in Fig. 4.

Fig. 4 Sectional profile of a dressing trajectory

Fig. 5 Relationship between l_a and VR (parameter m)

Fig. 6 Relationship between l_a and VR (parameter t)

Figures 5 and 6 show the calculated curves of the contact length l_a for various values of VR , which is defined as the velocity ratio of the RDD to the grinding wheel ($VR = V_d / V_g$). In the figures, negative values of VR indicate down-cut dressing and positive values indicate up-cut dressing. The effect of the length of the diamond grit m is shown in Fig. 5 and that of the depth of cut t is shown in Fig. 6. It can be seen from the figures that l_a increases with m and t for all values of VR . By examining the effect of VR , it can be seen that the value of l_a

in the case of down-cut dressing is less than that in the case of up-cut dressing for a given absolute value of VR . It can also be seen that an inflection point exists at $VR = -1$ in down-cut dressing. This is due to the relative velocity of the RDD to the grinding wheel decreasing as the value of VR approaches -1, becoming zero at $VR = -1$ and increasing away from the value of $VR = -1$. This discontinuity in the relative velocity results in the point of inflection at $VR = -1$. The dressing process at $VR = -1$ is called crush-mode dressing.

The pitch of the dressing trajectories formed on the circumferential surface of the grinding wheel (see Fig. 2) is given as

$$P = \frac{V_g}{V_d} \cdot \frac{\pi D_d}{n}, \quad (9)$$

where n is the number of diamond grits on the surface of the RDD.

The gap between two successive trajectories l_a (see Fig. 2) is given as

$$g = P - l_a. \quad (10)$$

If $g > 0$, a series of separated dressing trajectories is generated on the surface of the grinding wheel, as schematically shown in Fig. 2. If $g < 0$, the dressing trajectories overlap with each other, and a series of continuous trajectories is generated.

The critical depth of cut in dressing t_c that realizes continuous dressing trajectories is derived by substituting l_a given by Eq. (5) and P given by Eq. (9) into Eq. (10) and setting g equal to zero as follows:

$$t_c = \left(\frac{1}{D_{eg}} \right) \left[\frac{\frac{V_g}{V_d} \left(\frac{\pi D_d}{n} - m \right)}{2 \left| 1 \pm \frac{V_g}{V_d} \right|} \right]^2. \quad (11)$$

Fig. 7 Relationship between t_c and VR (parameter m)

Figure 7 shows the calculated curves of t_c for various values of VR . The three curves are for $m = 0, 0.2$ and 0.4 mm. It can be seen from the figure that the maximum t_c is 5 to 10 μm in the case of up-cut dressing; however, in the case of down-cut dressing, it exceeds 20 μm for almost all values of VR . From Fig. 7, the dressing conditions that realize continuous dressing trajectories can be obtained. For example, in the case of $m = 0.2$ mm, $t = 2$ μm and up-cut dressing, it can be seen from the figure that continuous dressing trajectories are formed when VR is greater than 1.0.

2.3 Sectional profile of dressing trajectory

As shown in Fig. 8, the sectional profile of the dressing trajectory is formed by two trochoid curves, curve AB at the front and curve CD at the rear, and the straight line segment BC connecting the two curves. When the depth of cut t is very small compared with D_g and D_d , the trochoid curve can be approximated by a parabola. Taking this into consideration, the sectional profile (l, z) of the dressing trajectory can be expressed as

$$\begin{aligned} z = t - \frac{l^2}{D_{eg} \left(1 \pm \frac{v_g}{v_d}\right)^2} & \quad -\frac{l_a}{2} \leq l \leq -\frac{1}{2} \frac{V_g}{V_d} m \\ z = t & \quad -\frac{1}{2} \frac{V_g}{V_d} m < l \leq \frac{1}{2} \frac{V_g}{V_d} m \\ z = t - \frac{l^2}{D_{eg} \left(1 \pm \frac{v_g}{v_d}\right)^2} & \quad \frac{1}{2} \frac{V_g}{V_d} m < l \leq \frac{l_a}{2}. \end{aligned} \quad (12)$$

Figure 9 shows the sectional profiles of dressing trajectories to illustrate the effects of the length of diamond grits m and the dressing strategy, i.e., up-cut dressing or down-cut dressing. These profiles were calculated by substituting the dressing conditions listed in Table 1 into Eq. (12). Note that the velocity ratio V_g/V_d shown in Fig. 9 is the inverse of VR shown in Figs. 5-7. $V_g/V_d = 0$ in Fig. 9 means that the grinding wheel stops rotating and only the RDD rotates; therefore, the sectional profile of the dressing trajectory is that of the grinding wheel surface, whose diameter is given by Eq. (2). In Fig. 9, $V_g/V_d = -2, -1, 1$ and 2 correspond to $VR = -0.5, -1, 1$ and 0.5 in Figs. 5-7, respectively.

Fig. 8 Sectional profile of dressing trajectory used in analysis

Fig. 9 Sectional profiles of dressing trajectory (parameters, V_g/V_d and m)

3. Simulation Process

3.1 Simulation procedure

The previous section provided basic information regarding the dressing trajectory on the working surface of the grinding wheel. However, to optimize the dressing conditions and to provide some useful feedback when using or developing an RDD, it is important to know the dressing performance with respect to the RDD specifications D_d , m and n ; the dressing conditions VR , t and f_d ; and the dressing strategies, i.e., up-cut or down-cut dressing, and single-pass or multipass dressing. The most interesting issue is whether or not the entire surface of the grinding wheel is completely dressed by the RDD. Knowing the minimum feed of the RDD in single-pass dressing and the minimum number of passes in multipass dressing required to realize complete dressing is useful for reducing the dressing time. This section describes the simulation process developed to determine the dressing performance for a given set of dressing conditions and a means of evaluating the completeness of dressing.

Figure 10 shows the flow chart of the simulation process. The simulation process requires a set of inputs, D_g , D_d , V_g , n , m , D_b , f_d , t , VR , N_D ; and the dressing method: up-cut or down-cut dressing. N_D is the number of passes, and $N_D = 1$ corresponds to single-pass dressing. Using the set of inputs, the parameters l_a , P , g , L_d and θ are first calculated. In the second step, a series of dressing trajectories are formed on the grinding wheel surface using the calculated parameters as illustrated in Fig. 2. In the final step, the dressing ratio D_r , which is defined in the next section, is calculated. This procedure is performed N_D times.

Fig. 10 Flow chart of simulation process

3.2 Dressing ratio

The RDD forms a series of separated or continuous dressing trajectories on the working surface of the grinding wheel, depending on the dressing conditions and dressing strategies. To evaluate the areal ratio of the dressing trajectories to the working surface of the grinding wheel, i.e., to evaluate the amount of the grinding wheel surface dressed by the RDD, the dressing ratio D_r is defined as the areal ratio of the grinding wheel surface covered by the dressing trajectories to the entire working surface of the grinding wheel.

We set a rectangular segment that is sufficiently large to include the series of dressing

trajectories on the working surface of the grinding wheel, as illustrated in Fig. 11. The rectangular segment is cut into a number of mesh points at intervals of Δx and Δy . The numbers of mesh points in the width and circumferential directions of the grinding wheel are I and J , respectively. The location of each mesh point (i, j) ($i = 1, \dots, I$, $j = 1, \dots, J$) is represented by the coordinates of the center of the mesh point (x_i, y_j) . Each mesh point (i, j) has one bit value s_{ij} , which represents the state of dressing, i.e., dressed or undressed.

We define s_{ij} as

$$s_{i,j} = \begin{cases} 1 & \text{when } (x_i, y_j) \text{ is inside the dressing trajectory} \\ 0 & \text{otherwise.} \end{cases} \quad (13)$$

Let K be the number of dressing trajectories existing in a rectangular segment. The $(k-1)$ th, k th and $(k+1)$ th dressing trajectories are shown in Fig. 11 as examples.

Focusing on the k th dressing trajectory, the number of mesh points located inside the dressing trajectory is given as

$$S_k = \sum_{i=1}^I \sum_{j=1}^J s_{i,j}. \quad (14)$$

The total number of mesh points inside the dressing trajectories existing in the rectangular segment is given as

$$S = \sum_{k=1}^K S_k. \quad (15)$$

Dividing S by the total number of mesh points, the dressing ratio D_r is calculated as

$$D_r = \frac{S}{I \cdot J}. \quad (16)$$

Fig. 11 Calculation of dressing ratio

4. Results of Simulation

Figure 12 shows examples of dressed patterns obtained from the dressing simulations carried out for a diamond grit width D_b of 0.2 mm, a depth of cut t of 2 μm and a dressing lead L_d of 0.4 mm/rev. It can be seen that continuous dressing trajectories are formed at $VR = +1.2$ and that separated dressing trajectories are formed at $VR = +0.7$ and $+0.5$. Note that these results are derived from Fig. 7, which shows the critical depth of cut. For example, the critical depth of cut in dressing at $VR = +1.2$ is 1.7 μm , which is 0.3 μm smaller than the depth of cut, $t = 2 \mu\text{m}$. This result indicates that continuous dressing trajectories are formed at $VR = +1.2$.

Comparing the two dressed patterns for $VR = +0.7$ and $+0.5$, it is found in the case of $VR = +0.5$ that every dressed area is located at the same circumferential position of the grinding wheel, regardless of the width position of the grinding wheel, namely, there is no offset of the dressing trajectory, which is shown in Fig. 2. This is because the pitch of the dressing trajectories P divides into the circumference of the grinding wheel πD_g when $VR = \pm 0.5$. The quotient is calculated to be 168 in this case.

By investigating the dressing lead L_d that realizes complete dressing, i.e., $D_r = 1$, the following dressing strategies are found. In the case where continuous dressing trajectories are formed (see Fig. 12 (a)), complete dressing can be realized by setting L_d to the same value as the width of the diamond grit D_b . In the case where the separated dressing trajectories have an offset (see Fig. 12 (b)), complete dressing is realized by setting L_d to a value less than D_b so that the series of dressing trajectories overlap with each other. However, in the case where the separated dressing trajectories have no offset (see Fig. 12 (c)), L_d cannot be tuned to achieve complete dressing.

Fig. 12 Dressed patterns in single-pass dressing ($D_b = 0.2 \text{ mm}$, $L_d = 0.4 \text{ mm/rev.}$, $t = 2 \mu\text{m}$)

4.1 Effect of the feed rate of RDD in single-pass dressing

As a parameter to evaluate the effect of the dressing lead on the dressing ratio, the dresser feed rate FR is defined as

$$FR = \frac{L_d}{D_b}. \quad (17)$$

Figure 13 shows the change in the dressed pattern formed on the grinding wheel surface when FR is changed from 1 to 0.6. The dressing conditions are the same as those for Fig. 12 (b), and the dressed pattern shown in Fig. 12 (b) corresponds to the result for $FR = 2$. It can be seen from the figure that the area of the undressed parts decreases with decreasing FR .

Figure 14 shows plots of the dressing ratio D_r against FR for various values of VR . As mentioned before, complete dressing, i.e., $D_r = 1$, is not achieved when $VR = \pm 0.5$. On the other hand, complete dressing is achieved for $FR = 0.5$ when $VR = +0.7$ and for $FR = 0.001$ when $VR = -0.7$. In the figure, $FR = 0.5$ and 0.001 correspond to dresser feed speeds of 500

and 1 mm/min, respectively. The dresser feed speed of 500 mm/min is a value set in actual dressing; therefore, it can be concluded that complete dressing is realized in the case of up-cut dressing with $VR = +0.7$ if the dresser feed speed of the RDD is set at 500 mm/min. However, in the case of down-cut dressing with $VR = -0.7$, the dresser feed speed of 1 mm/min is too slow to realize using practical dressing apparatus; therefore, complete dressing is almost impossible to achieve.

Fig. 13 Effect of FR on the dressed surface in single-pass dressing ($VR = +0.7$, $t = 2 \mu\text{m}$)

Fig. 14 Dressing ratio vs. dresser feed rate in single-pass dressing at $t = 2 \mu\text{m}$

4.2 Effect of the number of passes in multipass dressing

Figure 15 shows the dressed pattern formed on the grinding wheel surface after two passes, i.e., $N_D = 2$. The dressing conditions are the same as those for Fig. 12 (b) except for $FR = 1$. A depth of cut of $t = 2 \mu\text{m}$ was given for each pass on both side edges of the grinding wheel. The dressed pattern shown in Fig. 13 (a) corresponds to the result for $N_D = 1$. It can be seen from the figure that the undressed area almost disappears after two-pass dressing.

Figure 16 shows plots of D_r against N_D . It can be seen from the figure that the number of passes that realizes complete dressing, i.e., $D_r = 1$, is three in the cases of up-cut dressing with $VR = +0.5$ and $+0.7$, and 8 and 14 in the cases of down-cut dressing with $VR = -0.5$ and -0.7 , respectively. The reason why a large number of passes is required to achieve complete

dressing in the case of down-cut dressing is that the contact length of the dressing trajectory in down-cut dressing is markedly smaller than that in up-cut dressing (see Figs. 5 and 6), although the pitch of the dressing trajectory given by Eq. (9) takes the same value in up-cut dressing and down-cut dressing for a given value of VR .

Fig. 15 Dressed surface after two-pass dressing ($VR = +0.7$, $t = 2 \mu\text{m}$, $FR = 1$)

Fig. 16 Dressing ratio vs. number of passes ($t = 2 \mu\text{m}$, $FR = 1$)

5. Conclusions

The dressing mechanism of a rotary diamond dresser was analyzed by a kinematic approach and the performance was investigated by computer-aided simulation. The results are summarized as follows.

- 1) The length of the dressing trajectory increases with increasing circumferential length of the diamond grits and increasing depth of cut.
- 2) The length of the dressing trajectory in the case of down-cut dressing is shorter than that in the case of up-cut dressing for a given velocity ratio of the rotary diamond dresser to the grinding wheel, and decreases with increasing velocity ratio, although an inflection point exists in the case of down-cut dressing.
- 3) The dressing conditions that realize complete dressing of the whole surface of the grinding wheel can be obtained from the dressing simulation, namely, the maximum feed speed of the dresser in single-pass dressing or the minimum number of passes in multipass dressing can be obtained.
- 4) In the case of down-cut dressing, it is impossible to achieve complete dressing by tuning the feed speed of the dresser in single-pass dressing.
- 5) In multipass dressing, the minimum number of passes required to achieve complete dressing is larger in the case of down-cut dressing than in the case of up-cut dressing.

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