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Applying wire electrical discharge dressing (WEDD) to improve grinding performance of metal bounded diamond wheels

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Abstract

In order to improve grinding performance of metal-bonded diamond wheels, a proper conditioning method has to be used. In this work, wire electrical discharge dressing (WEDD) is evaluated. With a self-designed WEDD-device the dressing process can be carried out inside a grinding machine, reducing non-productive time. Moreover, the in-process WED-dressing was assessed, showing potential for future applications. Dressing experiments indicated that high erosion material removal rates can be achieved and, in comparison to conventionally conditioned wheels, a better grinding wheel topography is generated. Finally, a model to calculate the axial dressing feed rate in WED-sharpening is proposed.

Keywords: Wire EDM, Dressing, Grinding, Diamond, Ceramics

1. Introduction

The conditioning technology plays a decisive role in grinding. Within the grinding community the slogan "grinding is dressing" [1], points out that the preparation of the grinding tool has a significant influence on grinding results. Depending on the material to be ground, special grinding wheels are required. Hence, the choice of both the right abrasive and bond material are important and dressing is required. When grinding high performance ceramics, metal bonded diamond wheels are the first choice [2]. This bond material offers advantages especially regarding grain retention and thermal conductivity, which is important for keeping the grinding wheel profile within the specified tolerances and helping to dissipate heat generated during grinding. Moreover, diamond is the hardest material in the world [3]. Apart from these advantages, metal bonded diamond wheels are considered difficult-to-dress tools [1,4,5]. It has no pores, so that bond material has to be removed between grains to generate chip pockets and provide sufficient grain protrusion. Thus, the main challenge, for the use of metal bonded diamond wheels concerns conditioning.

Conditioning can influence grinding in different ways. First of all directly, since the workpiece accuracy depends, among others, on the grinding wheel macro geometry. Moreover, grinding forces, workpiece roughness and heat generation depend on the grinding wheel micro geometry. Therefore sharpening plays an important role. Second of all indirectly, since it impacts grinding productivity, given that dressing represents non-productive time.

Metal-bonded diamond wheels are usually conditioned by conventional silicon carbide wheels [2,6]. This method, however, has limitations. The high wear of the SiC wheel limits dressing accuracy [4], so that usually only non-complex wheel profiles are dressed. In addition, SiC-dressing is very time consuming, so that metal-bonded diamond wheels are, in many cases, conditioned on independent dressing machines. In this case, however, another problem arises, since after dressing the grinding wheel has to be carefully reassembled to the grinding machine, in order to avoid clamping errors [2]. Consequently, different non-conventional dressing methods have been proposed [5,7,8] aiming to overcome the above mentioned limitations. Wire electrical discharge dressing (WEDD)

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is also an alternative to the conventional dressing method [9-11]. Given that diamonds are generally electric insulators, WED-dressing can generate grain protrusion in metal-bonded diamond wheels, since only electrically conductive materials can be eroded.

In this work, the WEDD method is evaluated. The direct and indirect influence of dressing on grinding is discussed, comparing WED-dressing to SiC-dressing. The wire electrical in-process dressing was also analyzed. Finally, a method for calculating the constant axial dressing feed rate needed in sharpening is proposed based on a thermo-electrical erosion model.

2. Dressing time

In manufacturing, short cycle times are desired since it often leads to less manufacturing costs, especially because of rising machine and labor costs. According to [12], machining cycle time t_e can be defined as

$$t_e = t_v + t_{er} + t_g \tag{1}$$

where t_v represents the downtime, i.e. the time in which the machine is in a passive state, t_{er} is the machine idle time, and t_g is the sum of the main production time t_h and non-productive time t_n. Normally, there is a great potential for reducing machining time when the events which have an associated non-productive time are carefully investigated, like the dressing process.

Aiming to evaluate to what extend the dressing process can influence grinding productivity, WEDD was compared to SiC-dressing. A WEDD-device was first designed and integrated into a CNC universal cylindrical grinding machine Studer type S31. It is composed basically of a two axes feed system and wire drive system. The axes are controlled by an Adaptive Control System “AC Progress VP4” from GF AgieCharmilles.

Fig 1 shows results of dressing MRR (material removal rate) obtained using a grinding wheel type 1A1-50-5-20-D46-C125-M263, WED-dressed. Depending on the erosion peak current, dressing MRR ranging from 33 to 100 mm^3/min were achieved.

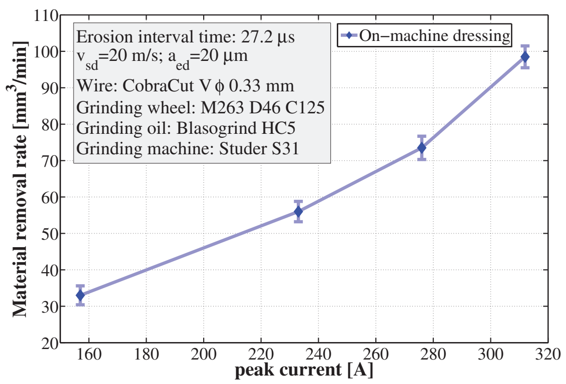

Fig. 1. Material removal rate in WED-dressing.

The same metal bonded diamond wheel used in the above mentioned WED-dressing experiments was also conventionally dressed by a SiC-wheel of diameter 420 mm, width of 20 mm, hardness G and grain mesh size 320, which was chosen based on recommendations given by Diametal AG [6]. A reciprocating dressing method was applied, using a dressing axial feed rate of 500 mm/min, a dressing wheel speed of 30 m/s, a dressing speed ratio of 30 and a depth of dressing cut per dressing stroke of 10 µm. After a total dressing time of 10 minutes, the amount of dressed volume was measured, resulting in a dressing MRR of only 8.5 mm^3/min. Thus, WED-dressing can be more than 10 times faster than SiC-dressing. In addition, after SiC-dressing a sharpening process is usually necessary, for generating grain protrusion, which leads to a further increase on the non-productive time associated with the conventional dressing method.

3. Topography of conditioned grinding wheels

In a grinding wheel, the total volume of the grinding component consists of abrasive grains, bond material and pores [2]. Pores are important, since they open up the surface of the grinding tool and provide space for chip collection and help forcing the cooling lubricant into the grinding zone. Unlike vitrified bonds, metal bonds have no pores, so that the conditioning process has to open up the surface and provide chip space, which is called sharpening and plays a decisive role.

Fig 2 shows SEM-micrographs of a grinding wheel (1A1-50-5-20-D46-C125-M263), conditioned in a) by the conventional method using a silicon carbide wheel and in b) by wire electrical discharge dressing. In comparison to the SiC-dressed surface, diamonds are clearly more exposed in the WED-dressed wheel.

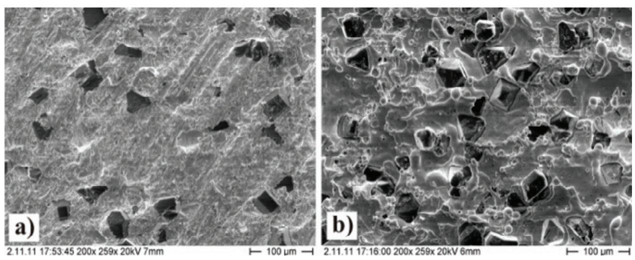

Fig. 2. SEM-micrographs a) SiC-dressed and b) WED-dressed wheels

Three dimensional measurements of the grinding wheel’s topographies were also made, in this case using an optical 3D measurement device type Alicona InfiniteFocus. The surface roughness and the Abbott-Firestone curves of those topographies presented in Fig 2 were analyzed, and some resulting 3D-parameters are presented in Table 1.

Table 1. Surface parameters of grinding wheel topography

Conditioning method	Surface 3D-parameters			
	S_a [µm]	S_k [µm]	S_{pk} [µm]	S_{vk} µm]
SiC-dressing	3.4	7.8	4.7	9.4
WED-dressing	17.5	31.5	8.2	11.5

The WED-dressed grinding wheel has a rougher topography, indicated by the higher value of S_a, which represents the average height of the selected surface area (similar to R_a in a 2D-measurement). Moreover, the higher values of core roughness depth S_k and reduced peak height S_{pk} indicate higher grain protrusion. The reduced valley height S_{vk} is similar in both topographies. It can be interpreted as corresponding to pores on the grinding wheel surface. The SiC-dressed wheel has lots of craters left by diamonds pulled-out during dressing, so influencing the value of S_{vk}. In both cases, the most protruding grains will however pull out upon first workpiece contact, changing the wheel topography.

4. Grinding forces and workpiece quality

During grinding, high process forces can negatively impact workpiece accuracy, and often represent a sign that the grinding process is not running as it should. It can be consequence of friction between workpiece and bond, which occur when little chip space is available on the grinding wheel. In this case, not only the forces are higher, but the heat generated is also increased. Fig 3 shows results of grinding forces obtained by grinding Si_3N_4 workpieces with a SiC-dressed and a WED-dressed metal bonded grinding wheel with one and the same specific grinding MRR. One can clearly see that higher forces result when the SiC-dressed wheel is used. The WED-dressed wheel has a more open structure, with higher grain protrusion, which is an important and desired characteristic of a grinding wheel.

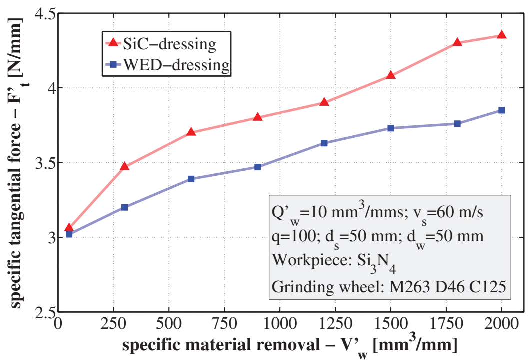

Fig. 3. Grinding forces in WED-dressing and SiC-dressing

The roughness R_z and waviness W_t of silicon nitride workpieces ground by SiC-dressed and WED-dressed grinding wheels were also analyzed, and the results are presented in Fig 4. No significant difference between both dressing methods was found, although the WED-dressed wheel has a more aggressive characteristic, which could lead to a worse surface quality

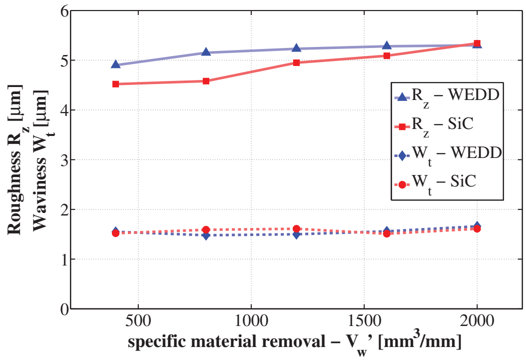

Fig. 4. Workpiece surface quality (SiC-dressing vs. WEDD)

5. In-process dressing

In-process dressing is a form of dressing during grinding, which can be designed as continuous dressing or be carried out at pre-defined time steps during grinding. There are basically two main advantages when in-process dressing is used. First, dressing time no longer influences the machining cycle time t_e, since the process is carried out during the main production time t_h. Second, the grinding wheel micro and macro geometry can be kept more constant over time, since dressing constantly corrects small deviations caused by wheel wear. Thus, this method can positively impact grinding accuracy as well as increase grinding productivity.

Fig 5 shows the influence of the dressing process on grinding forces, where the raw signal acquired using a rotating dynamometer type Z15168 SN473735 from Kistler was plotted (it follows a sine curve due to the workpiece rotation). Four out of seven measurements steps are shown in Fig 5, each one corresponding to a specific material removal of V'_w = 750 mm³/mm. A total V'_w of 5250 mm³/mm was ground, which is achieved at the end of the fourth step. In-process-dressing was carried out during the third step, where the acquired signal clearly dropped to a similar level as in step one. During this experiment, a large dressing depth of cut of a_{ed}=20 µm was used, aiming to clearly show that the process can be carried out parallel to the grinding process and bring the benefits already mentioned before.

Fig 6 shows results of grinding force measurements, achieved in a grinding experiment where in-process dressing was designed to remove a dressing depth of cut of a_{ed}=2 µm after every removal of 300 mm³/mm. These results are compared to a normal on-machine dressing process, in which the same total dressing depth of cut of a_{ed}=10 µm was applied only after a specific material removal of 1500 mm^3/mm was ground. When in-process dressing is carried out, the grinding forces are kept more constant over time, and do not reach the same maximum level as in on-machine dressing. This can lead to a better grinding repeatability, in which the grinding accuracy can be kept within tighter tolerances. The forces have a growth trend during in-process dressing, indicating that no enough material was dressed per dressing pass.

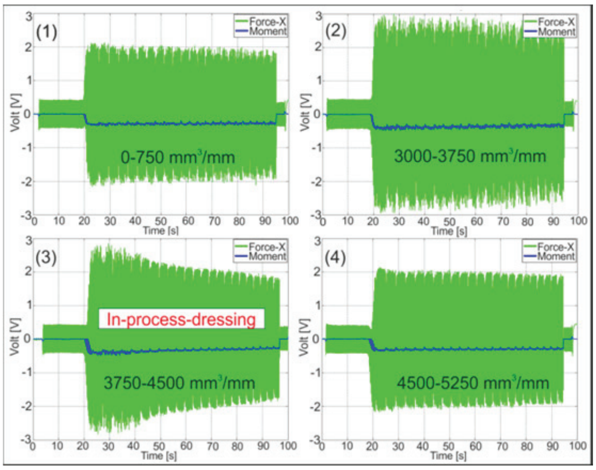

Fig. 5. In-process-dressing

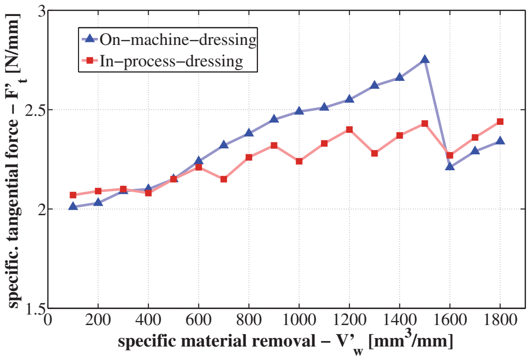

Fig. 6. In-process dressing vs. on-machine dressing

6. WED-dressing strategy

High dressing accuracy is the pre-requisite for a successful grinding process. In WEDD, the use of a special wire guide, as proposed by Weingärtner et al. [9], helps increasing accuracy, since wire vibrations are minimized. However, not only wire vibration is important, but also the way how the erosion process is controlled, i.e. whether a controlled or constant wire dressing feed rate is applied. Axial feed rate with closed loop control is especially important during profiling, where larger depths of dressing cuts are applied. In this case, the wire feed rate changes depending on some monitored erosion parameters, like the erosion delay time or the average process voltage. It was found, however, that during sharpening and in-process dressing, where primarily small dressing depth of cuts are applied, axial dressing fed rates with closed loop control lead to poorer dressing accuracy in comparison to constant feed rates. During dressing, if a small disturbance occurs, the control system quickly reacts by increasing or decreasing the feed rate. As a result, irregular marks appear on the surface of the grinding wheel, which are then transmitted to the workpiece after grinding. Thus, the use of constant v_{fad} in WED-sharpening is desired.

Depending, for instance, on the grinding wheel size, type on metal bond material and erosion parameters, different dressing feed rates have to be used when different dressing depth of cuts are applied. Thus, the right choice of the dressing feed rate v_{fad} has to be made, to guarantee better dressing results. To support calculating v_{fad}, a method based on a thermo-electrical erosion model is proposed.

6.1. Axial dressing feed rate in WEDD

In wire electrical discharge dressing, the axial dressing feed rate v_{fad}, the dressing material removal rate Q_d and the dressing material removal V_d can be written as follow

$$v_{fad} = b_s / t_d \tag{2}$$

$$Q_d = V_d / t_d \tag{3}$$

$$V_d = \pi(r_s^2 - (r_s - a_{ed})^2) \cdot b_s \tag{4}$$

where b_s is the grinding wheel width, t_d is the time per dressing pass, a_{ed} is the dressing depth of cut and r_s represents the grinding wheel radius. By substituting Eq. (3) and Eq. (4) in Eq. (2) and rearranging the equation, the axial dressing feed rate v_{fad} can be expressed as

$$v_{fad} = Q_d / \pi(2r_s \cdot a_{ed} - a_{ed}{}^2) \tag{5}$$

The dressing material removal rate Q_d is thus the only variable in Eq. (5) which cannot be directly chosen, but rather has to be either previously measured or calculated. As an example, for a Q_d of 50 mm^3/min, a_{ed} = 3 µm, and r_s = 200 mm, the resulting axial dressing feed rate equals v_{fad} = 13.2 mm/min, so that carrying out one dressing pass in a 10 mm wide grinding wheel would last approximately 45 seconds. One has to consider, however, that this axial feed rate represents a maximum for the above mentioned conditions. For practical reasons, a factor of safety should be used, aiming to guarantee that the entire circumferential surface of the grinding wheel is eroded.

In order to reduce the amount of experiments needed for measuring dressing material removal rates, a model can be used to estimate it. In this work, a thermo-electric erosion model is used to calculate the effective eroded volume of a crater V_c, which is generated by one single discharge. Knowing the effective eroded volume per crater, the dressing material removal rate Q_d can be estimated based on simulation results and be written as

$$Q_d = V_c \cdot f_e / (1 - V_a) \quad (6)$$

where f_e is the effective discharge frequency and V_a represents the volume percentage of abrasives in the bond. V_a depends on the concentration of diamonds, which is usually specified in the grinding wheel designation by the letter C followed by a number. For example, typical concentrations are C75, C100, C125 and C150, which represent, respectively, a volume percentage of 18% (V_a=0.18), 24%, 30% and 36%. The term (1-V_a) used in Equation (5) is necessary, since the diamonds (insulators) are not eroded, but rather pulled-out of the bond after reaching a certain protrusion.

Knowing the effective crater volume, the final equation used to estimate the axial dressing feed rate can be expressed as follow

$$v_{fad} = \frac{V_c \cdot f_e}{\pi(2r_s \cdot a_{ed} - a_{ed}^2) \cdot (1 - V_a)} \quad (7)$$

To calculate it, the erosion process was modeled as a heat conduction problem. The finite-difference method, where time and space are discretized, was used to solve partial differential equation that describes the heat conduction. As a result, the temperature distribution in discrete nodal points inside the workpiece is calculated. The heat source was modeled as a time dependent heat flux applied to the workpiece surface. The amount of energy which enters the workpiece/anode was estimated based on single discharge experiments, by comparing these experimental results with simulation results. It was found that approximately 35% of the total available discharge energy enters the workpiece/anode when the used wire EDM pulses were applied. This value is thus used as input for further simulations. Fig 7 shows a comparison between experimental and simulation results regarding the effective eroded volume of a crater V_c. Six different erosion pulses were used, which are designated here as I1 to I6, and represents the following peak currents: I1=88 A; I2=100 A; I3=128 A; I4=152 A; I5=188 A; I6=233 A. The experiments were carried out in a wire EDM machine type Progress VP4 from GF AgieCharmilles, using a workpiece of brass CuZn39Pb3. The results presented in Fig 7 shows a good correlation between experiments and simulation. The erosion MRR can thus be obtained by multiplying these results by the effective erosion discharge frequency f_e, which was measured for different discharge pulses (I1-I6) using an oscilloscope type LeCroy WaveRunner 44MXi-A.w.

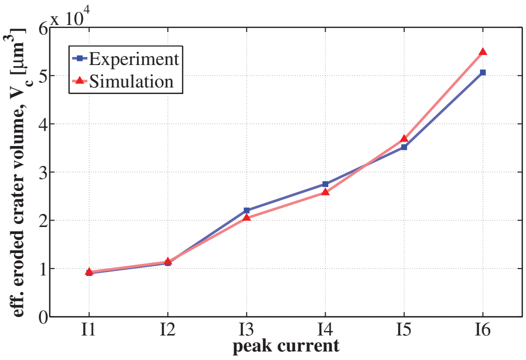

Fig. 7. Effective volume of eroded material V_c

Table 2 shows results of f_e obtained for the pulse type I4=152 A are presented in Table 2, together with the pulse frequencies f_p. The latter is calculated based only on the discharge interval time, assuming an ideal process, where no delay time exists and 100% of the discharges occur. The discharge frequency ratio λ is also shown, which represents the ratio of f_e to f_p.

Table 2. Discharge interval time and frequencies

Discharge interval time [µs]	50.5	35.0	27.2
Pulse frequency, f_p [kHz]	19.8	28.5	36.7
Effective frequency, f_e [kHz]	7.9	11.3	14.1
Discharge freq. ratio, $\lambda = f_e/f_p$ [%]	39.9%	39.6%	38.4%

Based on the presented results, a discharge frequency ratio of λ=39% was assumed for calculating the erosion MRR from here on. Fig 8 shows a comparison between experimental and simulation results obtained for a brass workpiece. Three discharge peak currents and three effective discharge frequencies were used (Table 2).

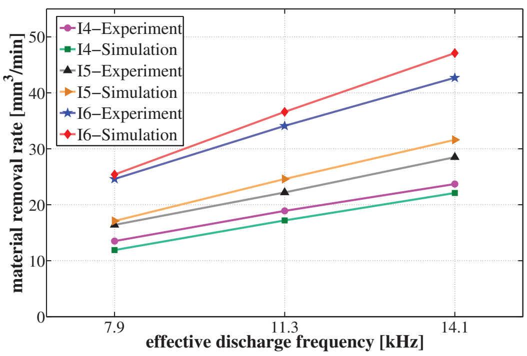

Fig. 8. MRR obtained for a brass workpiece

In Fig 8 the largest deviation between experiments and simulation is less than 10%. The proposed method can thus be applied to estimate v_{fad}. Fig 9 shows a comparison between simulation and experimental results regarding the material removal rate applied to a grinding wheel 1A1-50-5-20-D46-C125-M263. The experimental results are the same shown in Fig 1. Simulation results are shown considering the erosion MRR calculated with and without the volume percentage of diamonds C125 (V_a=0.3) according to (6). The results show a good correlation between experimental and simulation results when V_a=0.3 is applied.

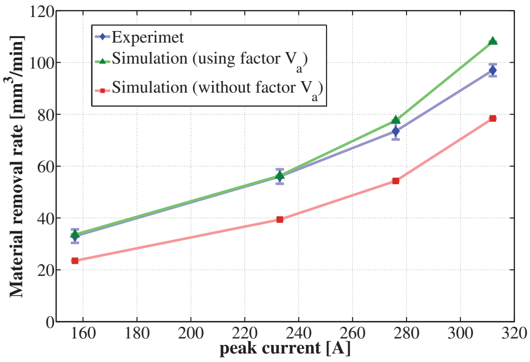

Fig. 9. MRR obtained for a diamond grinding wheel

Now that a good correlation of results has been found, the axial dressing feed rate can be calculated based on (7). Fig 10 show some examples of v_{fad} obtained for the chosen grinding wheel, when eroded using different peak currents, an effective erosion discharge frequency of f_e=14.1 kHz, and a two different dressing depth of cut a_{ed}.

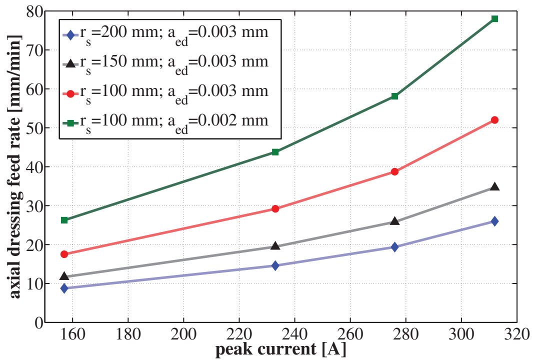

Fig. 10. Calculated dressing feed rates

7. Conclusions

In this work, the wire electrical discharge dressing (WEDD) method was evaluated and compared to SiC-dressing. It was found that in WEDD high dressing MRR can be achieved, even using grinding oil as dielectric. Since dressing represents non-productive time, high erosion MRR helps increasing grinding performance of metal bonded grinding wheels. Moreover, WEDD allows for generating more proper grinding wheel topographies, i.e. a grinding wheel with a more open structure. As a result, lower grinding forces were achieved. Although WED-dressed wheels are sharper than SiC-dressed wheels, this characteristic has shown no significant influence on the surface quality of workpieces. In-process WED-dressing has proved to be feasible showing potential for future applications. Finally, a method for calculating the constant dressing axial feed rate necessary for WED-sharpening was proposed. Dressing MRR is estimated based on simulation of single discharges. Good correlation between experimental and simulation results was found, enabling the wire feed rate to be estimated with this method. Based on all results achieved in this work, we can state that WED-dressing is a suitable method for conditioning metal bonded diamond wheels, and show great potential to increase its grinding performance.

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