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On mechanics and monitoring of plunge-roll rotary dressing of grinding wheels

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ABSTRACT

A study is made into the mechanics and monitoring of rotary plunge-roll dressing of grinding wheels using a roll with multi-layer diamonds contained in a hybrid, metal-ceramic bond. A fundamental relationship is obtained between grinding/dressing specific energy and the dressing aggressiveness number $Aggr_d$, revealing a distinct size effect. Results also indicate (i) a nearly linear relationship between grinding and dressing specific energy, and (ii) direct proportionality between dressing specific energy and the acoustic emission (AE) signal. SEM observations indicate that smaller $Aggr_d$ produces a grit-dulling phenomenon different from grinding-induced dulling of the grits by attrition, which causes rapid workpiece-material adhesion.

1. Introduction

Conditioning of grinding wheels has a major effect on grinding performance and workpiece quality [1]. Conditioning of conventional wheels usually refers to dressing, which also includes truing of the wheel [2]. Dressing can be done using a stationary diamond tool or a rotary-diamond dressing disk or roll. This work is concerned with plunge-roll dressing. Here, the dressing roll is fed radially into the wheel at a specified infeed, while both the dresser (roll) and the grinding wheel rotate (Fig. 1).

Initial research into rotary dressing at TU Braunschweig in 1969 [3] established key dressing parameters still in use today, namely the infeed and the speed ratio. Pahlitzsch and Schmitt also investigated the effect of dressing direction, as the dresser surface may move in the same/uni (+) or the opposite/anti (-) direction as the wheel surface. The authors experimentally observed that the grinding-wheel roughness increased when shifting from (-) to (+) dressing mode, with the greater wheel roughness resulting in a rougher workpiece surface finish and lower grinding forces [3].

The effects of dressing conditions on grinding wheel performance and ground workpiece surface roughness have been researched ever since, most recently by Macerol et al. [4] and Garcia et al. [5]. The trade-off between specific grinding energy and workpiece surface roughness with varying dressing conditions has been well established

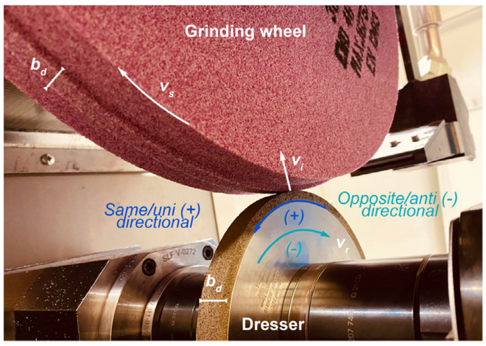

Fig. 1. Photograph of plunge-roll rotary dressing with its process kinematics.

for both rotary and stationary dressing tools for both aluminum-oxide wheels and cBN wheels [6−8].

In an effort to better understand rotary dressing from first principles of mechanics and provide additional fundamental information on specific dressing and grinding energies, as well as acoustic emission (AE) and monitoring, the current study was undertaken. For over fifty years, plunge-roll dressing has been quantified by three separate parameters: infeed, speed ratio and direction (+/−). This is cumbersome. Therefore, the fundamental dressing mechanics were analyzed to develop a single, unifying parameter to quantify the geometric and kinematic effects of dressing. It is called the dressing

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aggressiveness number $Aggr_d$. While this parameter has been established in rotary-traverse dressing, it has not been established for rotary-plunge dressing.

AE is a well-established technique for detecting wheel-workpiece contact and wheel collision and for monitoring stock allowance and the overall grinding process. In dressing, AE can detect initial wheel-dresser contact (gap control) and abnormal or severe contact (crash protection) and can monitor the quality and consistency of the dressing process. Recent research suggests [9] that AE signals are proportional to dressing power during single-point dressing. This possible relationship has not been investigated for rotary dressing. In addition, single-point contact contains zero-depth finishing passes (with plastic deformation), whereas rotary plunge dressing contains a non-zero effective dressing depth throughout. Therefore, the relationship between specific dressing energy and AE signal is made to determine if AE can be used to monitor dressing and indirectly quantify wheel sharpness. For this, dressing power and AE is measured over a wide range of dressing ($Aggr_d$) conditions. Finally, scanning electron microscopy (SEM) is used to provide further insights into the effects of $Aggr_d$ on dressing mechanisms, workpiece adhesion/wheel loading and the morphology of dressed wheels.

2. Dressing models

In 1978, Malkin and Murray [10] undertook a fundamental study of mechanics of rotary dressing. In this predominantly experimental study, the dressing conditions included the rotary-dresser type, the dresser infeed per wheel revolution, a_r, dressing speed ratio $q_d = v_r/v_s$ (where v_r is the dresser speed and v_s the wheel speed), and the direction (+/−). The dressing performance was evaluated in terms of specific dressing energy u_r. Infeeds and speed ratios were used to quantify the interference angle, δ, at which the dresser diamond impacts the grinding wheel:

$$\delta = \tan^{-1}\left(\frac{a_r}{\pi d_s|1-q_d|}\right) \tag{1}$$

where d_s is the grinding wheel diameter. This dressing model, however, does not account for the geometrical contact length between the dresser and the grinding wheel. In spite of this, a single-valued relationship was obtained between the dressing specific energy, u_r, and δ, with a less cumbersome correlation than using both a_r or q_d separately. It was also shown that coarser dressing – i.e., larger δ – leads to smaller grinding forces and rougher workpiece surfaces.

Dressing specific energy, the energy expended in removing a unit volume of grinding wheel, can be determined either by measuring the tangential dressing force $F_{t,d}$ [10] or the power in the dressing-wheel spindle, P_s, and dressing-roll spindle, P_r, according to:

$$u_r = \frac{F_{t,d}|v_s - v_r|}{b_d a_r v_s} = \frac{P_s + P_r}{b_d a_r v_s} \tag{2}$$

where b_d is the dresser width. In the opposite/anti (-) directional mode, the power is positive for both spindles, whereas in the same/uni (+) directional mode, the power of the faster wheel/dresser is positive while the power of slower wheel/dresser is negative (i.e., in the breaking mode).

While the interference angle δ was derived from a geometrical perspective, the fundamental dimensionless parameter can be derived from the dressing kinematics, i.e. the ratio of the normal v_n to tangential $v_t = |v_s - v_r|$ component of the relative velocity vector. This ratio is termed point aggressiveness $Aggr_d^*$ [11]. Averaging the $Aggr_d^*$ over the contact length gives the dressing aggressiveness number $Aggr_d$, expressed as:

$$Aggr_d = \frac{1}{|v_s - v_r|}\frac{Q'_s}{l_{c,d}} \tag{3}$$

where Q'_s represents the wheel specific material removal rate caused by the dressing action. Considering the removal of the abrasive layer by dressing in the circumferential (v_s) direction and the removal in the radial direction at the infeed velocity v_i, the following expression for Q'_s is obtained:

$$Q'_s = \int_{lc,d} v_n \, dl_{c,d} = v_s a_r + v_i l_{c,d} \tag{4}$$

where $l_{c,d} = \sqrt{d_{e,d} a_r}$ is the geometrical contact length and $d_{e,d} = d_r d_s/(d_r + d_s)$ is the equivalent dressing diameter. Here d_r is the diameter of the dressing roll and $v_i = v_s a_r/\pi d_s$ is the dressing infeed velocity. Combining all the above relationships gives the unifying expression for dressing aggressiveness number:

$$Aggr_d = \frac{1}{|1-q_d|}\sqrt{\frac{a_r}{d_{e,d}}} + \frac{a_r}{\pi d_s|1-q_d|} \tag{5}$$

The second term in the above equation accounts for the tangent of the interference angle $\tan\delta$ (see Eq. (1)), which is neglectable in comparison with the first term (adding less than 0.05% for dressing conditions used in the study). Therefore, modeling of the plunge-roll dressing using only the interference angle δ does not comprehensively quantify the role of $a_r/d_{e,d}$ in dressing. This is schematically shown in Fig. 2, where it is evident that the fundamental parameter $Aggr_d^*$ is a function dependent on the dressing contact length and not only a dimensionless constant.

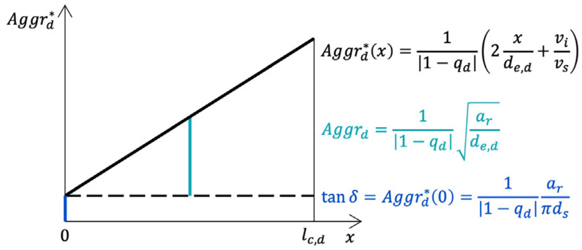

Fig. 2. Dimensionless scalar parameters quantifying the intensity of the abrasive interaction between the dresser and the grinding wheel.

Brinksmeier and Cinar introduced the collision number i_d [12] between the diamonds on a traverse dresser and the grits on the grinding wheel. Because the work considered traverse dressing, the collision number is proportional to $U_d|1-q_d|$, where U_d is the dressing overlap ratio. The collision number incorporates dressing geometry and kinematics, as well as the contact length. This model further includes the size of grits on the grinding wheel and the dresser, as well as the number of diamond points per unit area of the dresser. A larger δ and i_d both produced a greater tendency for the abrasive grit or bond to fracture rather than flatten, resulting in lower specific grinding energies [6,12]. Linke adopted the collision-number model [13] for traverse dressing and added a time-dependency to i_d. The application of $Aggr_d$, however, is simpler due to circumventing the necessity to measure or adopt topography parameters. Linke also extended the collision-number model to AE monitoring, as it was shown that the i_d widely correlates to the root mean square (RMS) value of the AE signal.

More recently, Spampinato and Axinte [14] described dresser and wheel topographies (grit size and protrusion) in probabilistic terms. The concerned contact length was not assumed geometric, but kinematic, which requires experimental calibration to account for the deflection in the abrasive contact. This work makes use of the discrete element method to model the abrasive interactions. The underlying derivations are related to actual and critical stress of an individual grit in the contact.

3. Experimental

Dressing and grinding tests were performed on a Blohm Planomat HP 408 surface grinder (Fig. 1) using a synthetic grinding fluid (Quakercool 2920 EVC) at 8% concentration. The rotary dresser (d_r = 150 mm, b_d = 12.83 mm), manufactured by Meister Abrasives, contained D42-size diamonds in an unconventional – hybrid, metal-ceramic bond. The grinding wheel was 46-mesh, soft-grade, friable-grit aluminum-oxide in a vitrified-bond (46G7VHK, d_s = 400 mm).

The dressing parameters are summarized in Table 1, showing a wide range of dressing aggressiveness numbers. The total dressing depth was 0.2 mm for each dressing set.

Table 1
Plunge-roll dressing parameters. Colored cells indicate dressing aggressiveness numbers $Aggr_d$ used.

		v_i, dressing infeed velocity [μm/s]				
		0.1	0.3	0.7	1.0	1.5
q_d, dressing speed ratio	-0.8	5.38E-4	9.32E-4	1.42E-3	1.70E-3	2.08E-3
	-0.4	6.92E-4	1.20E-3	1.83E-3	2.19E-3	2.70E-3
	+0.4	1.61E-3	2.80E-3	4.27E-3	5.10E-3	6.25E-3
	+0.8	4.84E-3	8.39E-3	1.28E-2	1.53E-2	1.88E-2

Dressing aggressiveness [-]: Low High

During all tests, the dressing AE signal (Accretech SBS in-spindle AE sensor, 250 Hz analysis rate) and the wheel (P_s) and dresser (P_r) spindle power were recorded (25 Hz). The AE-monitoring settings were: gain (26); frequency band (220 kHz); center frequency (880 kHz); bandwidth (124 kHz); process filter (1.5 ms). Different dwell times were investigated as well, but this factor did not affect the AE readings.

Following each dressing condition, the corresponding wheel performance was evaluated by grinding a workpiece made of ferritic-pearlitic micro-alloyed medium-carbon steel with an average Vickers hardness of 217 HV5. The grinding conditions were kept constant (wheel speed $v_s = 30$ m/s, workpiece speed $v_w = 50$ mm/s, depth of cut $a = 0.025$ mm). After each new dressing, it was ensured that the initial transient behavior of the wheel was overcome, and a steady grinding-power signal was reached. This was typically achieved in 10 grinding passes. The effect of dressing on grinding performance was evaluated in terms of grinding specific energy u_g, which was calculated as $P_s/b_d a v_w$.

For the analysis of the dressed wheel topography, small samples were extracted from the grinding wheel surface and inspected using a scanning electron microscope (FEI/Philips XL30) equipped with detectors for secondary electrons (topographical contrast) and back-scattered electrons (compositional contrast).

4. Results and discussion

Common quantification of dressing has typically focused on three different relationships: how the grinding (and sometimes the dressing) specific energy depends on (i) dressing infeed, (ii) speed ratio and (iii) direction (+/−). This is shown in Fig. 3. Quantifying these relationships separately ignores the fact that a sharp wheel, for example, can be achieved with a small dressing infeed and even with a highly negative, anti-directional speed ratio, depending on the other parameters chosen.

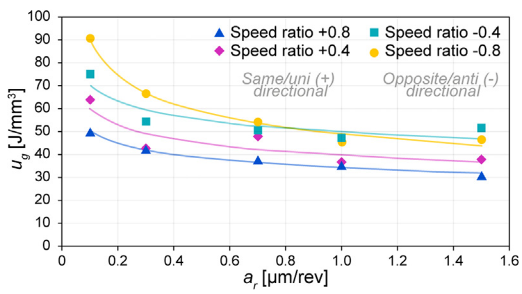

Fig. 3. Grinding specific energy u_g vs dressing infeed a_r for different speed ratios q_d.

The model for calculating the dressing aggressiveness number $Aggr_d$ (Eq. (5)) unifies the various input parameters into a single equation that more accurately correlates with specific energy and, consequently, wheel sharpness. Fig. 4 shows the measured grinding specific energy u_g plotted vs. $Aggr_d$. The correlation is good, particularly considering the wide range of speed ratios and infeeds tested, both for uni-directional and anti-directional dressing. A similar characteristic curve, with a distinct size effect, was obtained when plotting dressing specific energy u_r vs. $Aggr_d$. (It should be noted that the grinding specific energy is two orders of magnitude higher than the dressing specific energy.)

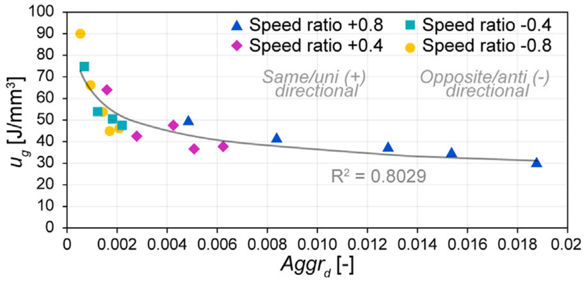

Fig. 4. Grinding specific energy u_g vs dressing aggressiveness number $Aggr_d$ for different infeeds and for different speed ratios.

Fig. 5 shows a near-linear correlation between the grinding specific energy u_g and the dressing specific energy u_r, regardless of dressing parameters and directionality. It's interesting to note the intercept: a minimum grinding specific energy of 20 J/mm^3, which is approaching the chip-formation energy observed by [2].

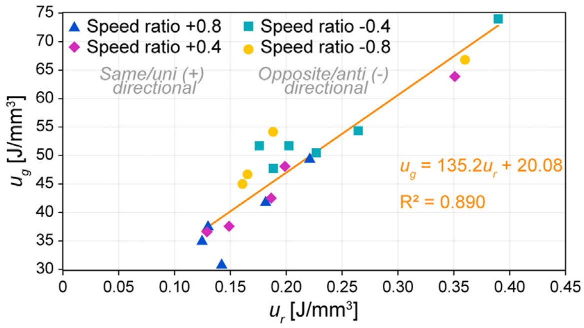

Fig. 5. Grinding specific energy u_g vs dressing specific energy u_r.

Based on the above, it should be possible to determine the relationship between dressing specific energy and AE intensity, a parameter that could be useful in predicting wheel sharpness. Indeed, it was found that the AE signal correlates closely with dressing specific energy u_r, both in the uni-directional and anti-directional mode. Fig. 6 shows the dressing specific energy plotted against the acoustic-emission specific energy u_{AE} (% of AE signal per dressing material removal rate). Because AE signal intensity is dependent on gain and frequency settings, the amplitude of the AE signal is given in percent of full input range (for the operating gain setting). As the analog input is used to connect the AE-sensor output to the CNC digital interface, the analogue input conversion refers to $\pm$10 VDC (voltage direct current) range. The obtained linear correlation proved strong. Therefore,

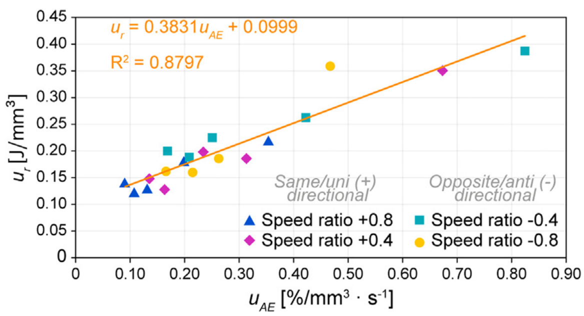

Fig. 6. Dressing specific energy u_r vs AE specific energy u_{AE}.

the u_{AE} could be used to quantify wheel topography and, in turn, grinding specific energy.

The roughness and the cutting-point density of the grinding wheel was shown to depend both on the speed ratio and the dressing infeed [3]. Finer dressing conditions decreased the peak-to-valley roughness and increased the cutting point density. However, once the speed ratio became less than +0.2 (and crossing over into the anti-directional regime), cutting-point density remained constant. In spite of this, numerous experiments [8,10] show that grinding power continues to increase in this region, even if wheel topography appears not to change.

This indicates grit dulling during dressing. Malkin found that plastic deformation of the grits occurs in diamond dressing [10]. Also, it is well established that grit-dulling occurs during grinding. The results here, however, indicate that the nature of the dulling is different. SEM was carried out to observe how the dressing conditions (i.e. $Aggr_d$) influence the grinding-wheel morphology and thereby provide insight into the dressing mechanisms. For this, two extreme dressing conditions were selected: very sharp ($Aggr_d$ = 1.53E-2), with a low specific dressing energy, and very dull ($Aggr_d$ = 5.38E-4), with a high specific dressing energy.

From the SEM micrographs in Fig. 7, differences in wheel topography are immediately evident. The dull-dressed wheel surface shown in Fig. 7a and c is characterized by more flat areas compared to the sharper condition shown in Fig. 7b and d. However, the dull-dressed grits do retain some degree of jaggedness, which is different than grits that became dull during grinding, which retain no jaggedness. This suggests that, in addition to plastic deformation, the dull grit from dressing is created by microfracturing, which creates the jagged edge but does not increase the cutting point density.

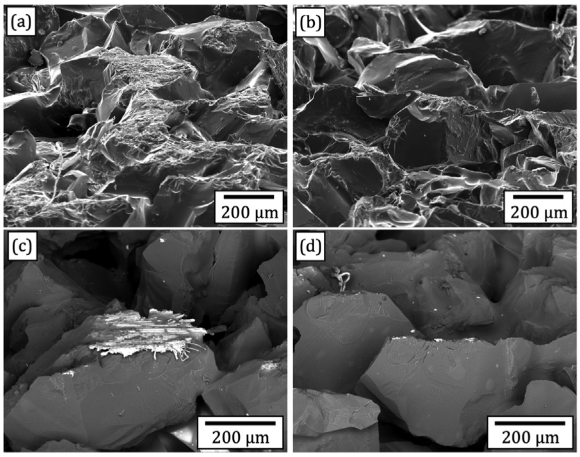

Fig. 7. Wheel topography after dressing the wheel dull (a and c) and sharp (b and d). Top row is imaged by secondary electrons and bottom row imaged by backscattered electrons (adhered steel appears bright).

To further analyze this, a small amount of material was ground after dressing in both the sharp and dull conditions (Fig. 7c and d). In spite of the very small grinding amount, the dull wheel showed severe adhesion of workpiece material smeared over the tips of the dull grits (i.e. loading, see Fig. 7c), whereas the sharp-dressed wheel showed minimal loading (Fig. 7d). This supports the idea [7] that using large, dull-dressed grits to achieve a given surface finish (instead of small, sharp-dressed grits) has negative repercussions. Badger quantified this problem in terms of grinding power. The results here indicate that it also severely increases wheel loading.

5. Conclusions

- Diamond dressing rolls with hybrid ceramic-metal bond behave similarly to standard reverse-plated diamond rolls, with more aggressive dressing conditions producing lower grinding specific energies.
- The theory of aggressiveness was applied to plunge-roll rotary dressing. Various combinations of dressing parameters can be unified into a single dimensionless parameter that correlates well with the grinding specific energy.
- SEM analysis suggests that the mechanisms of grit dulling are different in dressing and in grinding. Dull grits from dressing still retain a jagged look, whereas dull grits from grinding have a smooth look. This may be due to the nature of the dulling: mechanical in dressing and chemical-mechanical in grinding.
- Work-material adhesion, i.e. grit/wheel loading, was shown to be more severe in dull-dressed wheels.
- Acoustic-emission (AE) intensity in plunge-roll rotary dressing was proportional to dressing specific energy in both the uni-directional and anti-directional modes. Therefore, a new parameter was introduced, the acoustic-emission specific energy. This gives the opportunity for online monitoring of the wheel sharpness either from the dressing specific energy (obtained via dressing-spindle power monitoring) or the acoustic-emission specific energy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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