In-process grinding wheel wear evaluation using digital image processing

Sebastian Ludwig[1, a], Bahman Azarhoushang[1, b*]

[1]Institute for Precision Machining (KSF), Furtwangen University of Applied Sciences, Jakob-Kienzle-Str 17, 78056 Villingen-Schwenningen, Germany
[a]lse@hs-furtwangen.de, [b]aza@hs-furtwangen.de

Keywords: grinding, dressing, grinding wheel wear, grinding tool life, image processing

Abstract. The microtopography of the grinding tool surface is essential for the result of the grinding process. Micro wear (the flattening of the abrasive grits) and loading (the adhesion of chips between or on the grits), lead to an increase in process forces and temperatures. Subsequently, poor surface qualities, dimensional and profile errors and thermal damage to the workpiece, such as grinding burn, could be induced by the grinding process. Hence, cleaning (dressing) of the grinding wheel is necessary to restore the grinding ability of the tool. Industrial processes usually have short dressing intervals to avoid scrap parts. However, short dressing intervals cause a high loss of the valuable abrasive layer of both grinding and dressing tools. A novel process-oriented measuring method is developed in this study to evaluate quickly and efficiently the surface topography of grinding tools. Images of the tool surface, after being recorded via a camera system, are evaluated by an innovative image processing software for characterizing grit flattening and loading. This article describes the developed technique and the results of the application during grinding processes. The results show a direct proportionality between the output values of the proposed method and the measured grinding forces. Hence, the developed measurement method can be used for the evaluation of the grinding ability and for an assessment of the tool life.

Introduction

Grinding is generally the last machining process in the production of high-quality and precise components. The ground surfaces often serve as functional surfaces (sliding, sealing or visible surfaces). Therefore, for an economic and efficient production, a reliable, high performance and high-quality process is required. The ground workpiece surface may show changes in hardness, microstructure and residual stresses due to the involved thermo-mechanical loads [1]. High cutting forces and temperatures may damage the surface integrity of the workpiece. Effects can be cracking, grinding burn, change of residual stress or re-hardening zones and thus restrictions of the application characteristics.

For an effective and efficient grinding process, especially the state of wear of the grinding tool is of great importance [2,3]. Flattening of Abrasive grits due to mechanical abrasion, corrosion and diffusion processes results in a partial increase in friction between grits and the workpiece material, increasing the cutting temperature due to. Additionally, it leads to higher grinding forces and lower cutting performance. Adhesions of workpiece material on the grits and/or in the pores between the grits leads also to higher cutting temperatures in the contact zone. Hence, the chip removal and the cooling effect of the lubricant are negatively affected [2,4,5]. Therefore, an effective in-process method for monitoring the state of wear of grinding tools is necessary. The process understanding could be expanded by utilizing such monitoring techniques and the basis for a more effective design and extensive control of grinding processes could be developed.

To ensure process accuracy and process reliability in grinding, several methods for post-process, process-related and in-process control have been developed and are partially utilized in the industry [6,7]. Post-process methods are characterized by great precision and accuracy, but usually require special environmental conditions, such as a measuring laboratory or a complex preparation of the workpiece. Process-related methods can usually operate without special environmental conditions and pre-treatments and allow rapid testing of the components close to the production process. Hence, the production is not significantly affected, the necessary measurement parameters are quickly available and corrective intervention in the production process can be initiated quickly [8]. Since the requirements for reproducibility and accuracy of grinding processes are on a very high level and ensuring the profitability of the process flow is becoming more and more important, the need of process-integrated quality controls through in-process methods is growing [6].

Monitoring methods in grinding processes generally only set focus on the quality of the ground workpiece and not on the condition of the grinding tools. The indirect monitoring of the wear state of the grinding tool is currently carried out by various methods. The systems are based on the acquisition and evaluation of process variables such as acoustic emission (AE) signals, grinding forces, spindle power or process temperatures [6,9]. However, monitoring of these quantities provides only an indirect value of the wear state of grinding wheels, depending on the cutting forces and temperatures and environmental conditions such as the volume of coolant lubricant and its supply, vibrations and possible non-circularity of the grinding tools. Direct measurement of the grinding forces is associated with high investment costs for the measuring devices. When a high measuring accuracy is needed only expensive systems that detect the forces by means of piezoelectric sensors are suggestive. The monitoring of the spindle power is also associated with various challenges. Depending on the cutting speed 50-75 % of the total power consumption of the grinding spindle results from the braking of the grinding tool by the cooling lubricant or the acceleration and the transport of the cooling lubricant into the contact zone [10,11]. AE sensors, along spindle power monitoring, are the most widely used monitoring methods in industry [6]. The AE sensors record the structure-borne noise level generated by the contact between the grinding wheel and the workpiece surface. Conclusions about a change in the surface topography of the grinding tool could be drawn via comparing the measured values with a reference. However, the significance is limited because no direct proportionality can be established with individual wear mechanisms [12]. The acquisition and evaluation of AE signals, grinding forces, spindle power and temperatures can be used for process monitoring and process control, but the significance of a direct analysis of the surface topography of the grinding tool is clearly superior.

Various methods such as tactile scanning, microscopy, creating 3D topographies or making imprints are available for direct monitoring of the microtopography (wear state) of grinding wheels [7,13]. However, these methods are not suitable for in-process monitoring. Sensitivity to vibrations and large space requirements prevent permanent integration of these techniques into the grinding machine.

Measurement System

The functionality of the novel measuring method, presented in this work, is based on the fact, that wear characteristics such as flattened abrasive grits and loading can be detected under direct illumination on the images by light reflections. By setting apart the reflections from the rest of the picture, the worn abrasives and loadings can be extracted and evaluated using image processing methods. Fig. 1 (left) shows schematically the imaging principle with direct lighting. The light rays of LED ring illumination are parallelized by utilizing a Fresnel lens and thus they impinge parallel to the grinding tool surface. The light beams are reflected after contacting the microtopography of the grinding tool (grits and loadings). Sharp abrasive grits reflect the light sideways, flattened grits and loadings induce direct reflections of the light rays to the camera, which appear on the images as bright surfaces.

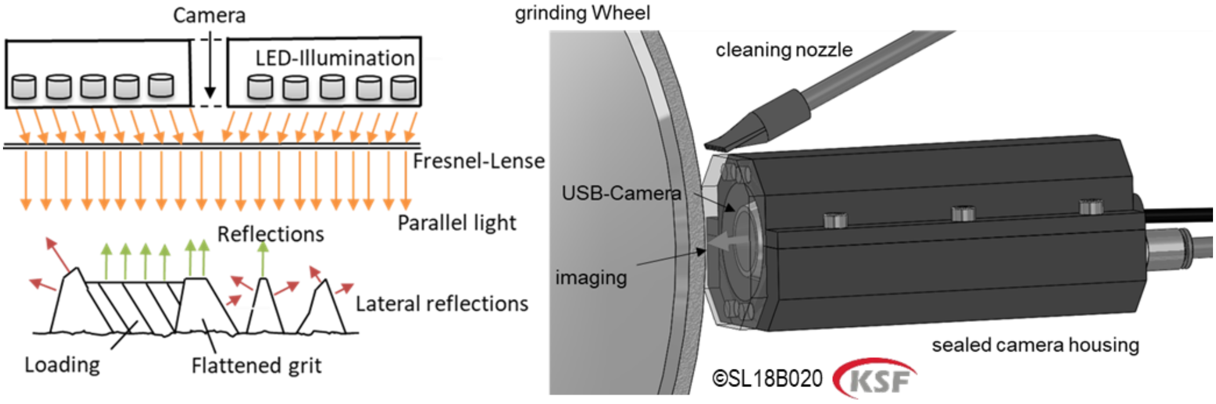

Figure 1. Imaging principle and camera system with housing and cleaning nozzle

The measurement system in the grinding machine uses a USB-microscope with an integrated ring illumination. A sealed housing was specially developed and manufactured using a 3D-printer. The system can be seen in Fig. 1 (right). During the evaluation of the wheel surface topography, the tool is positioned in the working distance of the camera system. To clean the surface area of the wheel, the grinding tool is further operated at the grinding circumferential speed for a few seconds, after turning off the coolant. When using oil as lubricant in the grinding process, compressed air is directed through a nozzle to the tool surface, whereby a sufficient cleaning effect can be achieved. The camera system then takes a microscopic image with a choice of 10 to 200x in magnification.

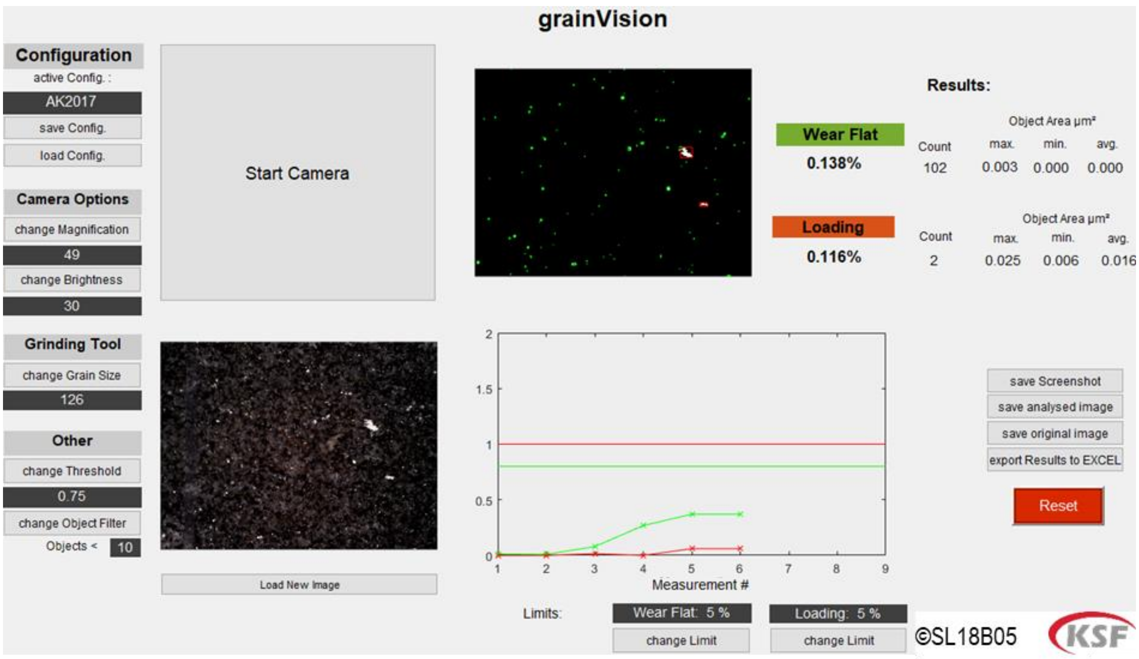

Figure 2. Analysis software

The image is processed by the analysis software within a few milliseconds, see Fig. 2. The image processing system can be taught on the grinding process by specifying a limit of the reflection ratios at which the process reliability and process quality can no longer be guaranteed. The frequency of the measurement depends on the respective grinding process. The measurement can be carried out according to a defined quantity of parts, a defined material removal volume or a defined time interval.

Grinding experiments

The aim of the grinding tests is to determine the effectiveness of the measurement method regarding the detection and differentiation of the wear characteristics, i.e. grit flattening and loading. The image microscopy method was used for the grinding tests. All experimental parameters are shown in Table 1. The tool was automatically moved to the imaging position after grinding or dressing and four images were captured around the circumference of the grinding tool at 0 °, 90 °, 180 ° and 270 °. The images were taken after dressing and after the grinding process. The experimental machine allows a precise angular positioning of the tool, whereby always the same position could be guaranteed. A total of 9 grinding tests were carried out. Before each test the tool was dressed with the same dressing parameters. In each test, one stroke with full grinding wheel width was performed (slot grinding). During the grinding tests, the grinding normal and tangential forces were measured via a dynamometer (Kistler).

Table 1. Parameters for the grinding experiments

grinding machine	ELB MicroCut, CNC surface grinding machine
cooling	emulsion; 4% Oil
grinding wheel	B126 C100 resin bond; Ø 400 mm; 15 mm width
workpiece	HSS; 64 HRc, 120 mm length
dressing parameters	depth of cut: a_{ed} = 3x3 µm; velocity ratio: q_d = +0,7; overlapping ratio: U_d = 2
grinding parameters	depth of cut a_e = 100, 200, 300 µm; cutting speed v_c = 40, 75, 120 m/s; feed speed v_{ft} = 5000 mm/min

Results and discussion

Fig. 3 shows a characteristic image from the surface topography of the grinding wheel for each of the grinding tests. Differences for the reflection ratios are clearly recognizable. The pictures indicate that with increasing of depth of cut, the load on the individual abrasive grit increases, leading to a distinct grit flattening. An increase in cutting speed has led to fewer reflection ratios, also, the individual reflections are significantly smaller. It can be concluded that the wear of the individual grit decreases with higher cutting speeds. The measuring method also shows that the extent of loading decreases with increasing cutting speed. The quality of the images is rich in detail, even the smallest reflections on abrasive grits are recognizable and can be determined with the measurement system.

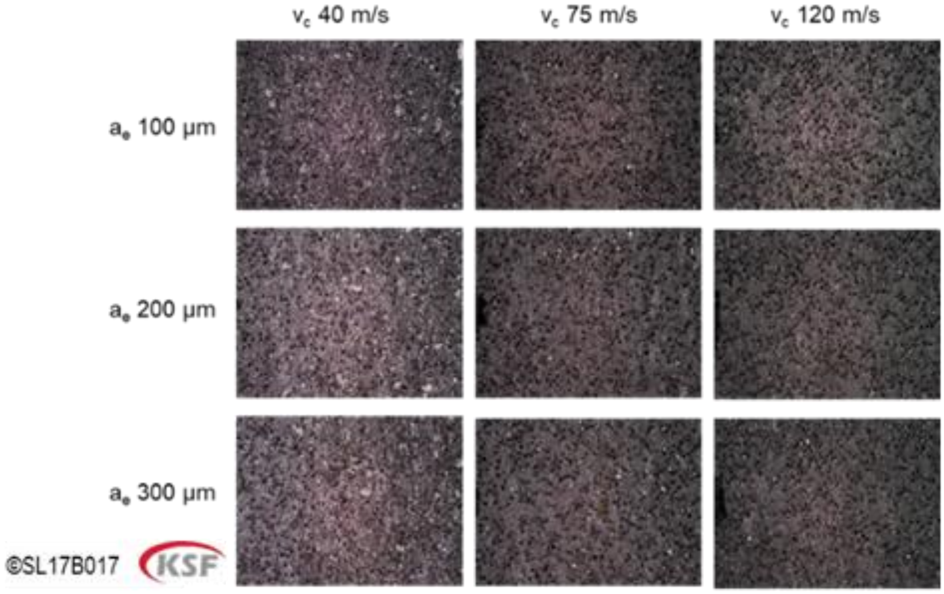

Figure 3. Characteristic Images for each of the grinding tests

Fig. 4 through Fig. 6 show the detailed results of the reflection ratios compared to the grinding normal and tangential forces. High correlation between reflection ratios and grinding forces is clearly visible at all cutting speeds and depth of cuts. The results also show that the reflection ratios increase with increasing depth of cut.

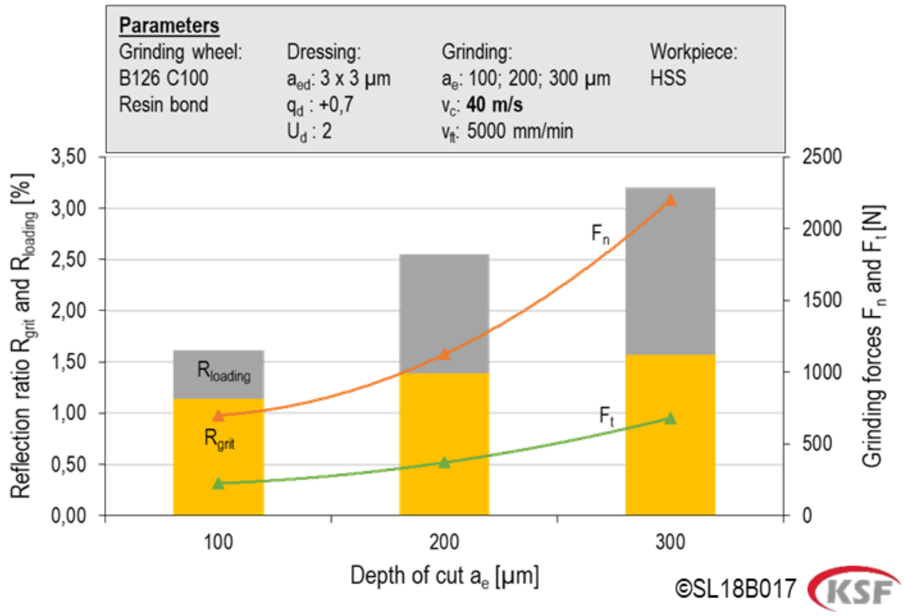

Figure 4. Results for the grinding tests at 40 m/s

This is also evident from the increase in grinding normal and tangential forces. The distinct tool loading at cutting speed of 40 m/s (Fig. 4) could be significantly reduced by increasing the cutting speed to 75 m/s (Fig. 5). With a further increase of the cutting speed to 120 m/s, no more tool loading could be detected at all three depths of cuts (Fig. 6). The only present wear mechanism at v_c 120 m/s is grit flattening. The increase in the depth of cut from 100 µm to 200 µm and 300 µm at a cutting speed of 40 m/s and 75 m/s led to a significant increase in tool loading. This is due to the fact, that the uncut chip thickness increased with increasing the depth of cut. The decrease in tool loading with increasing cutting speed can be related to the reduced chip thickness and higher strain rates, and thus altered chip formation mechanisms.

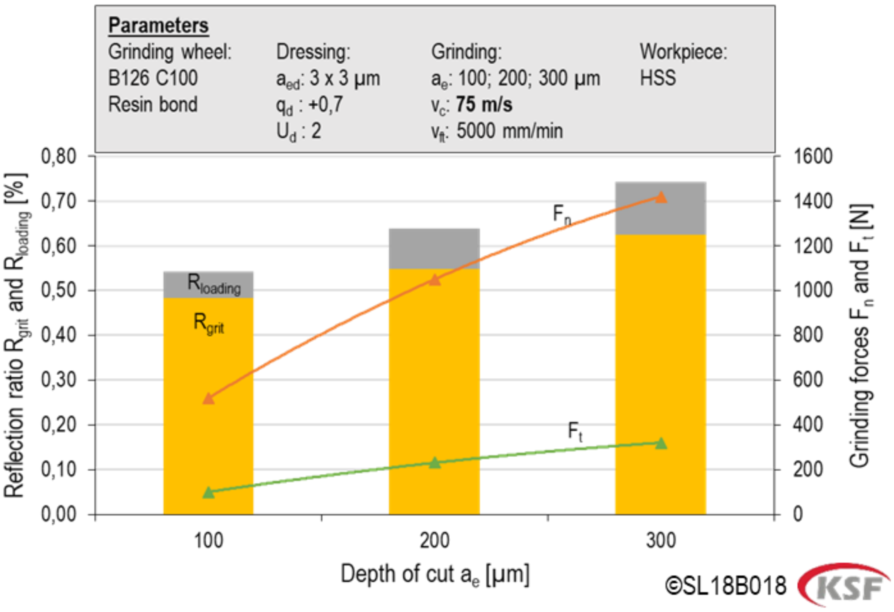

Figure 5. Results for the grinding tests at 75 m/s

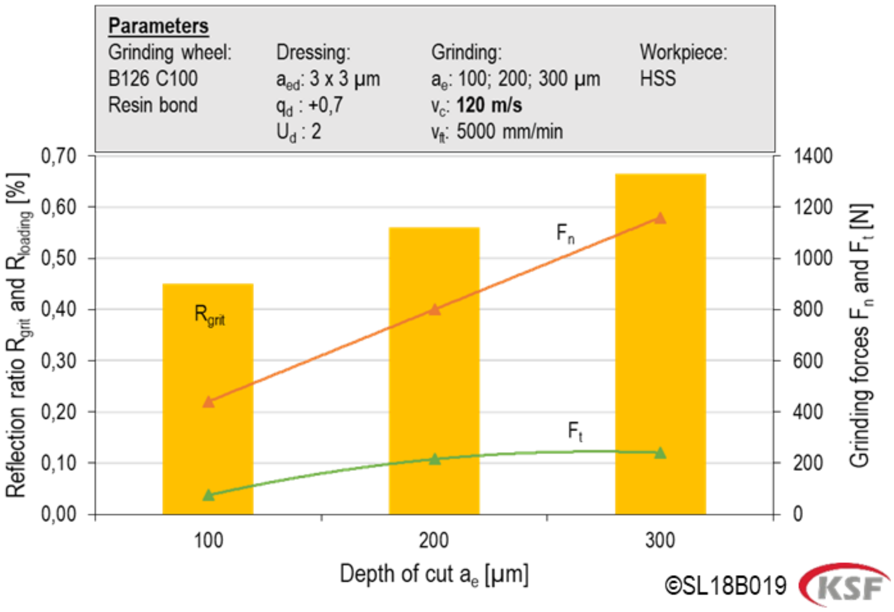

Figure 6. Results for the grinding tests at 120 m/s

Conclusion

- Using the novel measuring method, it is possible to create detailed images of the surface topography of grinding tools directly inside the grinding machine, which can be evaluated automatically via the developed analysis software. The analysis software supplies the reflection ratios for the wear characteristics, i.e. grit flattening and loading, which allow direct inference of the tool wear.

- The grinding tests have shown that the reflection ratios of grit flattening and tool loading correlate strongly with the grinding forces and can show changes in the surface topography of the tool, even with only short process times and small amount of material removal. This underlines the accuracy of the developed measuring method. Also, the differentiation between grit flattening and tool loading could be validated by the grinding tests.
- The wear behavior of the tool could be studied in detail via the developed method. Dressing intervals can be optimized since the degree of grit flattening and tool loading can be accurately determined.
- Optimal dressing and grinding parameters can be determined and the efficiency of different dressing and grinding tools, coolants and coolant supply systems can be compared, utilizing this novel method.

References

[1] Brinksmeier E, Heinzel C., Meyer M. Werkzeugseitige Temperatur- und Kraftsensoren zur Charakterisierung von Schleifprozessen: Schleifen Honen Läppen und Polieren. 63rd ed. Vulkan-Verlag; 2007.

[2] Azarhoushang B. Intermittent grinding of ceramic matrix composites: Unterbrochenes Schleifen von keramischen Faserverbundwerkstoffen. Zugl.: Stuttgart, Univ., Diss., 2011. Aachen: Shaker; 2011.

[3] Marinescu ID, Hitchiner MP, Uhlmann E, Rowe WB, Inasaki I. Handbook of machining with grinding wheels. CRC Press; 2006.

[4] Klocke F, König W. Fertigungsverfahren 2: Schleifen, Honen, Läppen. 4th ed. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg; 2005.

[5] Azarhoushang, B., Rasifard, A. Das Abrichten als integraler Bestandteil des Schleifprozesses: Mechanische Abrichtprozesse. diamond business 2014(49).

[6] Baus A. Anwendung der nichtlinearen Zeitreihenanalyse auf Schleifprozesse [Diss. RWTH Aachen]; 2002.

[7] Helletsberger H. Schleiftechnische Grundbegriffe: Grindology Paper G7. Tyrolit Schleifmittelwerke Swarowski K.G; 2004.

[8] Pfeifer T. Optoelektronische Verfahren zur Messung geometrischer Größen in der Fertigung: Grundlagen, Verfahren, Anwendungsbeispiele. expert verlag; 1993.

[9] Lange D, Kappmeyer G. Verfahren zur Erhöhung der Prozesssicherheit innerhalb der Prozessketten Kolbenlaufbahn- und Turbinenschaufelbearbeitung. Jahrbuch Schleifen, Honen, Läppen und Polieren 1997.

[10] Inasaki I. Monitoring and Optimization of Internal Grinding Process. CIRP Annals 1991;40(1):359–62.

[11] Tawakoli T. Hochleistungsflachschleifen: Technologie, Verfahrensplanung und wirtschaftlicher Einsatz. Düsseldorf: VDI-Verlag; 1990.

[12] Karpuschewski B, Wehmeier M, Inasaki I. Grinding Monitoring System Based on Power and Acoustic Emission Sensors. CIRP Annals 2000;49(1):235–40.

[13] Suzuki H. Development of 5 axis controlled ultraprecision grinding machine equipped with the system measuring and compensating profile error on the machine: Proceedings of symposium for key technology in precision machine. Shanghai; 1995.