

Tool optimization for high speed grinding

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Abstract Vitrified bonded cBN grinding wheels catches on for batch production especially in the automotive industry for components of power trains. In pursuit of higher productivity with steady quality the optimization of manufacturing processes and tools are getting more relevant. In this contribution potentials and challenges of structured grinding tools for the optimization of grinding processes are discussed. Technological investigations with structured and non-structured vitrified bonded cBN grinding wheels were carried out and the results of varying setting parameters were analyzed. The main aspects of interest for these studies were the detection of possible coolant savings and phenomena of vibrations, the reduction of the thermal damage of the workpieces as well as the influence on the workpiece roughness and the grinding wheel radial wear. The experiments show the potentials of structured cBN grinding wheels for roughing and finishing in cylindrical plunge grinding processes. But there are some basic requirements for the geometry of the structures especially due to the vibrations of the grinding process. For the roughing tests the adequate structured abrasive layers show less grinding forces and thermal damage of the workpiece. For finishing processes the results show comparable values of roughness and waviness referring to non-structured grinding wheels. In addition, a limit for suitable grinding wheel structures in conjunction with the setting parameters could be identified that offers valuable clues for

the dimensioning of structured abrasive layers even for non-circular grinding processes.

Keywords High speed grinding · Cylindrical grinding · Non-circular grinding · Superabrasives · Grinding wheel optimization · Structuring

1 Introduction

The production industry is increasingly pursuing ecological objectives in addition to technological and economical aspects due to rising public discussions. In the area of manufacturing technology this leads to significant pressure to innovate. Approaches to achieve these objectives are an innovative machine tool technology and process design as well as the use of suitable tools and new tool design.

Grinding processes are not restricted to fine machining and finishing processes any longer, but also to realize high material removal rates at low tool wear and excellent workpiece quality. The common trend to increase specific material removal rates, cutting speeds and feed rates leads to problems with thermal damage of the boundary layer of the workpiece. The outcomes are new requirements for grinding tools. Along with the adjustment of grains and bonds, the geometry of abrasive layers offers potential for more efficient grinding tools. Previous analyses have shown that structured abrasive layers or abrasive layers with a defined grain pattern decrease the heat development during the grinding process [1–9]. Uhlmann et al. [2] and Kirchgatter [4] additionally detected that the technological benefit of structured abrasive layers depends largely upon the terms of contact and the dynamic behavior throughout the grinding process.

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This leads to the hypothesis that the contact zone should be constant relating to the surface area.

Due to the demand for constant surface areas of contact, the geometry of the structures can just be controlled by the number of grooves z_n and the integer overlap of the grooves k_n . In conjunction with the percentage reduction of the abrasive layer P_n , the circumference of the grinding wheel U_s and the width of the workpiece b_w follows the angle of the groove α_n and the width of the groove b_n as shown in Eqs. (1) and (2).

$$\alpha_n = \arctan \frac{b_w \cdot z_n}{U_s \cdot k_n} \quad (1)$$

$$b_n = \frac{U_s \cdot P_n}{100 \cdot z_n} \cdot \sin \alpha_n \quad (2)$$

For constant widths of the workpieces b_w , numbers of grooves z_n , integer overlap of the grooves k_n and circumferences of the grinding wheels U_s an increasing percentage reduction of the abrasive layer P_n leads to an increasing width of the grooves b_n with a constant angle of the grooves α_n . Figure 1 illustrates the requirements concerning an adequate configuration of structured abrasive layers.

The objective of the conducted experiments was to identify the influence of the groove geometry on the process factors and the work result. It was also attempted to verify the

gain of the optimized geometry of the grinding tool structures. The long-term goal is to develop specifications of structured grinding wheels that lead to less thermal damage of the workpiece, less radial wear and equal values of roughness in comparison with a non-structured grinding wheel. Therefore the limitations of groove widths and angles have to be detected with respect to the setting parameters.

2 Experimental setup

To analyze the influence of different structured grinding wheels in comparison to a non-structured grinding wheel a peripheral plunge external cylindrical grinding process was chosen. With cBN grinding wheels this operation is used for the manufacturing of camshafts, crankshafts, bearings and other cylindrical functional surfaces. In addition, with cylindrical creep feed grinding processes, characterized in high geometrical contact lengths l_g and speed ratios q , it is even possible to draw conclusions to non-circular grinding processes because of the huge contact zone A_k .

The experiments ran on a universal cylindrical grinder type PF 51 by the company Schaudt Mikrosa BWF GmbH. This machine offers a high accuracy and stiffness as well as

Fig. 1 Adequate and less adequate configuration of structured abrasive layers

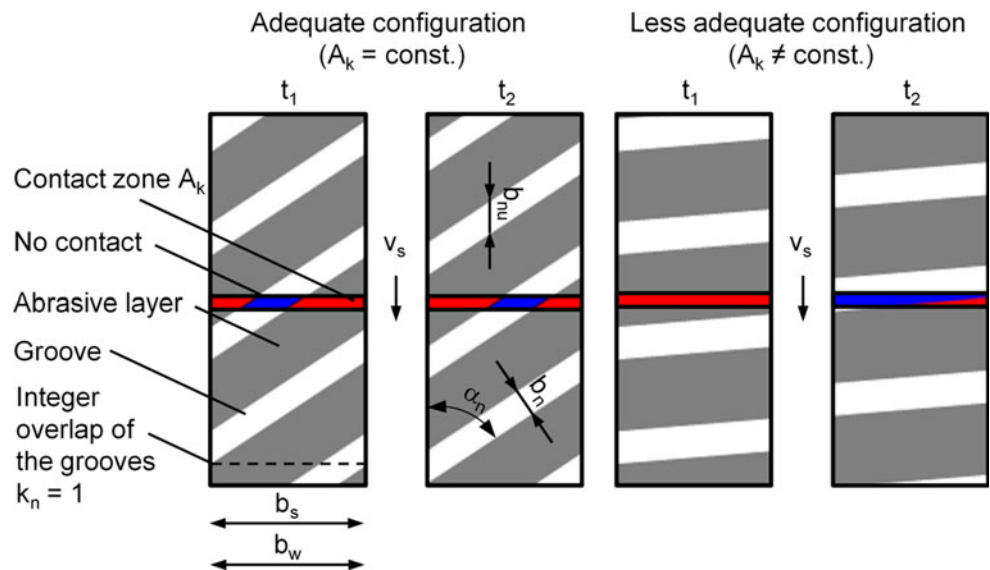


Fig. 2 Structured grinding wheels and experimental setup

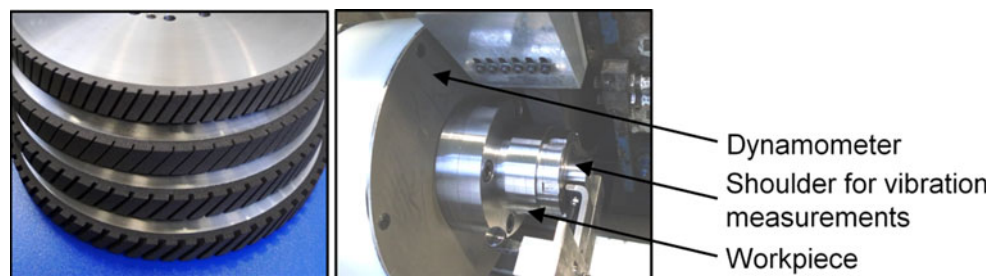


Table 1 Grinding conditions for the main investigations with adequate configurations of structured abrasive layers and typical speed ratios for cylindrical grinding [10]

<i>Grinding parameters</i>	
Peripheral wheel speed, v_s	100 and 140 m/s
Specific material removal rate Q'_w , roughing	20 and 30 mm ³ /mms
Specific material removal rate Q'_w , finishing	2 mm ³ /mms
Speed ratio q , roughing	–60
Speed ratio q , finishing	–120
Coolant flow rate Q_{KSS} , roughing	3.7 and 15.4 l/min
Coolant flow rate Q_{KSS} , finishing	36.9 l/min
<i>Dressing parameters</i>	
Diameter of dressing roller, d_R	120 mm
Active width of the dressing tool, b_d	0.6 mm
Depth of dressing cut, a_{ed}	3 μ m
Overlapping rate in dressing U_d , roughing	1.5, 3 and 4.5
Overlapping rate in dressing U_d , finishing	4, 6 and 8
Ratio of dressing speeds q_d , roughing	0.8
Ratio of dressing speeds q_d , finishing	–0.8
<i>Grinding wheels</i>	
Geometry	350 mm \times 30 mm \times 100 mm
Percentage reduction of the abrasive layer, P_n	0 % 10 % 25 % 40 %
Number of grooves, z_n	0 70 70 70
Grain	21B 126
Hardness/structure	X 24
Bond type	V8116
Abrasive grain concentration	C150
<i>Workpiece</i>	
Material	100Cr6
Hardness	60 \pm 2 HRC
Diameter, d_w	80 mm
Width, b_w	25 mm

a powerful spindle drive. To describe the process behaviour during the grinding tests the relevant process characteristics such as grinding forces and vibrations, Fig. 2, were measured by using a rotating cutting force dynamometer by the company Kistler Instrumente GmbH and a contactless position measuring system working with Foucault current by the company Micro-Epsilon Messtechnik GmbH & Co. KG. The work result was qualified by accuracy to size, accuracy of shape, waviness and surface roughness. The thermal damage of the workpiece boundary layer was detected by using the Barkhausen noise as well as the depth

of carburized and hardened cases according to DIN EN ISO 2639. The used equipment was a rollscan 300 by the company Stresstech GmbH and a micro hardness measurement system type Fischerscope H100C by the company Helmut Fischer GmbH.

The non-structured and structured grinding wheels were manufactured by the company Krebs & Riedel Schleifschleifenfabrik GmbH & Co. KG. The rectangular structures with a depth of 5 mm were ground into non-structured abrasive layers with the same specification. Vitrified bonded cBN grinding wheels with an average grain size of 126 μ m and an abrasive grain concentration of C150 were applied. The employed workpieces were fully hardened bearing rings by Nose Seiko Co. Ltd. and taken from the controlled bulk production. The grinding conditions are specified in Table 1.

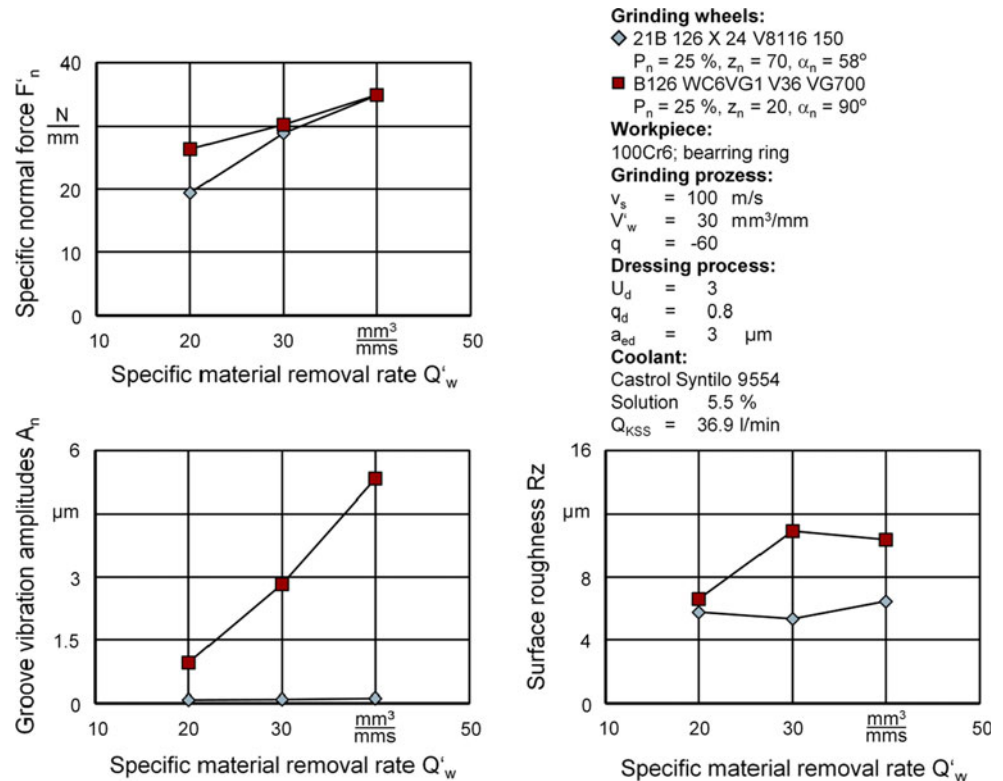
3 Results

3.1 Basic studies

To verify the hypothesis that the technological benefit of structured abrasive layers depends largely upon the dynamic behavior of the grinding process, some basic studies were carried out. Two structured grinding wheels with a percentage reduction of the abrasive layer of $P_n = 25\%$, but different numbers of grooves z_n and groove angles α_n were compared. The first grinding wheel was structured by an adequate configuration, Fig. 1, with $z_n = 70$ grooves and a resulting groove angle of $\alpha_n = 58^\circ$. The second abrasive layer was structured by a probably less adequate configuration, Fig. 1, with $z_n = 20$ grooves and a groove angle of $\alpha_n = 90^\circ$. The less adequate configuration leads, as shown in Fig. 3, to a significant increase of the groove vibration amplitudes A_n because of a short-time loss of contact between grinding wheel and workpiece, and bring up less proper surface qualities and a higher radial wear, whereas the grinding forces, especially with higher specific material removal rates Q'_w , show nearly identical data. The increasing groove vibration amplitudes A_n , that means vibrations with the frequency of the groove impact, bring up much higher short-term depths of cut and thus higher temperatures in the contact zone, partly even in comparison with non-structured grinding wheels [2, 4, 5].

The results show the advantage of the structure modification up to abrasive layers with a constant surface area of contact. Continuative grinding tests with different adequate configurations, Table 1, were conducted to identify the interaction of percentage reduction of the abrasive layer P_n , process factors and the work result.

Fig. 3 Results of the basic studies



3.2 Roughing

The roughing experiments of the main investigations were carried out to quantify the gain of the structured grinding wheels with respect to the heat reduction and the possibility of coolant savings. Because of the minimum time of contact for an incremental area of the workpiece, the heat development was identified indirectly by the use of Barkhausen noise and micro hardness measurements of the machined surface [11]. It is already known that the Barkhausen noise could lead to deceptive interpretation when the hardness of the surface layer is increasing [12]. To exclude the occurrence of white layers, the depth of carburized and hardened cases was identified for every workpiece and shows a nearly constant value of CHD 825 HV 0.1 \approx 20 μm. With regard to these results the Barkhausen noise could be qualified as an indicator for the residual stress of the surface layer of the workpieces. Figure 4 shows in extracts the results of the technological investigations for roughing processes with different overlapping rates in dressing U_d and a coolant flow rate of $Q_{KSS} = 15.4$ l/min.

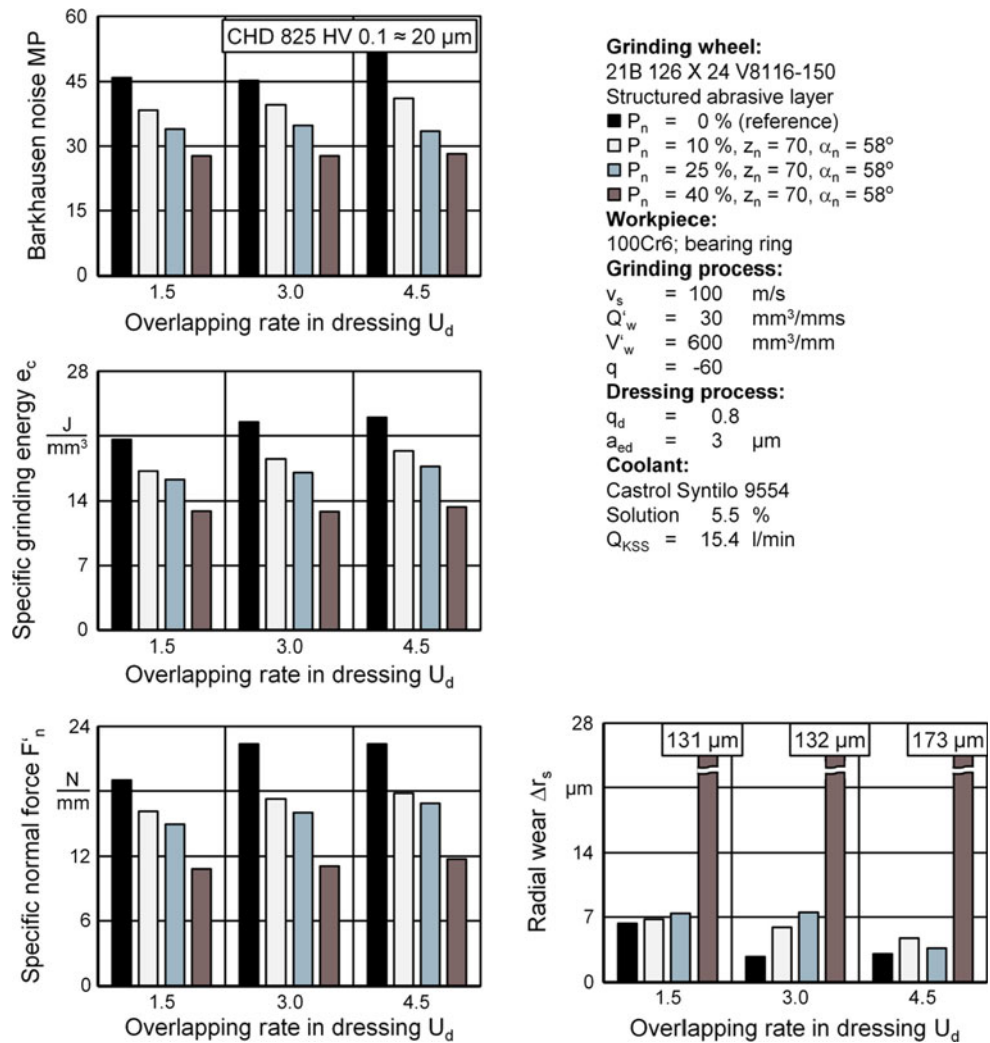
The advantages of an increasing percentage reduction of the abrasive layer P_n are clearly apparent in terms of decreasing thermal damage of the workpieces and decreasing specific grinding forces that additionally lead to less displacement of the workpieces. The lower heat development is resulting from the discontinuous cut in

parts of the contact zone and a better transportation of the coolant. Less grinding forces are the effect of a decreasing number of cutting edges in the contact zone. It is shown as well, that there is a trend of increasing radial wear Δr_s of the grinding wheels with less abrasive layer. This could be the result of the decreasing active number of cutting edges for the grinding wheels with a percentage reduction of the abrasive layer of $P_n = 10\%$ and $P_n = 25\%$ as well as a proceeding breakup of the bond bridges between the grains in the initial of a new abrasive segment for the grinding wheel with a percentage reduction of the abrasive layer of $P_n = 40\%$.

In addition to the differences of the values of the process parameters regarding the abrasive layer reductions, the influence of the overlapping rate in dressing U_d was analyzed. The graphs show by trend the typical relationships for the non-structured grinding wheels as well as for the structured grinding wheels. The increasing grinding forces and heat developments are the result of a more smooth topography of the abrasive layer with an increasing number of cutting edges in consequence of the increasing overlapping rate in dressing U_d .

Another objective of the studies was to qualify possible coolant savings with respect to the structured grinding wheels. Figure 5 shows the results of grinding processes with varying specific material removal rates Q'_w as well as varying peripheral wheel speeds versus with a coolant flow rate of merely $Q_{KSS} = 3.7$ l/min.

Fig. 4 Results of the roughing processes with varying overlapping rates in dressing



The gain of the structured abrasive layers with respect to a lower heat development is apparent for reduced coolant flow rates as well. In comparison with the results of the non-structured grinding wheel in Fig. 4 the values of process number 2 with structured grinding wheels show less thermal damage of the workpieces in spite of the reduced coolant flow rate Q_{KSS} . Additionally it strikes that a rising of the peripheral wheel speed versus as well as a rising of the specific material removal rate Q'_w do not cause an increase of the specific grinding energy e_c nor the thermal damage in terms of the values of Barkhausen noise. In return, by trend the typical characteristics of increasing specific grinding forces and grinding wheel radial wear Δr_s with increasing specific material removal rate Q'_w and decreasing peripheral wheel speed versus are detectable [13]. The results of these investigations also show the erratic increase of the radial wear regarding the groove width in direction of circumference b_{nu} and the setting parameters, compare Fig. 4. Therefore the processes 1 and 2 were excluded for the grinding wheel with a percentage

reduction of the abrasive layer of $P_n = 40\%$ because no further gain of knowledge but another significant loss of the abrasive layer was expected.

In conjunction with continuative testing, especially by varying the specific material removal rates Q'_w , peripheral wheel speeds versus and speed ratios q , limits for the structures could be identified regarding the grinding wheel radial wear Δr_s . The product of the maximum chip thickness h_{max} [14], caused by the groove width in direction of circumference b_{nu} , and the mean tangential forces leads to a limit for the bond bridges that result in a downwelling outbreak of grains starting at the rim of the grooves, Fig. 6.

In addition to the typical roughing processes of the main investigations with a speed ratio of $q = -60$, cylindrical creep feed grinding processes were conducted with a speed ratio of $q = -600$ with two grinding wheels. By varying this setting parameter without changing the peripheral wheel speeds versus, the conditions of contact change significantly, especially with respect to the geometrical

Fig. 5 Results of some roughing processes with a coolant flow rate of $Q_{KSS} = 3.7$ l/min

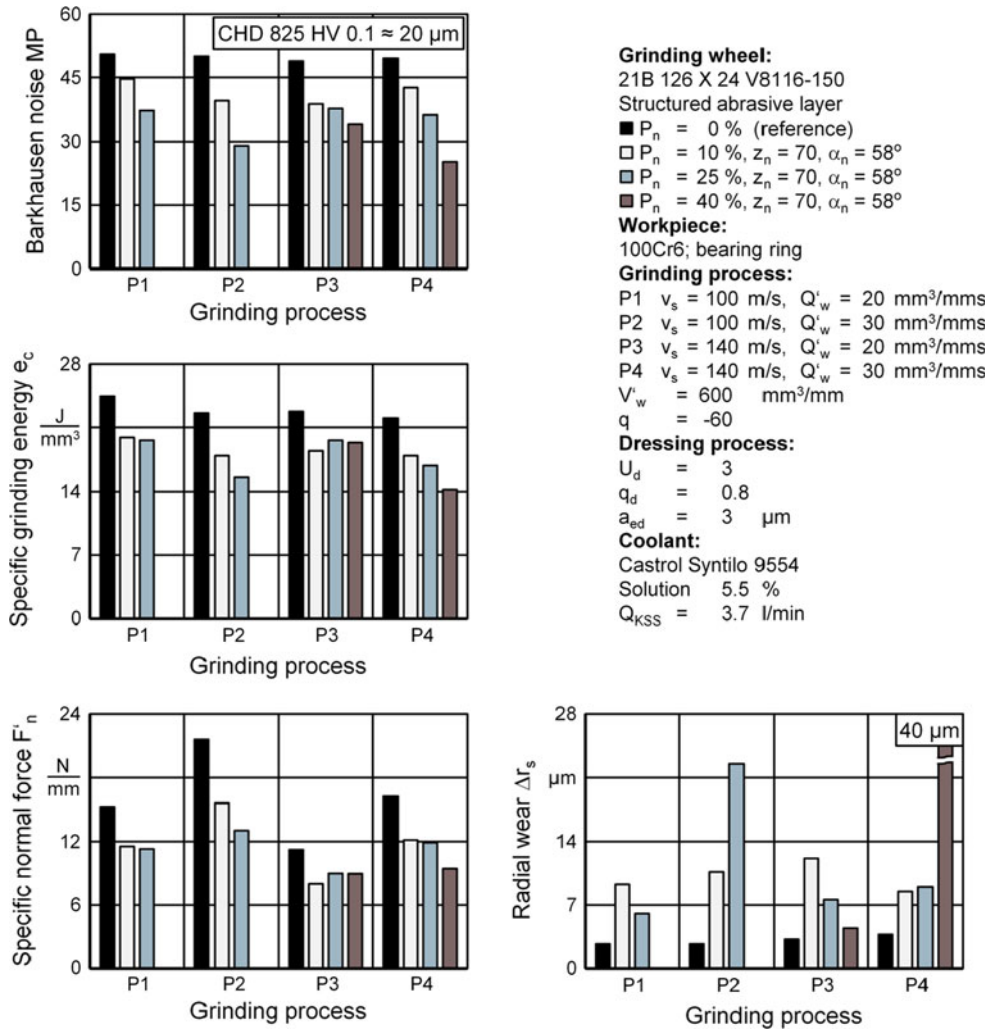
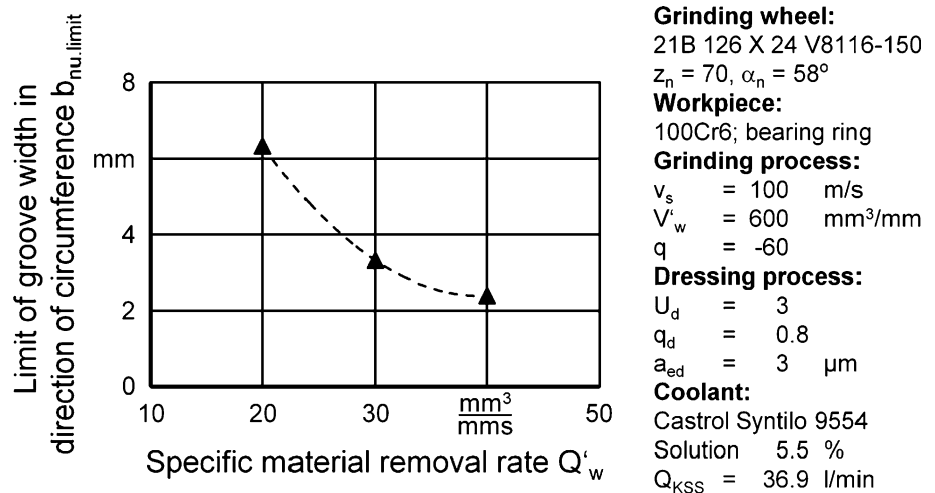


Fig. 6 Limit of groove width according to the specific removal rate

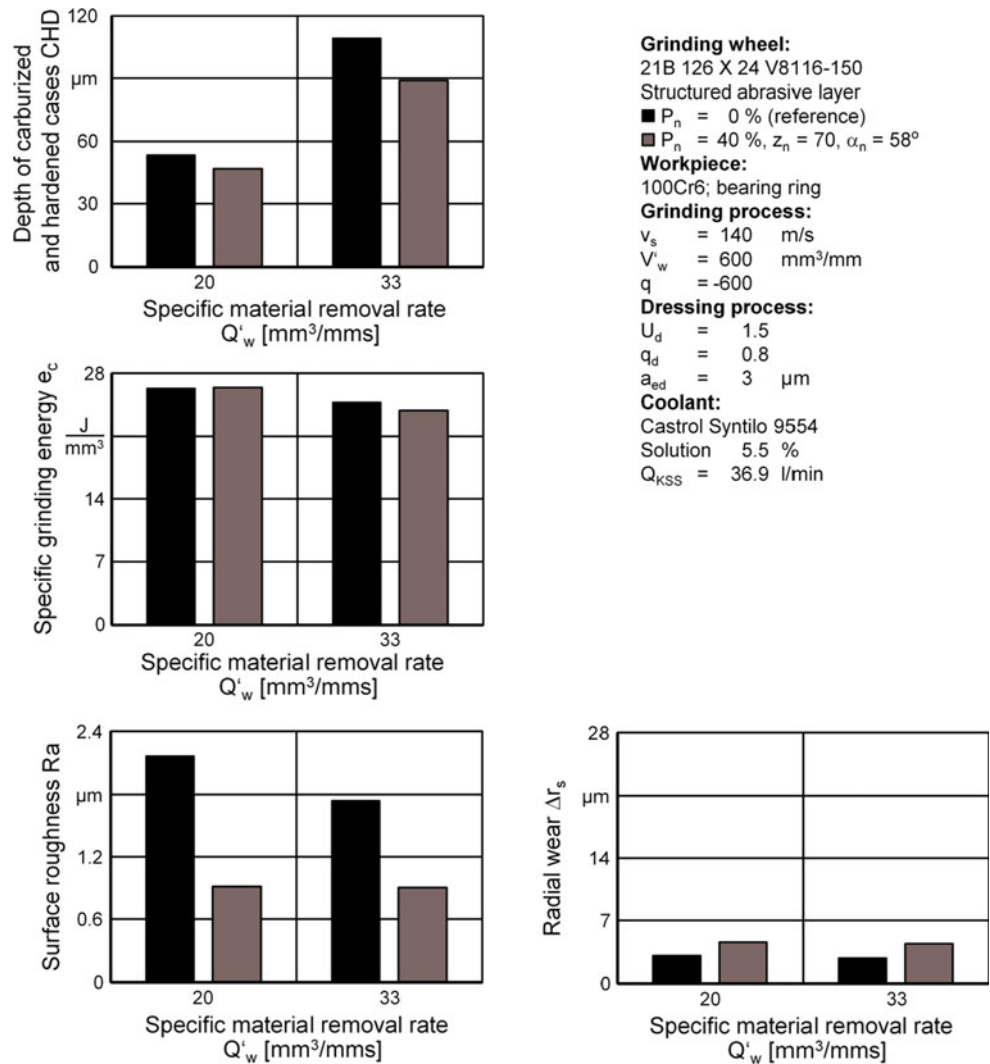


contact length l_g and the maximum chip thickness h_{max} . The conclusions offer valuable clues for the dimensioning of structured abrasive layers even for non-circular grinding processes with changing characteristics in contact. The

results of these testing are shown in Fig. 7 for two different specific material removal rates Q'_w .

The differences in the heat development of the non-structured and structured abrasive layer are clearly

Fig. 7 Results of the investigations in creep feed grinding



identifiable regarding the depth of carburized and hardened cases CHD. The tempered zones show significant lower values for the structured grinding wheel especially for higher specific material removal rates Q'_w . In addition, lower surface roughness Ra, similar specific grinding energies e_c as well as slightly higher radial wear Δr_s are detectable. This could be the result of the modified conditions of coolant, which could lead to a better lubrication in the contact zone and an altered chip formation. Because of the better lubrication, even by using water based solution, the portion of friction and resulting the ductile phase in chip formation could increase. Nevertheless the mean heat development is lower because of the discontinuous heat generation and the better accessibility of coolant for structured abrasive layers.

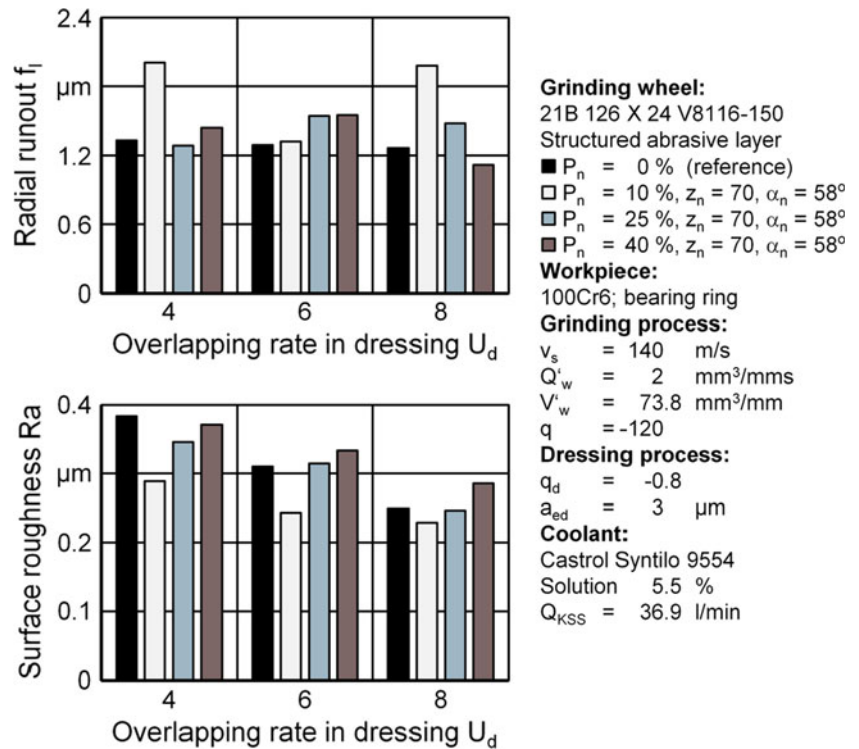
3.3 Finishing

The typical grinding processes are divided in roughing and finishing. The gain of the structured abrasive layers is shown for roughing processes by now. To analyze the

finishing process different testing with varying overlapping rates in dressing U_d were conducted. The results for some finishing processes of the main investigations are shown in Fig. 8 by the radial runout f_1 and the surface roughness Ra.

The values of the roughness measurements show the typical influences of the overlapping rate in dressing U_d for all used grinding wheels [13]. In consequence of an increasing overlapping rate in dressing U_d a decreasing surface roughness Ra is apparent. The workpiece roughness manufactured with structured and non-structured grinding wheels show nearly similar values. In trend a rising percentage reduction of the abrasive layer P_n leads to higher values of workpiece roughness but not in comparison to the non-structured grinding wheel. This could be explained by better lubricating effects and changing mechanisms in cutting in comparison with non-structured abrasive layers, as described above, and in return an increasing maximum chip thickness h_{max} in the area of the groove rims with rising widths of the grooves b_n . In addition, the waviness and the radial runout f_1 of the ground

Fig. 8 Results of some finishing processes with varying overlapping rates in dressing



bearing rings were detected. While there were no negative characteristics with respect to the waviness, neither for critical wavelength regarding the ratio of revolution nor regarding the ratio of revolution for the grooves, the radial runout f_1 shows slightly higher data for an overlapping rate in dressing of $U_d = 4$ and 8 for the grinding wheel with an percentage reduction of the abrasive layer of $P_n = 10\%$. But with regard to the other values of radial runout f_1 with structured abrasive layers there should be no systematic influence.

4 Conclusion and outlook

Structuring an abrasive layer provides one means of decreasing the thermal damage of workpieces for grinding processes in comparison to processes with non-structured abrasive layers. With an increasing percentage reduction of the abrasive layer P_n decreasing values of Barkhausen noise as well as decreasing tempered zones could be detected for roughing. In addition, the grinding forces and the displacement of the workpieces could be reduced. These advantages are achieved at the expense of radial wear Δr_s , Fig. 9, especially by exceeding a limit of groove width in direction of circumference $b_{nu.limit}$. In that case, where the average cutting edge spacing for a groove L_{sn} exceeds this limit, proceeding breakups of the bond bridges between the grains in the initial of a new abrasive segment could be determined, Fig. 10.

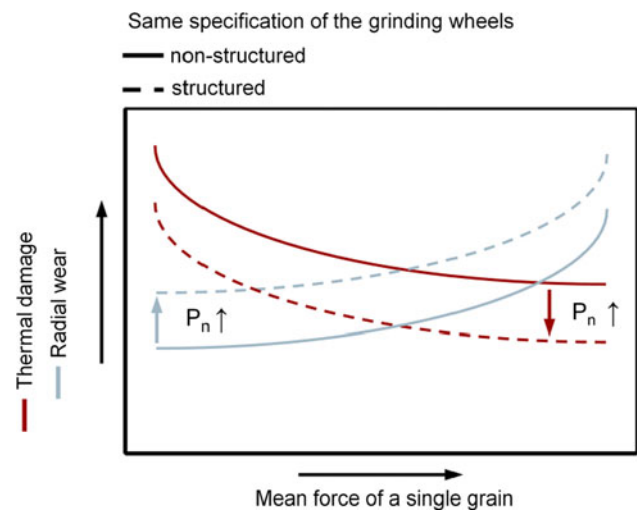


Fig. 9 Trend of thermal damage and radial wear according to the percentage reduction of the abrasive layer P_n and the mean force of a single grain

In further studies the influence of an adjusted specification of the grinding wheel with respect to the volume of bond V_{bond} and the abrasive grain concentration C shall be identified. It is expected that this could lead to a lower thermal damage of the workpiece as well as to a lower radial wear of the grinding wheel, Fig. 11.

This would afford a significant increase of productivity in roughing and could lead to an additive parameter to

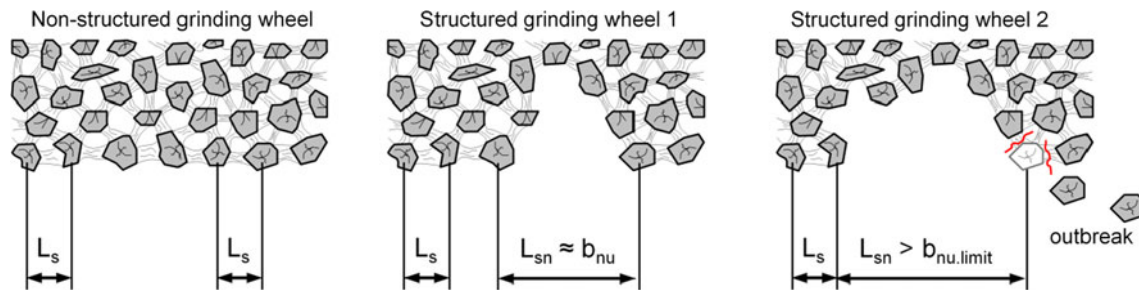


Fig. 10 Characteristics of different structured grinding wheels

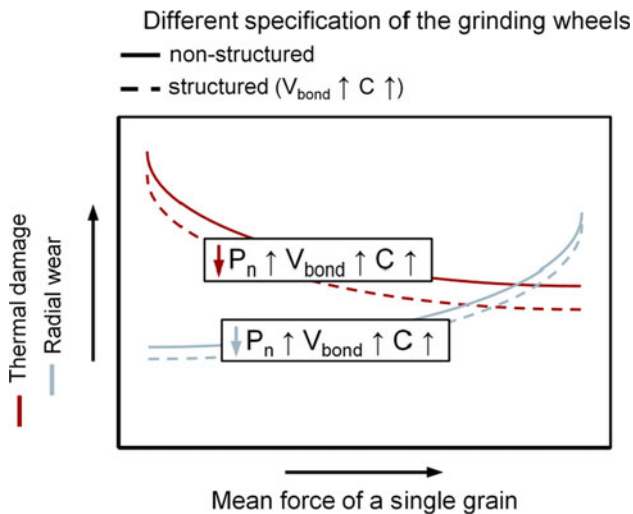


Fig. 11 Outlook on potentials for structured abrasive layers

describe a vitrified bonded grinding wheel. In excess of the volume of grain V_{grain} , bond V_{bond} and pore V_{pore} there could be a fourth addend that describes the volume of grooves $V_{\text{groove}}(P_n, z_n, k_n)$.

For finishing processes the adequate structured grinding wheels show comparable values of roughness, waviness and radial runout referring to non-structured grinding wheels with the same course of the process.

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