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Porous metal bonds increase the resource efficiency for profile grinding

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Abstract

Profile grinding is irreplaceable for the machining of various brittle and hard workpieces, e.g. cutting tools for milling and drilling, seal components made of ceramics and bearing components. Grinding is rather inefficient regarding the energy demand for the machining of one volume element of material compared to other manufacturing processes. However, the process forces can be reduced without influencing the tool wear by using grinding wheels with a porous metal bond and grains that tend to splinter. This allows higher material removal rates without increasing the process forces, ultimately reducing the energy consumption per workpiece manufactured. Additionally thermal and mechanical loads on the workpiece are reduced leading to increased life cycles of grinded products. The application of these grinding wheels is currently on hold for profile grinding since the dressing process is not in control. Therefore, this paper investigates the dressing operation for grinding wheels with a porous metal bond in order to reduce the energy consumption in profile grinding of brittle and hard materials.

Keywords: Resource Efficiency; Profile Grinding; Brittle Materials; Metal Bond

1. Introduction

In terms of the necessary energy for machining one volume element grinding is inefficient compared to other manufacturing processes. Compared to hard milling or hard turning, up to 200% more energy is required during grinding [1]. At the same time grinding is irreplaceable for machining various primarily brittle materials such as cemented carbide or ceramic materials [2, 3]. Especially the profile grinding process is of great importance for the stated applications [4, 5]. Cutting tools such as milling tools or twist drills, ceramic sealing components and bearing components or components made of quartz glass for the semiconductor industry are also processed by profile grinding [6]. Basically, the following two principal approaches are applicable in order to improve the energy efficiency of the manufacturing process.

Coolant pumps have the main impact regarding the total energy consumption of machine tools [7, 8]. The coolant supply is necessary during grinding to dissipate the heat of the process. It was shown for the production of camshafts that the use of minimum quantity lubrication can reduce the total energy requirement by up to 20% compared to flooding lubrication. Therefore, new tool concepts and new machine tool components were used [9, 10]. In order to implement the minimum quantity lubrication strategy, investments in new coolant units are necessary.

The second approach is the attempt to increase the material removal rate in order to reduce the energy consumption per produced part by reducing the machining time. Exemplarily, the application of cleaning nozzles prevents the clogging of grinding wheels. Therefore, the power demand of the spindle is reduced by up to 20% while maintaining a constant material removal rate. Low power demands allow an increase of the material removal rate and therefore an optimization of the energy efficiency is possible [11]. At the same time the cleaning nozzles are dependent on the highly energy consuming coolant pump units.

By using a new kind of metal bond with implemented pores, the spindle power can be reduced by up to 40 % compared to current applications with no need for additional energy

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consuming units [12]. The impact of using porous metal grinding wheels in terms of resource efficiency in general and compared to tools used in the industrial practice is addressed. Additionally, the influence on the ground workpieces and their life cycle performance will be discussed. Since the application of grinding wheels is directly dependent on their dressability, this paper focusses on the dressability and the influence of grinding wheel specifications and dressing parameters on the profile stability of the new bond type. The profile stability is of great importance for the application in the profile grinding process.

2. Porous metal bonds

Diamond grinding wheels with different bonding systems are used for the profile grinding of the materials mentioned before. Multilayer-metal bonds have similar to resin-bonded tools only very small pore fractions. This leads to low grain protrusion and consequently friction between bond and machined workpiece. Thus, the low grain protrusion has a negative effect on the energy efficiency. In contrast to the multilayer-metal bonded grinding wheels, widely used vitrified bonds can be dressed mechanically. They have bigger pore fractions, which leads to less friction in the grinding process. However, their wear resistance is comparatively low. Crushable metal bonds are an attempt to increase the dressability of multilayer-metal bonds by adding graphite inclusions into the bond that serve as artificial pores. This way they can be dressed with high dressing tool wear. Furthermore, the dressed grinding wheels show decreased resistance against tool wear. The conventional multilayer-metal bonds have a high resistance against tool wear and therefore a high profile stability. The main reason for the lack of their wide industrial application is that conventional multi-layer metal bonds are difficult to dress. Processes known in the state of the art, e.g. based on mechanical, optical, electrochemical or electrophysical principles, are either time consuming and or costly.

Novel highly porous metal bonds have the potential to increase the energy efficiency of grinding processes. These tools are similar in construction to vitrified bonded grinding tools, but at the same time show the high thermal conductivity, good profile stability and high grain retention forces of metallic bonds.

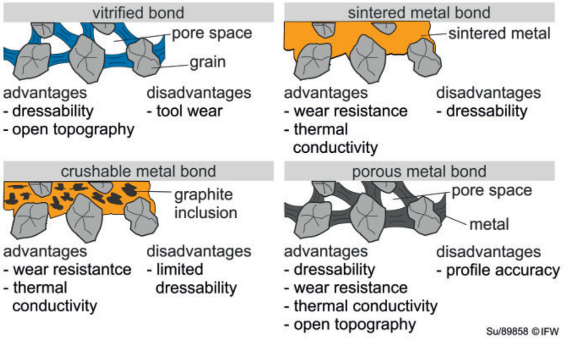


Fig. 1. Grinding wheel structure of the new bond type

Their structure in comparison to vitrified, sintered metal and crushable metal bonds is shown in figure 1. They can be mechanically dressed and provide coolant in the contact zone better than tools with a lower pore content. During profile grinding high thermal and mechanical loads occur since the contact length is higher and the coolant is difficult to distribute in the contact zone. Therefore, the porous metal bond is ideal to be applied in this case considering the tool and workpiece quality. The dressability of the new bond type is presented in this paper and its grinding performance is evaluated in terms of resource efficiency.

2.1. Experimental setup

A Walter Helitronic Vision 400L grinding machine has been used for all dressing and grinding experiments. Cemented carbide probes with the specification “KXF” measuring 10×20×100 mm have been machined primarily by a creep-feed grinding process. In all dressing experiments porous metal bonded grinding wheels with diamond grains have been used. The mechanical dressing process to implement profiles into the grinding wheel can be distinguished into form and profile dressing. While the latter needs less process time it is limited to one shape. Therefore, in this study a so called DDS-form roller is used to verify the dressability of porous metal bonded grinding wheels. This dressing tool consists of CVD-cutting particles implemented into a sintered multilayer bond. The different grinding wheel specifications are shown in Table 1. Profile wear is evaluated by means of imprints of the grinding wheel before and after profiling, after the sharpening process if it is performed and finally after the grinding process. A comparison of the different imprints of the grinding wheels allows the characterization of the profile stability of the new tool type.

Table 1: Grinding wheel specifications used for the investigations

Tool	Grain size	Concentration	Grain type	Porosity
1	D54	D168	Cracking	38
2	D30	D168	Cracking	38
3	D76	D168	Cracking	38
4	D54	D184	Cracking	38
5	D54	F152	Cracking	38
6	D54	D168	Cracking	0
7	D54	D168	Cracking	46

The imprints of the grinding wheels are measured by a Mahr LD130 contour measuring machine in order to estimate the grinding wheel wear at the edges and the loss of the profile. In order to evaluate the grinding wheel topography the process forces are measured parallel to the grinding process. The reaching of a certain grain protrusion level is represented by the performance of the grinding wheel while machining. The stated process steps are summarized in figure 2 and can be seen in the included photographs.

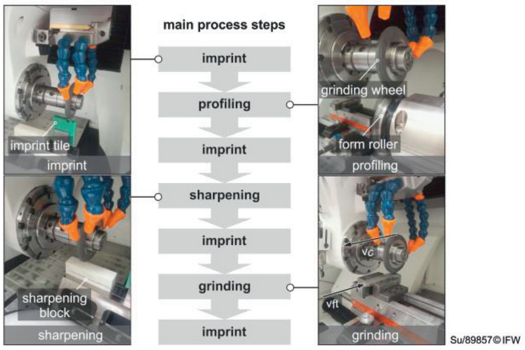


Fig. 2. Main process steps

3. Life cycle perspective and impact on resource efficiency

In order to verify the impact of using porous metal grinding wheels in terms of resource efficiency their grinding performance is compared to the one of tools used in the industrial practice. Additionally their influence on the grinded products and their life cycle performance is discussed.

3.1. Workpiece quality leads to increased life cycle

Essential for the life cycle of a workpiece are the thermal and mechanical loads it experiences while being machined. While measured process forces display the mechanical loads the measurement of the temperature in the contact zone of the workpiece allows statements regarding its thermal load. The temperature was determined by measuring it with thermocouples in defined distances from the contact zone and extrapolating it. Higher process forces induce compressive residual stresses, while higher thermal loads lead to higher tensile stresses. Tensile stresses cause a decrease of the life cycle time, since the chance for cracks and therefore workpiece failure is increased. In figure 3 the contact zone temperature is shown for the new bond type compared to resin bond tools with the same grain type, size and concentration.

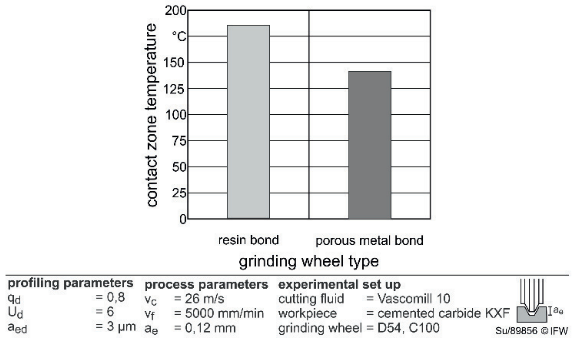


Fig. 3. Thermal loads on porous metal bonded grinding wheels and wheels used in the industrial practice

For constant process parameters the new bond type allows a reduction of the process temperatures of up to 23 %. The reduction of the process temperature comes from two main effects. Resin bonded grinding wheels do not have pores making the distribution of the contact zone with cutting fluid more difficult. Resin is also a bad heat conductor leading to a heat build-up in the contact zone. In contrast, the open structure of the porous metal bond leads to a better distribution of cutting fluid into the contact zone and the exit of heat by absorbing it while leaving the contact zone. Additionally, the metal bond is a better heat conductor allowing the heat to dissipate out of the contact zone over the bond itself. The effect of the better cutting fluid distribution is decreased by the use of oil as a cutting fluid. It is not able to conduct heat very well, therefore the difference in the process temperatures of both grinding wheel types is not as high as it could be by using other cutting fluids, e.g. emulsions. Therefore, the effect of the distribution of the contact zone with more cutting fluid is reduced. For the lubrication of the contact zone only a minimum quantity is necessary.

3.2. Grinding performance leads to increased resource efficiency

While the life cycle can be increased by improving the workpiece quality in terms of the subsurface properties, the resource efficiency is dependent on the productivity of the grinding process. The *VDI* defines resource efficiency as the ratio between cost and benefit. While the product or process result is seen as the benefit the cost can be summarized as natural resources [15]. Raw materials and energy resources are of special interest for the grinding process. The porous metal bonded grinding wheel allows a decrease of the process time and therefore also reduces the required energy consumption for the production of one component.

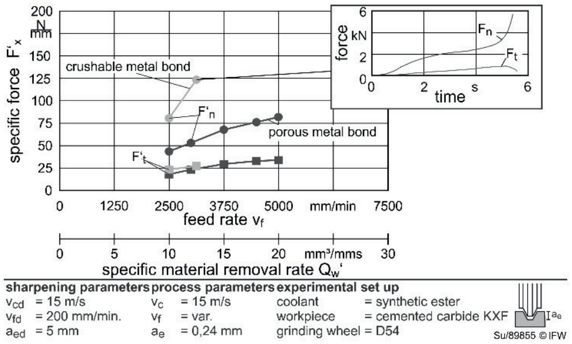
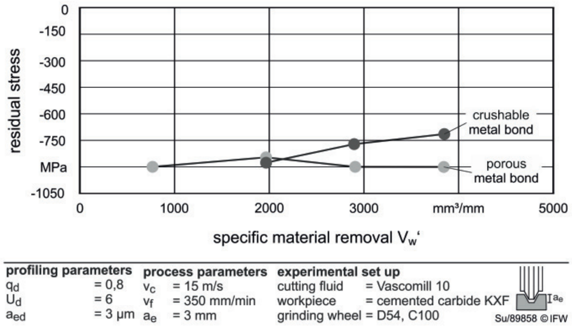


Fig. 4. Productivity of porous metal bonded grinding wheels and wheels used in the industrial practice

In contrast to conventional grinding wheels the new bond type allows a chemical bonding mechanism between grain and bond. This leads to superior grain retention and the ability of the wheel to be used for creep-feed and surface grinding. The crushable metal bond only allows for a material removal rate of 12,5 mm³/mms, because afterwards grains break out leading to the rubbing of bond and workpiece. This effect of grain break out can be seen in the second diagram on the right half of figure 4, where the normal forces increase significantly in a period of five seconds while the tangential forces remain low. By using the porous metal bonded grinding wheel the material removal rate is increased by 60 % up to 20 mm³/mms directly proving the possibility of energy and cost savings.

Figure 5 shows the surface quality in terms of surface integrity for the porous metal bond in comparison to the crushable metal bond. It was already stated that a decrease of compressive residual stresses causes a decrease of the life cycle time of the workpiece, since the chance for cracks and therefore workpiece failure is increased.



profiling parameters
q_d = 0,8
U_d = 6
a_{ed} = 3 µm

process parameters
v_c = 15 m/s
v_f = 350 mm/min
a_e = 3 mm

experimental set up
cutting fluid = Vascomill 10
workpiece = cemented carbide KXF
grinding wheel = D54, C100

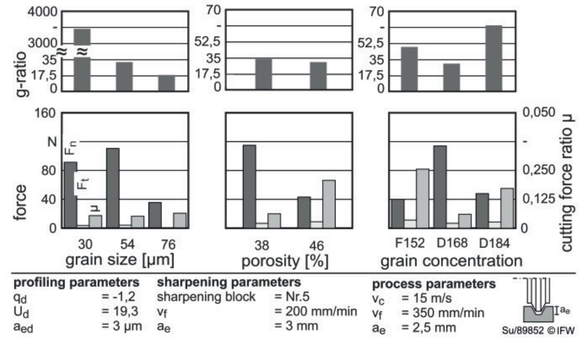
Fig. 5. Productivity of porous metal bonded grinding wheels and wheels used in the industrial practice

It can be seen that the porous metal bond leads to constant compressive residual stress values on a high level of approximately -900 MPa while the specific material removal increases. On the other hand the crushable metal bond leads to decreasing compressive residual stress values for increased specific material removal rates. The reason is the higher porosity of the new bond type. While the crushable metal bond holds the worn out cutting grains in the bond, the porous metal bond releases them and new cutting grains with sharp cutting edges engage in the machining process. This way the surface integrity stays free from subsurface damages when increasing the material removal.

In terms of the raw materials the porous metal bond shows a great resistance against tool wear which can be derived from the determined g-ratio values e.g in figure 6. G-ratios over 3000 are reached which show a significant increase compared to a value of 80 for conventional dressable vitrified bonded corundum grinding wheels [7]. Conventional multilayer metal bonds and galvanic bonds are able to reach similar g-ratios but can not be dressed or are very difficult to dress. For the profile grinding process the implementation of profiles with no or minimum deviations between actual and target profile is necessary. This paper shows the impact of grinding wheel specifications and the possibility of reducing tool wear and increasing cutting abilities by varying only the profiling parameters while eliminating the sharpening process.

4. Significant parameters for the profile stability

In order to compare the influence of different grinding wheel specifications on the profile stability, the g-ratio is used. The difference of the grinding wheel imprint before and after grinding allows the calculation of the grinding wheel wear. By dividing it with the removed workpiece material, the g-ratio is calculated. A high g-ratio indicates a high resistance of the grinding wheel against wear. In order to judge the ability to machine material, the cutting force ratio µ is calculated by dividing the tangential component of the occurring grinding forces with the normal component. A high cutting force ratio is achieved by high tangential forces and low normal forces. This means that the grinding wheel has a rather sharp topography and high grain protrusion and is therefore rather machining by cutting than rubbing and ploughing. The cutting ability is high for high g-ratio values. figure 6 shows the influence of the grinding wheel specification on the profile stability and the grinding performance.



profiling parameters
q_d = -1,2
U_d = 19,3
a_{ed} = 3 µm

sharpening parameters
sharpening block = Nr.5
v_f = 200 mm/min
a_e = 3 mm

process parameters
v_c = 15 m/s
v_f = 350 mm/min
a_e = 2,5 mm

Fig. 6. Influence of the grinding wheel specification on the profile stability and grinding performance

The different grain sizes were used to machine cemented carbide workpieces. While the cutting force ratio does not indicate any significant difference the lowest investigated grain size of 30 µm leads to an increased resistance against tool wear. The g-ratio is significantly higher compared to bigger grains. The tool wear is extremely low and difficult to measure. The main reason are thicker bond bridges between grains with reduced grain size while maintaining a constant grain concentration. Therefore porous grinding wheels with smaller grains are able to hold their profile and are more resistant against mechanical loads. Another aspect is the ability of smaller grains to penetrate the matrix of the cemented carbide workpieces. This way the material removal occurs with less cutting of the very hard carbide particles. Contrary, the particles are removed by machining the surrounding soft bond matrix primarily consisting of cobalt. Therefore, for the machining of the fine grained cemented carbide specification investigated in this paper a grain size of 30 µm is most suited. While the cutting force ratio variation is rather small, the process forces are significantly lower for bigger grain sizes. For 76 µm the normal force is less than half of the value of the 30 µm grain. The process forces are measured by a force measuring platform located underneath the workpiece. It therefore measures the total load on the workpiece and not the single grain. While the grain concentration is kept constant and therefore the volume of cutting grains a smaller grain size leads to a higher account of grains and cutting edges participating in the machining process. This leads to increased process forces but constant cutting force ratios.

As expected increased porosities lead to higher tool wear but also increased cutting force ratios. The wear can be explained by the decreasing bonding bridge thickness and the force ratio by the decrease of normal forces. Since the grain concentration was kept on a constant level the grinding wheel with a porosity of 38% has 8% more bond material than the wheel with a porosity of 46%. This leads to the increased resistance against tool wear. The increased porosity for the 46% grinding wheel allows for better cutting fluid and chip transport decreasing the friction between workpiece and grinding wheel and ultimately the normal force. Since both the tool wear and cutting ability, displayed by the g-ratio, are increasing with increasing porosities there seems to be a balance of the two values for a porosity between 38 and 46%. The opposite effect can be seen for the variation of the grain concentration.

F152 has the highest amount of bond material and the lowest grain concentration of the investigated tools. This way the load on the single grit but also the grain retention is maximized. This leads to a high cutting ability of μ = 0,25 while maintaining a moderate wear behaviour. D184 has a lower amount of bond material and the highest grain concentration. This way more cutting edges are engaged in the cutting process leading to lower single grain chip thickness values. This way the lower grain retention is compensated leading to a high resistance against tool wear and moderate cutting abilities. As for the F168 grinding wheel, the amount of bond material is kept constant while the grain concentration is reduced. This way the load on the single grain is increased further without increasing the grain retention. This leads to the lowest cutting ability and highest tool wear. In comparison to the D168 reference wheel with a porosity of 38%, the F152 wheel has less cutting grains and the difference in volume filled up by bond material. This way the same porosity is reached. Since the D168 and D184 wheels have the same amount of bond material but different amounts of cutting grains, the porosity of the D184 wheel has to be lower. This explains its higher resistance against tool wear but lower cutting ability compared to F152.

The sharpening process is not necessary for grinding wheels with conventional vitrified bond systems. It is an additional process step needed for multilayer metal bonds. Since the porous metal bond is a hybrid the necessity of this process step has been investigated.

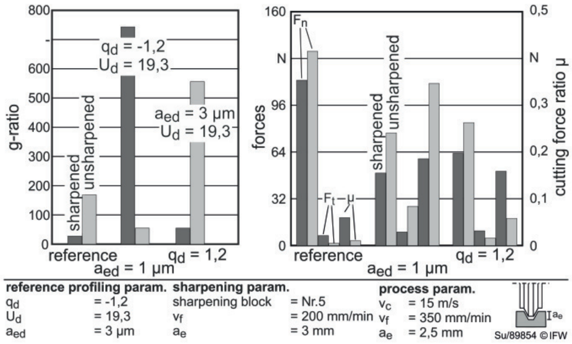


Fig. 7. Influence of the sharpening process on the profile stability and grinding performance

Figure 7 shows that it is possible to carry out the grinding process without sharpening and that sharpening has a great impact on the grinding wheel wear. By grinding without sharpening and using the profiling parameters from the previous experiments before the g-ratio can be increased by over six times in case of the applied sharpening parameters. At the same time the cutting force ratio is decreased significantly by factor 38. The sharpening process therefore seems to damage the bond bridges but also increase the grain protrusion.

By decreasing the depth of dressing cut from 3 to 1 μm the wear of the grinding wheel is increased but its cutting ability is improved. The grinding grits splinter for smaller depth of dressing cuts and are flattened for higher ones. Splintered grits have higher cutting abilities but also less resistance against wear. By changing from up to down dressing the effect is reversed again. The g-ratio is increased over 10 times while the cutting force ratio is still about half of the value with sharpening. This indicates the possibility of eliminating the sharpening process. Therefore the profiling parameters have been varied and the following grinding experiments were conducted without a sharpening process. figure 8 shows the variation of the overlapping rate, depth of dressing cut and a variation of the ratio of dressing speeds.

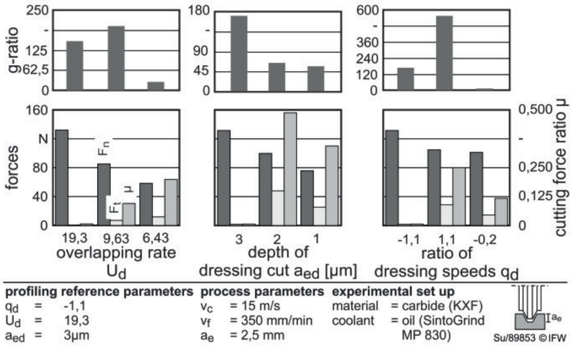


Fig. 8. Influence of the profiling parameters on the profile stability and grinding performance

While all parameters seem to have a significant effect on the wheel wear or its grinding performance the change from up to down grinding with a dressing speed ratio of 1,1 seems to improve both evaluation criteria. Compared to the experiments shown in figure 6 the g-ratio is only second to the grinding wheel using 30 μm grains and the cutting force ratio is on a comparable level. As it is for the grinding wheels using a 54 μm grain the sharpening process can be eliminated as it is the state of the art for conventional grinding wheels with vitrified bonds. Summarizing a grain size of 30 μm and a grain concentration of D184 with a porosity of 38% seems to be the grinding wheel specification with a balanced tool wear and cutting ability. This combination should be profiled in down dressing with an overlapping rate around 10, depth of dressing cut between 2 and 3 μm and a ratio of dressing speed close to 1.

5. Conclusion and outlook

In the framework of this paper the potential of porous metal bond grinding wheels for the application of profile grinding was shown while considering a life cycle perspective and their possible impact on resource efficiency. The fact that this metal bond type of wheel can be dressed by a form roller qualifies it for grinding complex geometries. Their increased chip space and high profile stability further increases the workpiece quality and allows an increase of the material removal rate. This way the thermal and mechanical load on the workpiece is decreased while the process time is shortened. Therefore this new tool concept allows for a simultaneous life cycle increase and saving of energy for machine tools and highly energy consuming coolant pumps. Additionally, high g-ratios lead to an increased resource efficiency since less grinding wheels, dressing tools and process steps are needed. While attempts to substitute the usually inevitable sharpening process by adapting the profiling process have been shown further sharpening experiments are scheduled. They include a variation of the sharpening stone specifications and sharpening parameters. The use of rubber based bond types and adapted grain sizes is expected to decrease the profile wear of the grinding wheels and to increase their grinding performance further. Additionally a FEM-model will be built in order to predict the profile wear of the grinding wheel depending on the dressing forces. It enables the user to verify their dressing parameters in advance.

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References

[1] Klocke, F.; König, W.: Fertigungsverfahren - Schleifen, Hobeln, Läp-pen, Springer - Verlag, Berlin - Heidelberg, 2005

[2] Malkin, S.: Hwang, T.W.: Grinding Mechanisms for Ceramics. CIRP Annals-Manufacturing Technology, Vol. 45(2), S. 569-580, 1996

[3] Biermann, D.; Würz, E.: A Study of grinding silikon nitride and cemented carbid materials with diamond grinding wheels. Production Engineering Research and Development (WGP), Volume 3, S. 411-416, 2009.

[4] Denkena, B.; de Leon, L.; Wang, B.; Krawczyk, T.: Manufacturing of Riblet-Structures by Profile Grinding with Metal Bonded Wheels. Proceedings of the 10th International Conference of the European Society for Precision Engineering and Nanotechnology (euspen), Volume 2, May 31st - June 4th 2010, Delft, Netherlands, S. 295-298

[5] Ruff, A.W.; Sin, F.; Evans, C.J.: Damage process in ceramics resulting from diamond tool indentation and scratching in various environments, Wear 181–183, 551, 1995

[6] Van der Meer, M.: Bearbeitung keramischer Funktionsflächen für Knieimplantate. Dr.-Ing. Dissertation, Leibniz Universität Hannover, 2011

[7] Denkena, B.; Tönshoff, H.-K.: Spanen Grundlagen, Springer - Verlag, Berlin - Heidelberg, 2011

[8] Hülsemeyer, L.: Energieeffizienz spanender Werkzeugmaschinen und bedarfsgerechter Betrieb am Beispiel der inneren Kühlschmierstoffzufuhr, Dr.-Ing. Dissertation, Leibniz Universität Hannover, 2016

[9] Gentzen, J.: Energieeffiziente Feinbearbeitung mit geometrisch unbestimmter Schneide und Minimalmengenschmierung, Jahrbuch Schleifen, Honen, Läppen und Polieren, Hrsg. Hoffmeister, H.W.; Denkena, B., Ausgabe 66, S. 111-128, 2013

[10] Brinksmeier, E.; Heinzel, C.; Wittmann, M.: Friction, Cooling and Lubrication in Grinding, CIRP Annals, Volume 48, Issue 2, 1999, p. 581-598

[11] Antsupov, G.; Heinzel, C.; Brinksmeier E.: Einsatz der Werkzeugreinigung beim Schleifen zur Steigerung der Leistungsfähigkeit und Energieeffizienz des Schleifprozesses, Jahrbuch Schleifen, Honen, Läppen und Polieren, Hrsg. Hoffmeister, H.W; Denkena, B., Ausgaben 66, S. 129-146, 2013

[12] Denkena, B., Köhler, J., Krawczyk, T.: Schleifen von Hartmetall mit porösen metallisch gebundenen Diamantschleifscheiben, Jahrbuch Schleifen, Honen, Läppen und Polieren, Ausgabe 66 (2013), S. 171-178

[13] Rowe, W.B.: Principles of Modern Grinding Technology, Elsevier Science, Burlington, 2013

[14] Schmitt, R.: Abrichten von Schleifscheiben mit diamantbestückten Rollen. Dr.-Ing. Disserstation, TU Braunschweig, 1968

[15] VDI 4800 Blatt 1 Ressourceneffizienz – Methodische Grundlagen, Prinzipien und Strategien, 2015