Technological Potential and Performance of Gears Ground by Dressable CBN Tools

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Dressable vitrified bond CBN grinding tools combine the advantages of other common tool systems in generating gear grinding. Yet despite those technological advantages, there is only a small market distribution of these grinding tools due to high tool costs. Furthermore, scant literature exists regarding generating gear grinding with dressable CBN. This is especially true regarding the influence of the grinding tool system on manufacturing-related component properties. The research objective of this report is to determine the advantages of dressable CBN tools in generating gear grinding.

Introduction

In order to improve load carrying capacity and noise behavior case hardened gears usually are hard finished. One possible process for hard finishing of gears is generating gear grinding which has replaced other grinding processes in batch production of small and middle gears due to high process efficiency. Depending on grinding task and batch size different tool concepts can be used in generating gear grinding. The latest concept is dressable vitrified bond CBN grinding tools.

Dressable vitrified bond CBN grinding tools combine the advantages of other common tool systems in generating gear grinding. The CBN grains are a highly productive cutting material due to their high specific stock removal rate. Vitrified bonds are dressable and thereby very flexible. By dressing different profile modifications can be set up and constant gear quality can be guaranteed during the tool life time. Despite those technological advantages there is only a small market distribution of these grinding tools due to high tool costs. Furthermore, only a few published scientific analyses of generating gear grinding with dressable CBN exist. Especially, the influence of the grinding tool system on manufacturing related component properties has not been analyzed yet.

State of the Art

Generating gear grinding. One of the most efficient processes for the hard finishing of gears in batch production of external gears and gear shafts is the continuous generating gear grinding. Generating gear grinding is used for the hard finishing of gears with a module of $mn = 0.5$ mm to $m_n = 10$ mm (Refs. 1, 2, 4). By the application of new machine tools, the process can be used for grinding large module gears (up to $d_a = 1{,}000$ mm) (Ref. 4).

The cylindrical grinding worm, whose profile equates a rack profile in a transverse section, hobs with an external gear (Fig. 1, left). The involute is generated by continuous rolling motion of the grinding worm and workpiece by the profile cuts method (Refs. 5, 2). Profile cuts method in the generating processes means the profile form is generated by a finite number of profiling cuts. Due to the closed grinding worm no generating cut deviations, known from gear hobbing, occur in generating gear grinding.

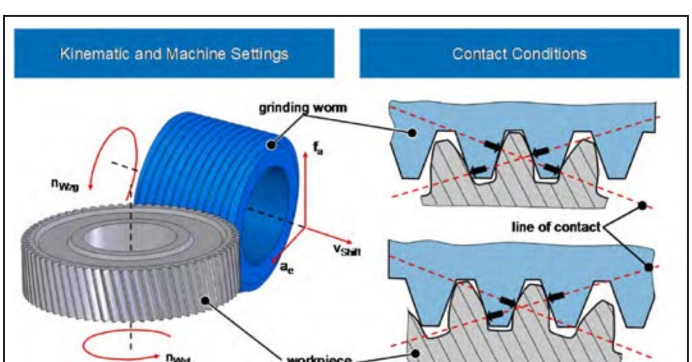

Figure 1 Generating gear grinding: principle, machine settings and contact conditions (all images courtesy WZL).

In comparison with other gear grinding processes, the stock removal rate in generating gear grinding is very high. In most cases, it is only limited by the reachable gear quality (Ref. 2). In generating gear grinding, always multiple points of the grinding worm are in contact. The number of contact points change continuously during the tool rotation, Error! Reference source not found. (right).

The contacts on the right and on the left tool flank are equal by an even number of contact points. This leads to a consistent distribution of forces. By an uneven number of contact points also the distribution of forces will be uneven. This leads to an inconsistent distribution of the cutting forces. In Figure 1, lower on the line-of-contact of the left tool flanks the forces are split in two contact points. On the right tool flank the cutting force is increased because only one point has contact. This fact can lead to a higher stock removal at this contact point and to a higher excitation. The consequence can be the appearance of profile form deviations that reduce the reachable gear quality. Scientific publications by Meijboom (Ref. 6) and Türich (Ref. 7) describe this theoretical relationship.

Publications, such as those listed in References 8, 9 and 10, and existing doctoral theses by Meijboom (Ref. 6), Türich (Ref. 7) and Stimpel (Ref. 11), show the influence of several parameters (axial feed, number of starts, etc.) on the process results. But several technological correlations have yet to be analyzed or verified in trials, and investigation of different tool systems cannot to date be found in the literature.

Tool systems in generating gear grinding. In gear grinding, usually two types of tool systems are used. On one hand for small batch production with changing gear geometries and modifications flexible solutions are needed. Therefore, dressable vitrified bond grinding wheels made of corundum are used. A huge advantage is constant gear quality and surface roughness due to the possibility of dressing. A disadvantage can be found in short tool life times and additional dressing time.

On the other hand, for mass production with only a few variants concerning profile modifications a productive grain material is needed. Therefore, electroplated CBN tools are used. In contrast to dressable vitrified bond corundum tools electroplated CBN has a higher productivity due to wear-resistant grain material. A huge advantage is time saving due to reduction of dressing processes. But disadvantages can be found in changing gear quality during tool life time and the significant higher tool costs.

To combine the advantages of both tool systems vitrified bond dressable CBN tools have been developed. Due to high tool costs and existing risk in tool handling this tool system has not been used in many industrial applications so far. Furthermore, only a few published scientific analyses of generating gear grinding with dressable CBN exist (Refs. 13, 14, 15). What's more, the influence of the grinding tool system on manufacturing-related component properties has yet to be analyzed. But in recent years the tooling system has become increasingly attractive for industrial applications (Ref. 12).

Objective and Approach

The research objective of this report is to determine the advantages of dressable vitrified bond CBN tools in generating gear grinding. The manufacturing-related properties of gears that are ground with dressable CBN will be analyzed and compared with conventional-ground gears.

The tested gear sets are manufactured identically despite the gear hard finishing process. In generating gear grinding, different tool systems are used for the hard finishing. The properties, e.g., surface structure, residual stresses and gear quality, are analyzed and compared.

After gear grinding, pitting tests according to the DIN-ISO standard for low cycle fatigue area are carried out (Refs. 16, 17). In the end, a relation between different tool systems, manufacturing-related properties and fatigue strength will be demonstrated. Furthermore, initial results showing the tool wear behavior will be shown.

Performance of CBN-Ground Gears in Fatigue Tests

In the following section the performance — especially the flank fatigue strength — of gears ground by different grinding tools, will be investigated in pitting tests. Therefore gear geometry, initial situation of the ground gears, test rig, and test approach are described. (Sample results to follow.)

Workpiece Geometry, Test Bed, and Approach

Geometry and initial situation of test gears. For the fatigue strength test, a standardized, gear geometry of the Laboratory for Machine Tools and Production Engineering (WZL) was chosen. The gear set has a module of $m_n = 4.0$ mm with 20 teeth at the pinion, 33 teeth at the wheel, and a gear face width of $b = 21.2$ mm. The pressure angle is $\alpha_n = 18°$ and helix angle is $\beta = 20.4°$. This leads to a standardized center distance of a = 112.5 mm. The complete gear geometry data are shown in Figure 2.

All gear sets have been machined from the same material batch (20MnCr5) and have been heat treated in one batch. The gears are case-hardened with a case-hardening depth of $CHD_{550HV} = 1.0$ mm at the flank, and a surface hardness of 60 + 2 HRC in one batch. All soft- machining operations, e.g., turning, milling and gear hobbing, have been carried out in each case with the same set of process parameter in one batch. The only differences can be found in the gear grinding process.

All gear sets were ground by continuous generating gear grinding with identical process parameters on the generating gear grinding machine LCS380 of LIEBHERR at the Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University. Gears and pinions have been ground by a two pass strategy.

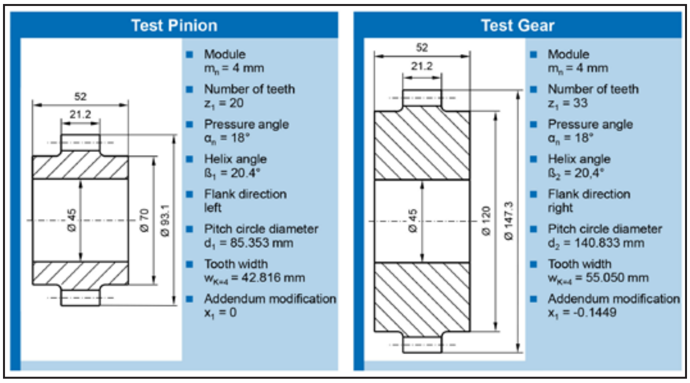

Figure 2 Gear geometry — test pinion and gear.

In the first pass, the gears were roughed with a cutting speed of $v_c = 60$ m/s, an axial feed of $f_a = 0.50$ mm and a removed flank stock of $\Delta s = 0.13$ mm. In the second pass the gear sets have been finished with the same cutting speed but with an axial feed of $f_a = 0.37$ mm and a removed flank stock of $\Delta s = 0.02$ mm. A grinding worm with a number of starts of $z_0 = 1$ has been used.

One half of tested pinions is ground by a dressable vitrified bond CBN tool, the other half is ground by a state of the art vitrified bond corundum tool with 30% sintered corundum. Other process parameters and the clamping situation can be seen in Figure 3.

Geometrically all gear sets are identical concerning gear geometry deviations and surface topography. Figure 4 shows for example the gear quality of all gears after the grinding process. All gears are ground in gear quality 4 or better according to DIN 3962 (Ref. 18).

In addition to the geometrical gear properties, manufacturing related component properties of the surface zone have to be considered. Figure 5 shows residual stresses in the surface zone in axial and tangential direction for both tool variants.

In tangential direction, respectively the profile or generating direction, residual stresses σ_t of the CBN-ground gears are significantly higher. Due to high productivity of the CBN grains, the grinding process, especially the chip formation, induces less thermal energy to the surface. Additionally, the higher hardness of CBN grains creates higher compressive stresses which also extend deeper into the surface zone. At the surface, gears ground with CBN have compressive residual stress of $\sigma_t = -940$ MPa. The conventional ground only $\sigma_t = -690$ MPa.

The surface roughness of both variants is nearly identical. Average CBN-ground gears have a surface roughness of $R_z = 2.5\,\mu m$ and the conventional ground gears of $Rz = 2.9\,\mu m$. Referring to ISO 6336-1 the difference on load carrying capacity of the both variants concerning gear and surface quality is insignificant (Ref. 17).

Test bed and approach. Gear testing has been carried out at the Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University. The gears were tested on a 112.5 mm center distance back-to-back contact fatigue test rig at $n_2 = 2{,}450$ rpm, at the pinion and with $n_1 = 1{,}500$ rpm, at the input shaft. As lubricant Shell Omala F220 oil at T_{oil} = 90°C was used for splash lubrication. The used back-to-back test rig, according to DIN 51354-1 (Ref. 16) and its principle, are shown in Figure 6.

Low-cycle, fatigue pitting tests were carried out with constant torque at pinion and by adhering to the FVA guideline for pitting tests (Ref. 18). These tests were conducted for each ground variant at two different torque levels of $M_2 = 650$ Nm and $M_2 = 750$ Nm. These torques gave peak contact stress levels of $\sigma_P = 1{,}471$ MPa and $\sigma_P = 1{,}578$ MPa, respectively. These values were calculated by the finite element tooth contact analysis *FE-Stirnradkette* developed by the Laboratory of Machine Tools and Production Engineering. Each test involves five tests per variant (CBN or corundum) and torque level.

Results

As criterion for low cycle fatigue strength a damaged surface of a single tooth of four percentage ($V_{EZ} = 4\%$) is defined. In Figure 7 an example of typical pitting damages can be seen for differently ground variants at test end.

The two pictures at the top of Figure 7 show the size of the pitting at test end. All pitting of the tested pinions is located below the pitch circle, in the middle or left of the middle of the tooth flank with a similar size. Furthermore, measurements show that the pitting has similar depth and form. The difference can be found in the number of load cycles at the test end. In this example the pinion ground with dressable CBN has a number of load cycle of $N_2 = 11{,}434{,}500$. That is nearly 50% higher than the corundum-ground gear

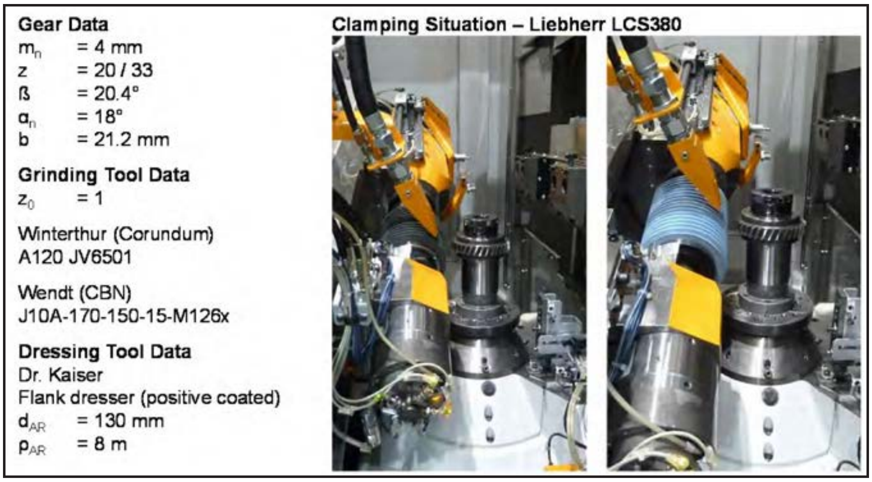

Figure 3 Gear geometry, machine tool and tool data—pitting tests.

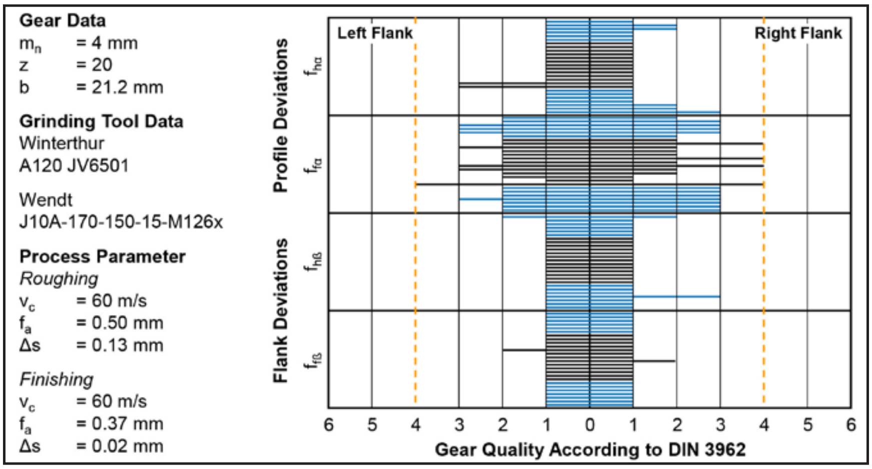

Figure 4 Gear quality of tested pinions—selected values.

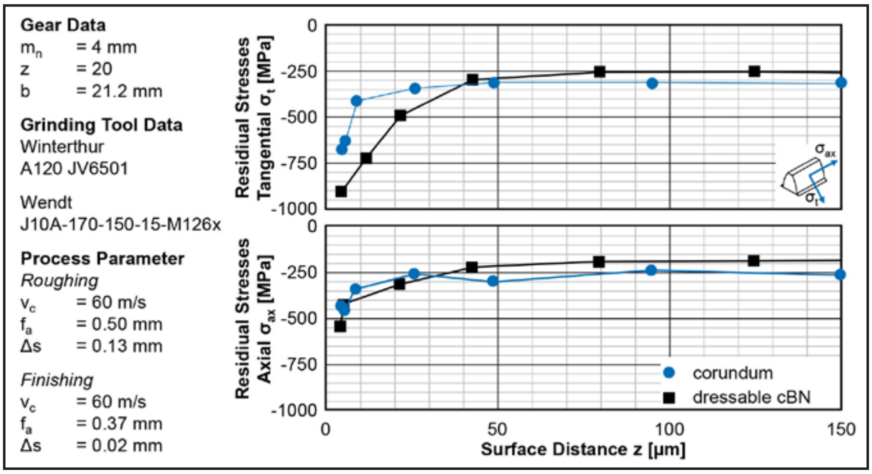

Figure 5 Comparison of residual stresses in axial und tangential direction after generating gear grinding.

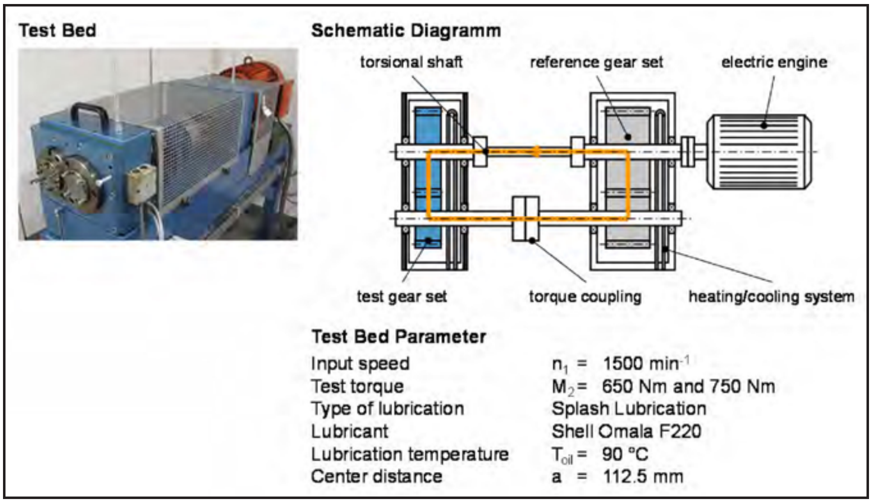

Figure 6 Back-to-back test rig according to DIN 51354-1 and testing parameters.

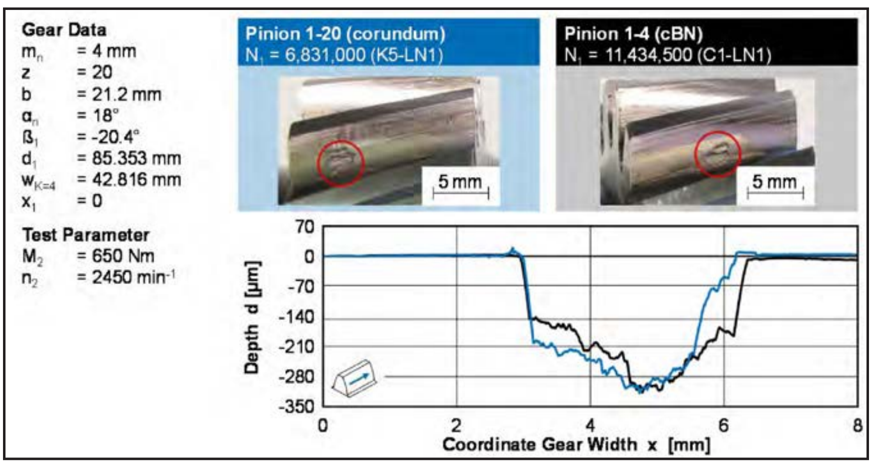

Figure 7 Comparison of pitting size and depth for different ground gears.

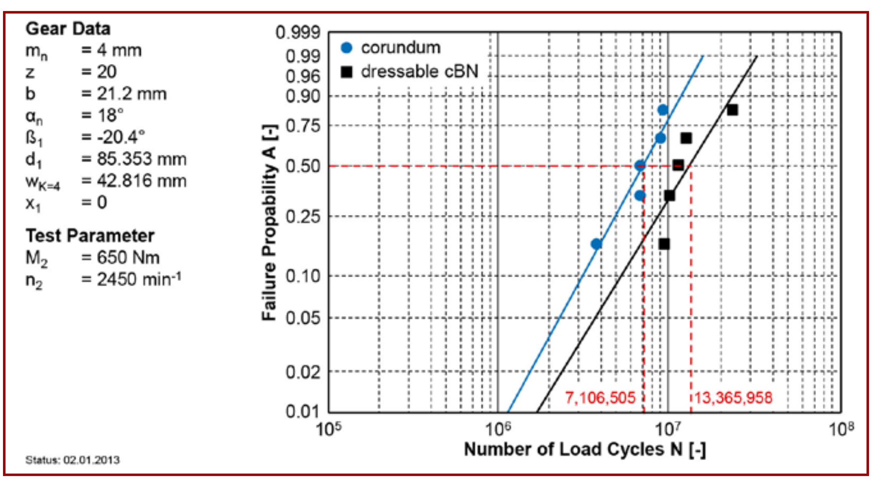

Figure 8 Comparison of failure probability, according to Weibull-Gassner for a torque of $M_2 = 650$ Nm.

with a number of load cycles $N_2 = 6{,}831{,}000$ at the same pitting size.

A complete overview of the number of reached load cycles for a torque of $M_2 = 650$ Nm is shown in Figure 8. In the chart the failure probability over the number of load cycles reached for a torque of $M_2 = 650$ Nm according to the probability distribution of Weibull-Gassner is shown.

A significant gap between the lines of best fit for the two ground variants can be seen. At a failure probability of $A = 0.50$ (50 %), the pinions ground with dressable CBN reach, in average, a number of load cycles of $N = 13{,}365{,}958$. The conventional ground gears only $N = 7{,}106{,}505$. That means that by changing the tool system, a low cycle fatigue twice as high as with conventional tool systems can be achieved.

Furthermore, tests show that dressable CBN-ground gears can reach the same or higher low cycle fatigue strength at a torque level of $M_2 = 750$Nm, compared to the conventional-ground- gear at a torque of $M_2 = 650$ Nm. That means a gear with the same gear geometry and approximately 15% more torque can be transferred merely by changing only the tool system in the gear grinding.

Conclusion

Due to the higher compressive residual stresses gears ground with dressable vitrified bond CBN tools can transferee higher loads or reach a higher low cycle fatigue. Therefore, dressable CBN has a high potential in grinding gears to increase the power density.

Performance of Vitrified Bond CBN in Generating Gear Grinding

In the following section, the performance — especially the wear behavior — of dressable CBN grinding tools will be investigated in grinding trials. Therefore, gear geometry and approach are described. Afterwards, first grinding results will be shown.

Machine tool, workpiece geometry and grinding tools. The objective of the performance tests is the analysis of the wear behavior of the tools with which the gear sets for pitting test were ground with. Therefore, gear geometry of the gear wheel was modified concerning its gear width to have a larger removable stock per gear.

The gear set has a module of $m_n = 4.0$ mm with 33 teeth, and a gear width of $b = 50.0$ mm. The pressure angle is $\alpha_n = 18°$ and helix angle is $\beta = 20.4°$. The complete gear geometry, the grinding and dressing tool data are shown in Figure 9.

All gears have also been soft-machined from the same material batch, 20MnCr5, and have been heat treated in one batch like the gear sets in the pitting test. The gears are case-hardened with a case-hardening depth of $CHD_{550HV} = 1.0$ mm at the flank and a surface hardness of 60 + 2 HRC.

Results

The graphs in Figures 10 and 11 show the high technological potential of dressable vitrified bond CBN in generating gear grinding. Figure 10 shows the change of profile angle deviation for the two grinding tool systems and constant process parameters. Furthermore, Figure 11 shows changes of two ball dimension for same grinding trial.

For a cutting speed of $v_c = 80$ m/s, an axial feed of $f_a = 0.37$ mm in roughing and $f_a = 0.27$ mm in finishing at one fixed shifting position of the tool, workpieces were ground until a significant wear of the tool could be detected (dashed line). For the grinding worm made of corundum, a diagonal movement according to the state of the art is used in roughing process. The complete grinding process with the dressable CBN tool and the only finishing process with corundum are performed without shifting.

With the corundum tool in one shifting position, only 10 gears can be ground until one of the defined quality criteria is crossed. In this case, the tooth width or the two-ball dimension, respectively, has changed more than $\Delta M_k = 30\,\mu$m (dashed line), a change of the profile angle more than $\Delta f_{H\alpha} = 15\,\mu$m.

For the CBN tool, both key values, the change of profile angle and two-ball dimension, are staying within the defined limits. Because no change could be detected, the trial was cancelled after grinding 100 workpiece without any traceable wear at the tool.

Summarized dressable CBN tool can be used to increase process efficiency. Due to minimal tool wear dressing time per part decreases significantly. Furthermore, the tool life time itself increases significantly.

That means tool costs per part are comparable with corundum tools (Ref. 4).

Figure 9 Gear geometry, machine tool and tool data—tool wear tests.

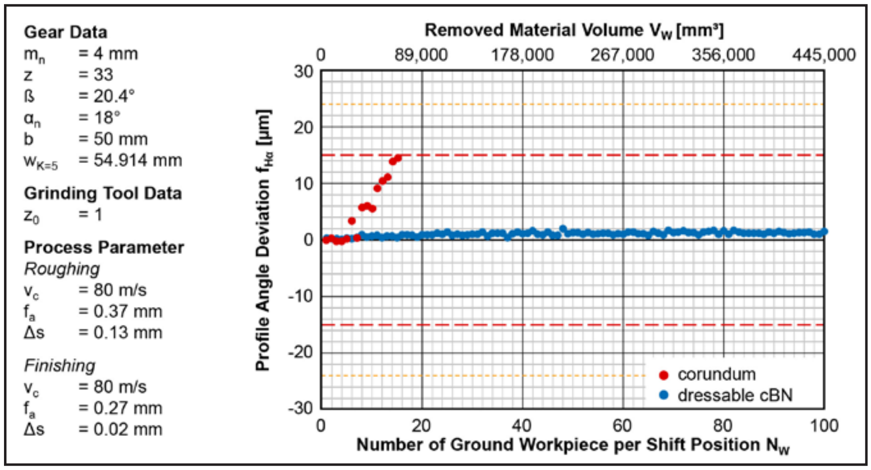

Figure 10 Change of profile angle deviation for different grinding tool systems and constant process parameter.

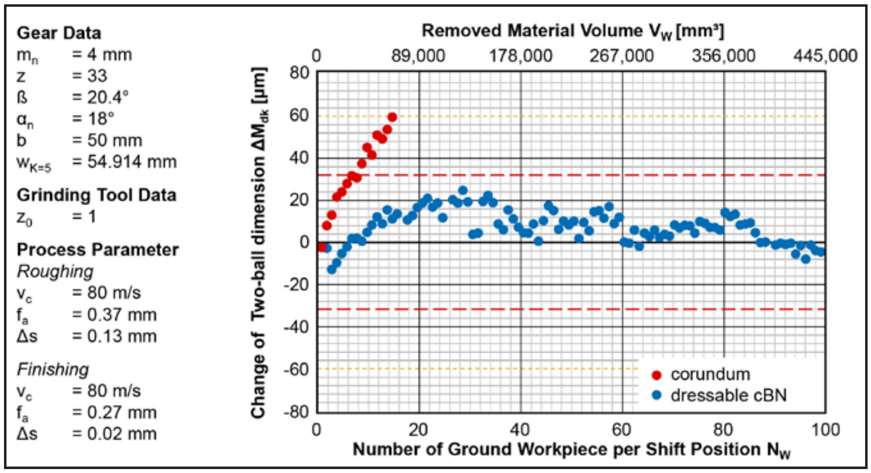

Figure 11 Change of two-ball dimension for different grinding tool systems and constant process parameter.

Conclusions

With its higher hardness gained through the thermal and chemical resistance of grain material dressable vitrified bond, CBN tools can handle higher tool loads with less wear and higher tool life times. Therefore, dressable CBN has a high technological potential in generating gear grinding gears to increase the process efficiency.

Summary and Outlook

Dressable, vitrified-bond, CBN grinding tools combine the advantages of other common tool systems in generating gear grinding. But only a few published scientific analyses of generating gear grinding with dressable CBN exist. Furthermore, there is at present limited distribution of these grinding tools.

First results from grinding investigations in this report show that dressable CBN is a highly productive cutting material due to its high specific stock removal rate. This leads to minimum tool wear and comparable tool-cost-per-part, as in the state-of-the-art process with corundum.

Despite those technological advantages, the analysis in this report shows that with dressable CBN, higher compressive residual stresses in surface zones can be reached. In particular, the influence of the grinding tool system on these manufacturing-related component properties leads to a higher, low cycle fatigue strength. In short, gears ground with dressable CBN can reach a higher number of load cycles or transferee higher torques at the same level of load cycles as conventional ground gears.

In future, all results of this report must be validated; that means grinding technology has to be tested for further process designs; e.g., number of starts, cutting speeds and feed, and for other gear geometries.

Furthermore, to decrease tool costs, manufacturing technologies of grinding worms themselves have to be optimized by tool suppliers.

In gear testing, the results have to be verified with other gear geometries. Especially, occurrence of residual stresses depending on gear geometry, tool specification and process design in grinding have to be analyzed in more detail. Therefore, a fundamental research project is planned at the Laboratory of Machine Tools and Production Engineering (WZL).

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