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Practical analysis of productivity of grinding tools in the process of internal generating gear grinding

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Abstract

Internal generating gear grinding is an innovative solution to improve the quality of ring gears with high productivity. Despite of the advantages, an investigation of influence of different grinding wheels on process productivity was not performed yet. Based on this scientific gap, this paper investigates corundum and cBN tools performance for the process. The investigation starts with an analogy test, where one cBN and six corundum specification tools are tested in terms of geometry, roughness and tool life. According to the results, corundum tools provide tool life, quality similar to cBN tools, with the advantage of 1.5 times higher productivity.

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Keywords: Hard finishing; Internal gear grinding; Ring gears; Corundum grinding wheels

1. Introduction and Motivation

On the trend of integrated power train development, planetary gear stages can provide a higher transmission ratio in a significantly more compact and lighter package than conventional power trains, leading to a positive effect on the efficiency of the overall system [1]. At the same time, the application of planetary gear sets encounters new challenges, especially concerning noise and vibration behavior [2]. For this type of gears, even the slightest geometric distortions in the ring gear will lead to unwanted noise and vibration. These unwanted excitations are easily perceptible in e-axle transmissions, which rely on fewer elements in comparison to conventional combustion engine transmissions [3]. Due to this, the requirements for the ring gear quality have increased in the last years and the importance of hard finishing for these gears has increased as well.

For the manufacturing of external gears, generating gear grinding is a hard finishing process used frequently in mass production, due to its high productivity combined with high quality. The process has been widely investigated in the last years, in different researches [4, 5]. However, until recently hard finishing solutions suitable for mass production of ring gears were not studied in detail.

Internal generating gear grinding is a hard finishing process developed by the company NIDEC MACHINE TOOL CORPORATION that aims at the manufacturing of internal gears with high quality while considering the productivity requirements of mass production. This high productivity is achieved by a unique small grinding wheel design matched to a high precision spindle and a cross-axis angle. One important aspect influencing not only the process productivity but also the achievable gear quality is the selection of grinding wheel type. Grinding processes use in general 2 types of grinding wheels : cubic Boron Nitride (cBN) or corundum grains. The cBN grains are characterized as super abrasive grains, with very beneficial properties such as high hardness and wear resistance [6, 7], leading to an extended tool life and therefore to an increase in productivity. Despite of their advantages, cBN grinding wheels are very costly in comparison to corundum grinding wheels. In addition, cBN grains require conditioning after dressing process, which might lead to an undesired increase in process time. Meanwhile, corundum grinding wheels are the most applied type of wheels in grinding processes. In comparison to cBN,

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corundum wheels have a lower cost but also a lower wear resistance. To investigate the productivity of the internal generating gear grinding process, an analysis of both types of grinding wheels, corundum and cBN, is required.

2. State of the Art

Internal generating gear grinding is a hard finishing process with geometrically undefined cutting edges. Similarly, to generating gear grinding, the tool used in internal generating gear grinding has threads that engage continuously from one tooth after another in the gear. Simultaneously, the grinding wheel moves in axial direction to complete the grinding process along the whole flank [8]. The sliding speed between the flank of the gear and the grinding wheel can be typically up to 30 m/sec. To enable this process, two distinguishing features on the machine are very important: the grinding wheel shape and the tool spindle, see Fig. 1.

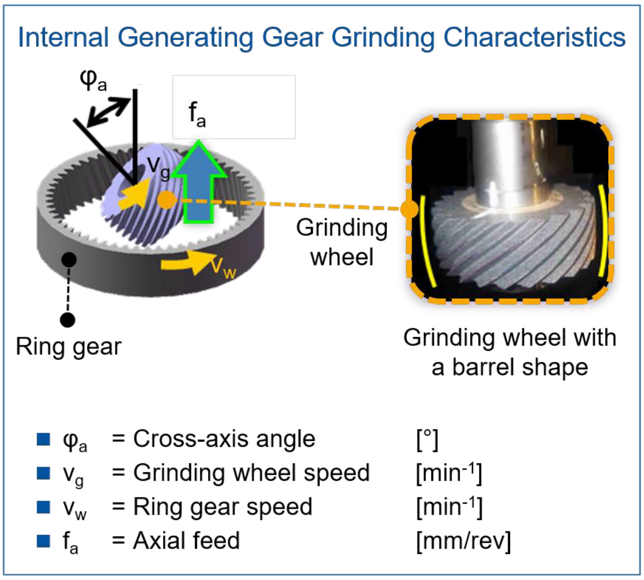

Fig. 1. Operational principle of internal generating gear grinding.

The relative sliding motion between gear and grinding wheel is obtained by a cross-axis angle φ_a, as shown in Fig. 1. The cross-axis angle would normally cause an interference between a tool and a gear, if the tool would have a strict cylindrical shape. Therefore, a slight barrel shaped design for the grinding wheels is used in the process, as shown in the right of Fig.1. The grinding wheels curvature avoids the interference and optimizes the contact pattern with the internal gear flanks.

The second feature to enable the process is a high-speed precision spindle. At up to 15,000 min^{-1}, the tool can be meshed with the existing teeth of the gear precisely and provide high sliding speed. A special internal cooling system minimizes spindle heat distortion and allows the process to meet the high requirements of the finished internal gear in a mass production scenario.

In previous research performed by Fujimura et. al., the productivity of the internal generating gear grinding process was investigated considering the influence of process parameters, such as cutting speed and radial infeed [9]. In the research, the most suitable setup of process parameters was found, considering not only the process productivity but also the gear quality in terms of geometry and roughness [9]. Fig. 2 shows the quality results obtained in the work of Fujimura et. al. [9].

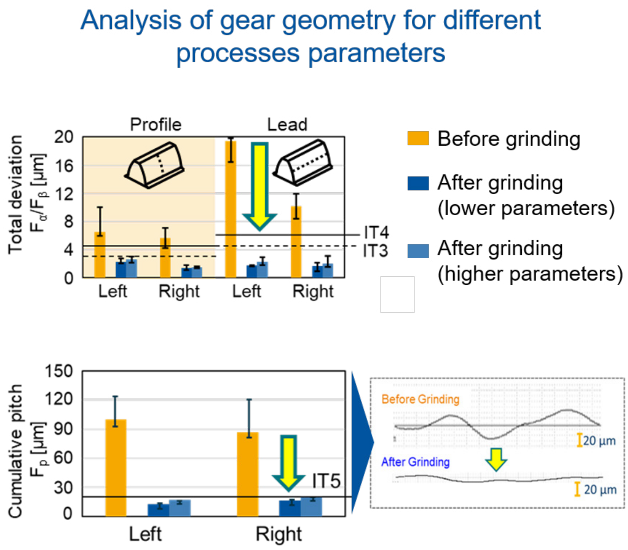

Fig. 2. Investigation of influence of process parameters on the gear quality for internal generating gear grinding.

It is possible to see that the deviation in profile and lead direction was below the class IT3 of the ISO system for cylindrical gears tolerance classification [10] for all the process parameters setups investigated. The study further showed positive correction of pitch line runout Fr and cumulative pitch error Fp, removing the distortions from the heat treatment, as shown lower of Fig. 2. Surface hardness and microstructure remained unaffected by the process parameter variation. Residual stress showed a less compressive state when using increased values for axial feed levels.

Despite of the positive results obtained in the work of Fujimura et. at., further investigation still needed to be performed regarding the internal generating gear grinding process. The influence of different types of grinding wheels, such as cBN and corundum, on the process productivity and quality was not yet considered.

3. Objective

Based on the research gap highlighted in the chapter before, the objective of this work is the investigation of the influence of cBN and corundum grinding wheels on the productivity as well as gear quality for the process of internal generating gear grinding. In the next chapter, the test design used to achieve the objective of the research will be presented.

4. Description of Materials and Methods

To investigate the influence of cBN and corundum grinding wheels, the test design was divided into two steps. In step 1, a process analogy was developed in order to investigate the grinding wheels behavior in less time-consuming trials. In the analogy trials, six different types of corundum and one type of cBN grinding wheels were investigated. The investigation was based on an analysis of gear geometric quality, roughness and tool life. Next, in step 2, standard process trials with one type of corundum grinding wheel selected based on the results of step 1 were performed. Therefore, verification of the results from the analogy process and the standard process is possible.

4.1. Analogy process trial

The corundum and cBN grinding wheels were investigated regarding tool wear and gear geometry quality. For the investigation, an analogy tool was developed, where the grinding wheel width reduced from the standard tool width, as shown in Fig. 3.

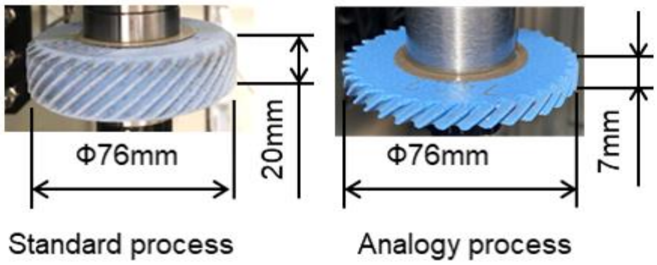

Fig. 3. Grinding wheel dimensions.

The thinner grinding wheels allow for an investigation of the grinding wheel wear in a time-lapse scenario. The wheel width was set to 7mm, one third of the standard tool. Due to this, the wheel life in the analogy process was expected to be three times shorter than in the standard process. The grinding wheels have an initial outer diameter d_a of 76 mm, a number of threads of 37 and a helix angle β of 30°. For the investigation, grinding trials were performed with a selection of different grinding wheel specifications. As already mentioned, six types of corundum grinding wheels and one type of cBN grinding wheel were investigated in this work. A detailed description of the grinding wheels is shown in Fig. 4. Grains, bonding systems and structure are major factors which decide grinding wheel performance. Grains are categorized by type, size and shape. Bonding systems are represented by hardness from A (soft) to Z (hard). Structure is expressed by classification number from 0 to 14 for corundum, from 25 to 200 for cBN. These numbers are connected to grain volume percentage [5]. In this trial, for corundum grinding wheels, the grain size was between 100 to 180, hardness between H, I, J and P, and structure between 42 to 50%. Corundum 1, 2, 3, 5 contained special shape grains. The cBN wheel used specification like in serial production.

For the grinding trials of all grinding wheels, the same ring gear specification was used. Table 1 describes the main specification parameters of the ring gear.

Table 1. Ring gear specification.

Name	Value	Unit
Module m_n	1.25	mm
Number of teeth z	85	-
Helix angle β	20	°
Profile angle α	20	°
Tip diameter d_a	111.17	mm
Root diameter d_f	116.92	mm
Addendum modification x	0.3	-
Gear width b	30	mm

The geometry of the ring gear and its dimensions were selected based on automotive applications.

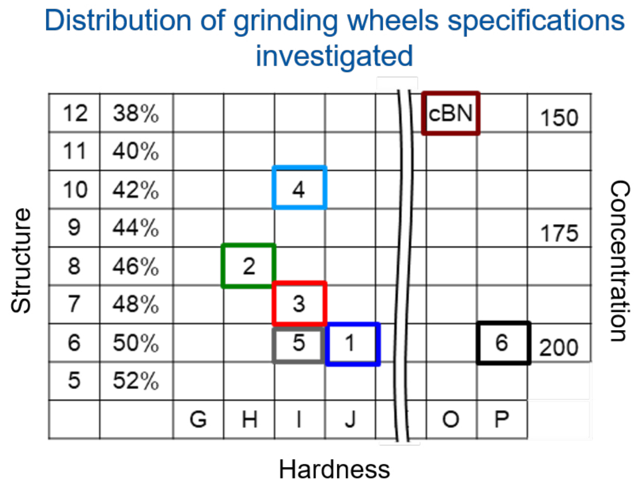

Fig. 4. Grinding wheel specifications for analogy process trials.

For the grinding trials of all grinding wheels, the same process parameters were used. On the lower part of Fig. 5, general information of the process parameters is described. For the trials, the grinding is divided into two stages, roughing and finishing. In the diagram on the upper part of Fig. 5, the radial infeed a_e and axial feed f_a used in the trials are highlighted in the upper green round points. In the diagram, the parameters used for both stages of roughing and finishing are shown, as well as respective material removal rate Q. This process parameters setup was obtained from the research of Fujimura et. al., and selected due to its high productivity combined with a good gear geometry quality result [8]. The parameters shown in lower black square points in the diagram of Fig. 5 represent the usual process parameters used in serial production for the process of internal generating gear grinding. The target material removable rate Q in the trials was set as 48 mm^3/sec. for roughing, and 26 mm^3/sec. for finishing. The cycle time of the process parameters used in this work is equivalent to 66% of the cycle time used in serial production scenario, an increase of 1.5 times in productivity. For the trials with cBN grinding wheels, conditioning of the grains after dressing was required. This was achieved by grinding at a reduced feed for the first five gears, after dressing.

For the grinding trials, a maximum of 50 gears were ground by each grinding wheel selected for investigation. The 50 gears were ground without a dressing cycle between them, in order to verify the performance of the grinding wheel regarding wear. During the grinding of the 50 gears, gear geometry and surface roughness were measured for each five gears ground, in order to verify the status of the tool wear along the trial. In this work, the tool wear was considered critical if the geometry quality was above the tolerance class IT5 or if the roughness parameter Ra was above 0.4 µm.

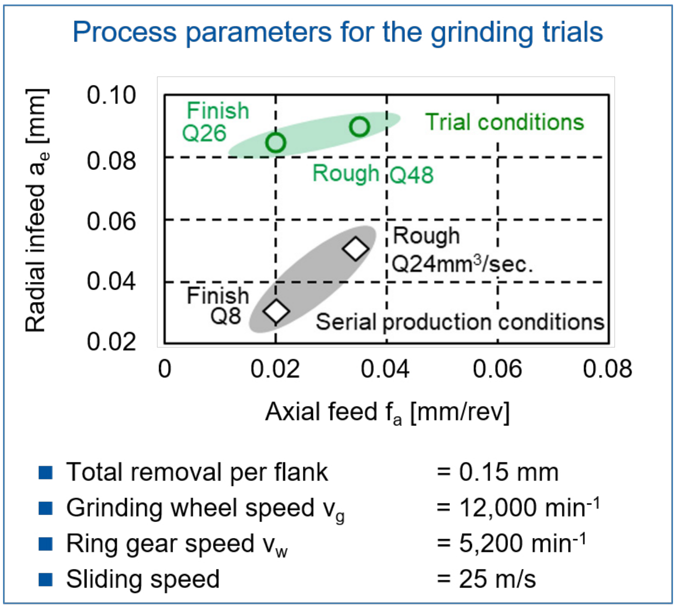

Fig. 5. Description of grinding parameters used in the trials.

The grinding test was stopped if either the geometry quality or roughness was above the tolerances pre-defined or the maximum of 50 ground gears was reached. Additionally, nital etching was performed for the last five ground gears to identify possible grinding burn.

4.2. Standard process trial

In step 2 of the test design, grinding trials with the standard tool width were performed. In comparison to the analogy process, the standard process had a grinding wheel with a larger thickness of 20 mm, as shown in Fig. 3. The objective of the standard process trial was to verify the comparability of the results obtained in the analogy process trials to the standard grinding process. The standard process is the one usually applied in the industry. In this work, only one corundum grinding wheel was investigated with the standard tool width. The wheel selected for the trial was the corundum 1, showed in Fig. 4. The grinding wheel was selected based on its performance on the analogy trials. The grinding wheel with the best performance in terms of gear quality and tool life was selected for the trials with the standard grinding wheel width. The process parameters used in the standard process trial were the same as used in the analogy process trial. For the grinding trials, a maximum of 145 gears were ground and for each five ground gears, gear geometry and roughness were measured to verify the tool wear. Equivalent to the trial with the analogy process, the tool wear was defined as critical if the geometry quality of the ground gear was above the IT5 tolerance class or the roughness parameter Ra was above 0.4 µm.

In the end of the tests, an analysis of the influence of different grinding wheel specifications on the process of internal generating gear grinding will be obtained. In addition, a comparability between the results of the analogy trial and the standard trial will also be possible.

5. Analysis of Gear Quality

In this chapter, the results of both trials, with analogy and standard tools, will be shown and discussed. Therefore, this chapter will be divided into two sub-chapters, which will discuss in detail the analogy and standard trials separately.

5.1. Analogy process trial

As mentioned in the previous chapters, the performance of different corundum and cBN grinding wheels was analyzed by means of the gear quality and roughness measurements during the trials. In the diagram of Fig. 6, the variation of the total profile deviation Fα of the gear flank for the trials of all the grinding wheels is shown. According to the diagram, the results of the wheels corundum 1, 2 and 3 regarding the profile deviation Fα was recorded below the tolerance class IT5 for all 50 gears ground. Especially corundum 1 showed stable results within IT4. Under the same conditions, the grinding wheel corundum 3 showed lower quality results in comparison to other tools, despite keeping below the tolerance class IT5. The results of corundum 4 are also shown in Fig. 6. According to the diagram, a critical state of wear was reached after grinding seven gears. Corundum 5, 6 are not showed in Fig. 6, because wheels were broken after the first workpiece trial. The different performances observed in the grinding wheels can be attributed to the balance between single grain grinding force and bonding force which are decided by grain material and binding system. Based on the results, it can be assumed that the value of the grain volume percentage, defined by the parameter "structure", has an influence on the performance of the grinding wheel. The grinding wheels with higher values of structure (see Fig. 4) had a performance lower than the ones with lower values of structure. Hardness P of corundum 6, for example, which is generally used for honing application was too hard and brittle for internal generating grinding application. Regarding the results of the trial with the cBN wheel, the diagram of Fig. 6 shows that for the first 20 gears ground, the quality was below IT4, and very similar to Corundum 1. However, after 20 gears ground, the quality begins to deteriorate and the critical state of tool wear was reached when gear number 46 was ground.

Regarding the roughness, the analysis of the Ra for each grinding wheel tested is shown in lower part of Fig. 6. According to the diagram, the values of Ra did not reach the defined tolerance of 0.4 µm, in any of the grinding wheels investigated. However, it is possible to see the influence of the grinding wheel wear on the roughness, in all the tools. The value of Ra progressively increases along the trials, showing the effect of the grinding wheel wear. Comparing the results between corundum and cBN grinding wheels, the cBN showed in general better values of Ra than all the corundum tools tested.

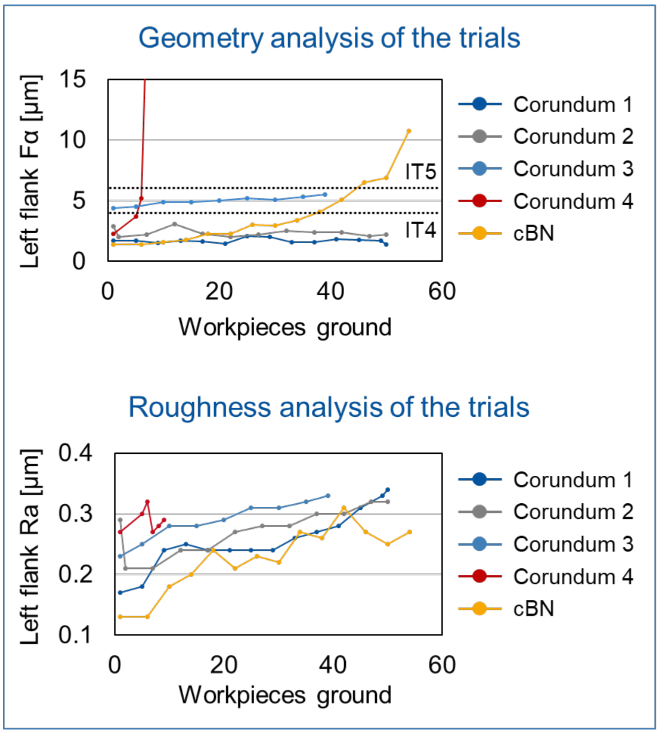

Fig. 6. Analysis of results for analogy trials.

By means of nital etching trials, no grinding burn was observed for any of the grinding wheels investigated. The results showed that the performances of specific corundum grinding wheels were better than the performance of cBN grinding wheels, for the analogy process of internal generating gear grinding. The investigation will continue with the analysis of the grinding trials with the standard process. For these trials, only one corundum grinding wheel will be used. Based on the good performance observed in results from the analogy trials, the corundum 1 grinding wheel was chosen.

5.2. Standard process trial

The results regarding quality from the grinding trial with the standard process is shown in the diagram in upper part of Fig. 7. The diagram shows the results regarding the profile deviation Fα for both flanks. According to the diagrams, all 145 gears ground presented geometry quality below the tolerance class IT4. The results showed a stable and high-quality process throughout the grinding of 145 gears, using a dressing cycle only once, at the beginning of the test. Therefore, in terms of geometric quality, no critical state of tool wear was achieved, and no sign of deterioration of the tool was detected.

Regarding the roughness, the results in terms of Ra are shown in the diagram in the lower part of Fig. 7. Similarly to the results obtained in the analogy trials, the influence of the grinding wheel wear can be seen on the values of Ra throughout the trial. As the amount of gears ground increases, the value of Ra increases as well, showing the increase of the tool wear. However, after the grinding of 140 gears, the critical tolerance of Ra of 0.4 µm was not reached.

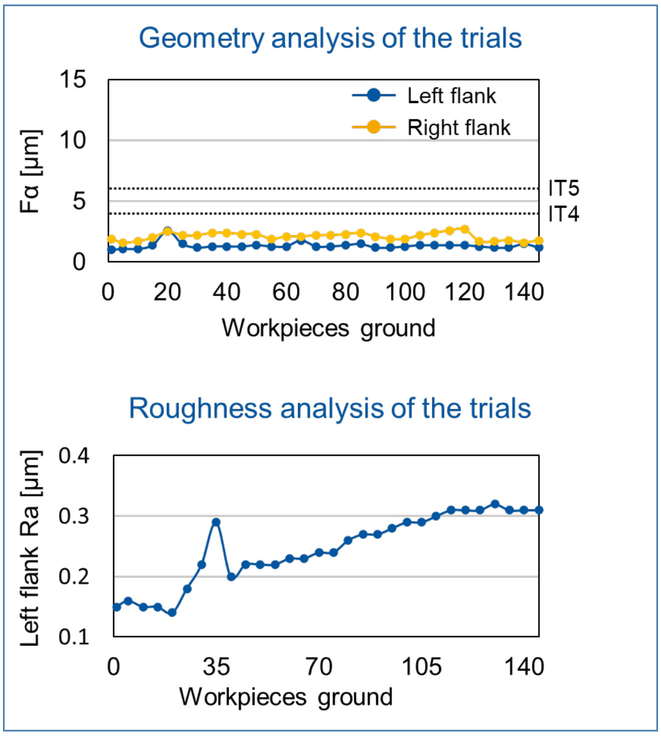

Fig. 7. Analysis of results for standard trials.

By means of nital etching trials, no grinding burn was observed in the grinding trials.

After analyzing the results of the standard process trial in terms of geometric quality and roughness, a comparison of results between analogy and standard trial must be performed. According to the results shown in Fig. 6 (corundum 1) and Fig. 7, no influence of tool wear was detected in the measurement of the profile deviation Fα. However, the influence of the tool wear was detected in the roughness analysis, shown in the diagrams in the lower part of Fig. 6, for the analogy trial and Fig. 7, for the standard trial. For the analogy trial, the roughness curve has a slope angle α_a of approximately 0.150°, while for the standard trial, the roughness curve has a slope angle α_s of approximately 0.065°. Therefore, the slope angle α_s is smaller than the slope angle α_a by a factor of 2.3 – which means that the influence of the tool wear on the roughness for the standard trial is 2.3 x smaller than the for the analogy trial. Hence, a correlation between the grinding wheel thickness and the roughness results by means of the slope angle can be found. Due to this, it is possible to assume that the analogy trial developed is able to report results which are correlated to the standard process.

After analyzing the internal generating gear grinding process for both grinding trials in terms of quality, the next chapter will discuss economic aspects of the process.

6. Economic Evaluation of Internal Generating Gear Grinding Process

The economic evaluation of the process was performed by an analysis between the grinding wheel cost ratio per workpiece and the number of gears ground per dressing interval. In this analysis, the grinding wheel corundum 1 and the cBN were considered. The analysis is shown in the diagram of Fig. 8. The green dotted curve represents the analysis for cBN grinding wheel. The curve is analyzed based on process parameters normally used in series production, with a material removable rate Q of 24 mm^3/sec. In this case, a dressing interval of 150-200 workpieces is achieved. The red solid curve represents the grinding wheel corundum 1, tested in this work. According to the results from the standard trial, a dressing interval of 145 workpieces was obtained, as marked in the diagram of Fig. 8.

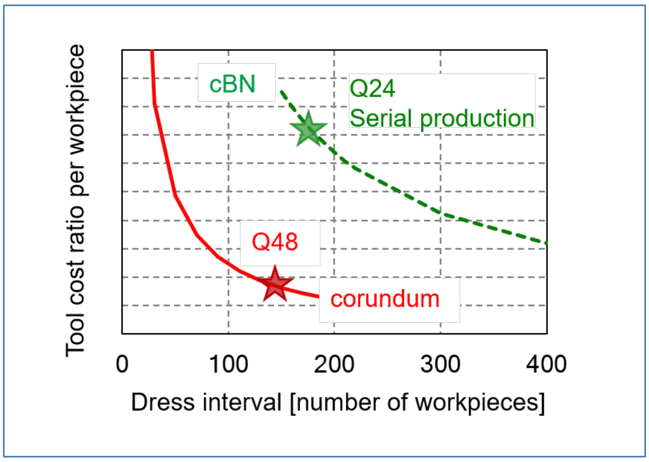

Fig. 8. Analysis of cBN and corundum grinding wheels in terms of economics.

Comparing both tools in the diagram, it can be seen that the tool cost ratio per workpiece of the corundum tool is approximately one-third of the cBN tool. This result was obtained due to the high number of workpieces ground per each interval of dressing during the process, for the grinding wheel corundum 1. Due to this, for the process of internal generating gear grinding, the corundum grinding wheels shown a competitive performance to cBN grinding wheels in terms of gear quality as well as tool wear. Ultimately, this performance is reflected to the economic aspect of the grinding process.

7. Conclusions

In this work, an investigation regarding the influence of corundum and cBN grinding wheels on the internal generating gear grinding was performed. The investigation was divided into two steps: Analogy process trial and Standard process trial. In both trials, target process parameters were set as 1.5 times more productive than in general serial production.

In the analogy trials, six corundum tools and one cBN tool were analyzed. According to the results shown, the corundum tool called corundum 1, which combines normal corundum grain and special shape grain with hardness J, showed quality below tolerance class IT 4 even after 50 gears ground. In general, it was observed that the tool life performance of the corundum grinding wheels is influenced by the balance between single grain grinding force and bonding force. It could be assumed that the value of the grain volume percentage has an influence on the performance of the grinding wheel in terms of tool life. The grinding wheels with higher values of structure had a performance lower than the ones with lower values of structure. Hardness P of corundum 6, for example, which is generally used for honing application was too hard and brittle for internal generating grinding application. The cBN wheel, on the other hand, showed critical wear after grinding 46 gears. Regarding the surface roughness, the critical tolerance value of Ra of 0.4 µm was not reached by any of the grinding wheels investigated, after the grinding of a maximum of 50 gears. However, it was possible to detect an influence of the tool wear in the results of Ra throughout the trials. Based on the performance regarding geometry and roughness, the grinding wheel corundum 1 was selected to be further investigated in the standard trial.

In the Standard process trial, after 145 gears ground, the geometry was still below tolerance class IT4. This means the dress interval of corundum 1 can be set after at least 145 workpieces for the standard process. With this result, it was shown that for the process of internal generating gear grinding, the use of specific corundum grinding wheels is able to have performance similar to cBN grinding wheels in terms of tool life. With this finding, it was observed that the tool cost ratio per workpiece ground of the corundum tool can be approximately one-third of the cBN tool. Therefore, the application of corundum grinding wheels can be very interesting and productive for the process of internal generating gear grinding.

8. Outlook

Based on the results obtained in this work, it was shown that a more detailed investigation of the balance between bonding force and single grain grinding force is required. Therefore, the next step of the research will be focused on this subject, in order to understand this mechanism and to further improve the tool performance.

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