Wear mechanisms of CVD diamond tools for patterning vitrified corundum grinding wheels

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ABSTRACT

Grinding is one of the last manufacturing steps in the production chain of modern workpieces. Thus, product quality is more important compared to the productivity and is therefore the limiting factor. Exemplarily, thermal load due to the grinding process leads to thermal induced damage such as grinding burn or tensile residual stresses. Previous studies showed the capability of grinding wheels with mechanically induced patterns to reduce the thermal load on a workpiece throughout the grinding process. In this paper the patterning tool is investigated in regard to the grade of CVD thick layer diamond (CVD-D). In detail, three CVD-D grades are investigated in terms of their features and their wear mechanisms. SEM and X-Ray diffractometry as well as Raman measurements are conducted. A wear mechanism of surface fatigue is found to be dominant. Pole figures as well as the microscopic measurements indicate a correlation between the texture of the CVD-D grade and the wear extension.

1. Introduction

The manufacturing process grinding is often the final manufacturing process step. Thus, the process results are directly determining the quality of the entire manufacturing process chain. Previous studies showed a correlation between the residual stresses of the workpiece resulting from the manufacturing process and the lifetime of a product as well as that the grinding process has a high impact on these residual stresses [6–8,14].

Residual stresses are stresses that remain in the workpiece after the manufacturing process due to a load collective of deformation and temperature within the process. They can be either compressive or tensile [18]. Tensile stresses result of a high temperature in the process, compared to the mechanical load. Compressive stresses result of an increased mechanical load compared to the thermal load. The residual stresses are a result of this load collective [4].

There are various approaches to adjust the residual stresses throughout the grinding process. One of which is to modify the grinding tool in type of used grain. Splinterly grains cause less friction in the process, due to sharp cutting edges. This results in a lower thermal load on the workpiece [12,20]. Cubic boron nitride (CBN) grains can increase the heat transportation out of the contact zone due to higher thermoconductivity compared to conventional cutting grains, such as corundum, but are more expensive [25]. Another method is to adjust the porosity of the grinding wheel in order to increase the available volume for coolant and chips in the contact zone. This can be achieved by a modification of the sintering process of the grinding wheel or by means of a patterning process prior to the grinding operation [7]. As a result of this patterning process, there are local patterns on the surface of the grinding wheel, by which the available volume for coolant and chips is increased locally. However, the total, conventional porosity is not changed.

In previous studies, various authors investigated the influence of structured grinding wheels on the grinding process. These studies differ in their manufacturing technology as well as in the size of the implemented structures. Kirchgatter investigated the application behaviour of slotted CBN grinding wheels [16]. Aurich et al. developed a grinding wheel with closed pockets [2] as well as one with set grains [1]. Rabiey investigated a laser structured grinding wheel, an electroplated structured grinding wheel and a structured grinding wheel with spiral grooves [28].

The patterns used in this study are patterns, which are manufactured by using fly-cutting technique. The advantages of this method are, that this method is low in costs and easy to apply as well as it delivers the possibility to adjust a conventional grinding wheel, especially on local areas of the grinding wheel. In comparison, the previous mentioned methods, induce a structure by means of the manufacturing process. Therefore, it is not possible to adjust the structures, depending on the machined workpiece. In case of the slotted grinding wheel, it is also not possible to adjust the structure along the axial direction of the grinding wheel. The influence of the patterns on the machining behaviour of the grinding wheel were investigated in a previous study be Denkena et al. for the circumferential case [7]. However, the fly-cutting technique is not yet applicable for manufacturing companies. Three
major reasons limiting the realisation. First, the kinematic of the process is not yet established for profile grinding processes. Secondly, the design of the structuring tool is limited, as the wear behaviour of the tool is not yet known. The wear is of importance for the precision of the machined patterns. Thirdly, the influence of the patterns on the grinding process under the interdependencies of the grinding wheel properties in profile grinding processes is yet unknown. All these limiting factors are investigated at the IFW. However, the motivation for this study is the second limiting factor, the wear behaviour of the patterning tool. In detail, different kind of diamonds can be utilised, out of which CVD-D is most likely advantageous based on previous studies [9, 12].

CVD-D is a polycrystalline kind of diamond that has no binder phase. Different kind of diamonds are the monocrystalline diamond as well as the polycrystalline diamond including a binder phase. All kinds of diamonds are used in dressing processes, while CVD-D is mainly used in recent studies for its properties that are comparable to monocrystalline diamond and its low price compared to monocrystalline diamond [15, 21, 30].

Li and Axinte summarised recent developments in the field of textured grinding wheels in a review. They classified the different structures by a factor “texture dimension” (TD), which is the distance from one active area with grains to another. The structures of this study have been classified as macrotextures, as the width of structure is higher than 100 μm [19]. In addition to TD, structured grinding wheels are classified by their effective contact area $A_{eff}$. This value describes the active area in relation to the circumferential surface area of an unstructured grinding wheel $A_{gw}$. This can be expressed by the following formula, in which $A_{u}$ is the area of one pattern and $N_{p}$ is the number of patterns:

$$A_{eff} = \left(1 - \frac{A_{u} \cdot N_{p}}{A_{gw}}\right) \cdot 100\%$$

The area of one pattern is calculated as an ellipse with the length $l_{u}$ and the width $b_{u}$. These variables, as well as the used patterning technique, are shown in Fig. 1. Further variables to dimension the process are the radii $r_{p}$ of the patterning tool and $r_{gw}$ of the grinding wheel, the rotational velocities $v_{c}$ and $v_{gw}$, the tangential velocity of feed while patterning $v_{tp}$ and the depth of cut $a_{cd}$.

Fig. 1. Patterning technique with relevant process variables.

2. Material and methods

The structuring operation is conducted on a continuous gear grinding machine KAPP KX 1. This machine has a high consistency in revolution per minute of the main spindle at low cutting speeds. The cutting speed of the grinding wheel varies within this investigation between 0.1 and 1.5 m/s. This is due to the high rotational speed ratio of circa 100 and the limited rotational speed of the patterning tool of max. 3000 min$^{-1}$. The rotational speed ratio is needed, as the patterning process is conducted with a patterning tool with one single cutting insert and as this is defined by the needed patterns per revolution of the grinding wheel. In addition, the spindle of the patterning tool is designed for the dressing of grinding worms. Therefore, it allows a very high accuracy regarding its rotational speed. This is of particular importance in the present study since inaccuracies of the speed ratio between the patterning and grinding tool lead to an unwanted modification of the generated structures.

In this work, the wear behaviour of chemical vapour deposited thick film diamonds (CVD-D) in the application of patterning vitrified corundum grinding wheels is investigated. Therefore, CVD-D inserts are utilised as cutting edges of the structuring tool. The structuring tool is a custom made tool from Dr. Kaiser GmbH, mounted on a dressing spindle C 80 FAW from Dr. Kaiser GmbH. The spindle has a working range of 1–3000 rpm. The tool (radius $r_{p} = 75$ mm) has one pocket to carry a CVD-D insert of the geometry TNXX0X0350. The CVD-D layers were brazed onto a tungsten carbide carrier. Within the investigation three different CVD-D grades from Dr. Kaiser GmbH are analysed. For each grade, three different radii are investigated. The radii $r_{p}$ are 0.1 mm, 0.3 mm and 0.5 mm. In terms of type of CVD, three types are investigated (A, B, C). The differences in grade are shown in the results of this work. Each combination was investigated with three different relative speeds between grinding wheel and patterning tool. In this way, 27 samples are investigated. The cutting edge conditions were sharp. Prior to each structuring step, the grinding wheel is dressed by a multi grain dresser (M/100) from Jakob Lach-Diamant GmbH & Co. KG. It is mounted on a modular jig, which is positioned between the structuring spindle and the workpiece. A rotational dressing operation cannot be realised due to the limited space within the machine room. As a grinding wheel a vitrified bond corundum tool from Saint Gobain Abrasive GmbH (200 × 30 x 127 IPA 60 HA 17 VTX) is used. Fig. 2 illustrates the experimental setup.

Regarding the test procedure, the grinding wheel is dressed prior to each trial, with an overlapping ratio $U_{dp} = 4$, a dressing depth of cut $a_{cd} = 5\mu$m for 20 times. Thus, the radius of the grinding wheel was
reduced by 100 μm, which is selected to remove the patterns with a depth of 60 μm. The following step was the patterning of the grinding wheel.

The measurement equipment in this investigation consists of a Keyence microscope VHX-600, for macroscopic measurements. Furthermore, a scanning electron microscope (SEM) ZEISS EVO 60 XVP (tungsten cathode) is used for investigations on the wear mechanism on a microscopic level as well as to characterise the investigated CVD-D grades. This is also used for EDX measurements (detecting unit: EDAX PV7715/98 ME). In addition, a Bruker Senterra Raman microscope is used for Raman spectra, also in regard to the wear mechanism, which in case of diamond can be graphitisation [21]. The applied laser power was 10 mW. In order to characterise the different CVD-D grades in their texture, the samples were investigated by X-Ray diffractometry with a Seifert XRD 3003 eta. The CVD-D inserts are investigate before and after the application.

3. Preliminary analytical consideration

The structuring process and its calculation is performed according to previous studies at the IFW [7]. Subsequently, the calculation is outlined here in short. The kinematic is similar to the kinematic of a dressing process with a rotary dresser. The base length of one structure is calculated by the geometric intersection of both radii, of the grinding wheel and of the patterning tool. This length is elongated or shortened depending on the speed quotient between the circumferential speeds of the grinding wheel and the patterning tool. The maximum width of a structure results from the width of cut, which is measured prior to the investigation for each diamond. For this purpose the width of the diamond at the depth of cut is determined. The area of one pattern results of the formula for an ellipse geometry [12].

The primary target value is the effective contact area $A_{eff}$. This value describes the resulting share of area that is not structured in relation to the overall circumferential area surface of the grinding wheel. This value is a setting parameter of the process. It does not describe the resulting topography.

The kinematic energy is altered in the investigation to influence the load on the CVD-D inserts. This is done by changing the relative speed between the grinding wheel and the cutting insert. Therefore, three different relative speeds are calculated, that cover the range in this particular setup. This is done by the method of scenario analysis in which the number of cutting edges, the direction of cut, the effective contact area as well as the revolutions per minute of both spindles are varied full factorially between the values shown in Table 1. Other process setting parameters of the patterning process, i.e. the rotational speed of the grinding wheel and the axial feed are slave values, which are kept constant within each scenario. As a result of this calculation, the range of relevant relative cutting speed values is calculated.

The results of this analysis are shown in Fig. 3. The different graphs show that an increase of revolutions per minute within each scenario leads to an increase in relative speed in a linear relation. The relative speed also increases by changing from down grinding to up grinding and by decreasing the number of cutting edges in down grinding. This effect results of the constant $A_{eff}$ value for each scenario. A decrease in relative speed results out of an increase in $A_{eff}$ due to a change in rotational speed ratio. A decrease in number of edges in up grinding leads also to a decrease in relative speed.

The results of Fig. 3 show that the relative speed is within a range from approx. 5 to 25 m/s. To investigate the wear mechanism of the CVD-D inserts over the entire range, values of 5, 15 and 25 m/s were chosen for this study. For each speed, 5000 patterns were machined in order to maintain the workload, independent of the number of grinding wheel surfaces. The patterns varied in their length between 4.1 and 4.8 mm as the base length of a structure is prolonged or clinched depending on the rotational speed ratio and the direction of cut. The width of the pattern varied due to the varied corner radii and fixed depth of cut between 156 and 488 μm.

4. Results and discussion

As a result of the conducted calculation, the three CVD-D grades were investigated with the evaluated relevant relative speeds of 5, 15 and 25 m/s. Each combination was investigated with the corner radius of the inserts of 0.1, 0.3, and 0.5 mm. The inserts were investigated prior and after $N_p = 5000$ by the above mentioned measurement equipment. This number equals an average value after patterning the grinding wheel of this study once. The corresponding results are outlined in the following.

The significance of the quantitative wear extension is however limited in regard to a standard deviation. Due to the phenomenological focus of this study on, one sample per test setting combination was taken. To achieve values with a proper confidence interval, the number of samples has to be increased significantly, especially in regard to the brittle failure mechanism of the CVD-D.

4.1. Characterisation of CVD-D grades prior to the experimental investigation

Prior to the investigation the different CVD-D grades were characterised, to reveal the differences in their conditions in order to generate correlations between the conditions and the wear mechanisms.

SEM micrographs of the inserts before the tests reveal that the surface of grade A was treated by lapping. The grades B and C, however, were not pre-treated. They vary in the layer side. According to Thornton, CVD layers have a growth direction of its crystals. The crystals grow from an initial nuclei and consequently increase in height and width [29]. This leads to smaller crystals at the substrate side and to bigger grains at the coating flux side. In case of grade B, the substrate side is investigated, in case of grade C, the coating flux side. Due to the lapping treatment of grade A, it cannot be verified, which side is investigated. The surfaces of the different CVD-D grades are shown in Fig. 5 on the left side.

Next to the surface condition, CVD-D grades can be determined by the internal condition, i.e. the internal orientation or texture of diamond grains. The texture of the different CVD-D grades is described by pole figures, measured by X-ray diffractometry (Fig. 4) for the lattice planes of diamond $\{111\}$, $\{220\}$ and $\{311\}$. The measurement was performed with an X-ray beam tilted in the Bragg angle $2\theta$ of $51.471^\circ$ ($111$), $90.363^\circ$ ($220$) and $112.562^\circ$ ($311$). Each sample was tilted by the angle $\psi$, expressed in the pole figure by the radius, and rotated by the angle $\phi$, expressed also by the rotation. This was done three times, once for each Bragg angle.

The results reveal a distinct fibre texture of grade A, as circles and a central peak are observed. The central peak reveals that the lattice plane ($220$) is oriented parallel to the CVD-D surface. The circles indicate that the grains are rotated around the normal vector of the CVD-D surface. The intensity is significantly lower for grades B and C, compared to grade A. Thus, a reduced grade of texturing was observed. In general, diamond has an anisotropic material behaviour. The

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<td>Factor</td>
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<td>Effective contact area $A_{eff}$</td>
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The preferred cleavage direction of diamond is [111]. A minor cleavage direction is [110], which corresponds to the direction [220] in (Fig. 4) [26]. In contrary to monocrystalline diamond, CVD-D consists of numerous grains. Each grain itself has an anisotropic material behaviour. Thus, the dependence of direction and material behaviour results of the texture of the diamond grains. With an increasing value of texturing level, the anisotropy of the CVD-D is increased.

Another material property of relevance is the modification of carbon. Carbon has the modification of thermodynamic stable graphite and metastable diamond, whilst diamond is the modification of higher strength. Both can be present at samples parallel to each other. They can be measured by hybridisation, which is the electron modification. The relevance is given, as in case of CVD-D, the resistance of crack propagation can be determined by the grade of hybridisation of CVD-D [17]. The hybridisation of carbon can be measured via Raman spectroscopy [13,22,27]. Herein, diamond can be detected by a local peak at a so-called D-band, which is at a wavenumber $\omega = 1332$ cm$^{-1}$ and representative for the sp$^3$ hybridisation [26]. Other possible forms are the sp$^2$-hybridised carbon (graphite) and a mixture of sp$^2$ and sp$^3$ in an amorphous metastable form [24]. The sp$^3$-hybridised carbon can be detected by two local peaks, one at $\omega = 1340$ cm$^{-1}$ and one at $\omega = 1550$ cm$^{-1}$, which are called G-bands. One cause for the presence of a G-band on CVD-D is given by imperfections due to the CVD process and the used gas concentration. E.g. Methane (CH$_4$) is commonly used as a gas for the chemical deposition. The concentration of Methane has an influence on imperfections, which are increased with an increasing concentration, and subsequently leads to presence and intensity of a G-band at $\omega \sim 1550$ cm$^{-1}$ [17].

The results show that the grades A and C have fully sp$^3$-hybridised carbon (diamond) (see Fig. 5, right side), as one distinct peak at a wavenumber of 1333 cm$^{-1}$ was observed [3]. A special case is grade B, in which a small level of sp$^2$ was measured. The surface of grade B can be described as isles (nuclei) and valleys (area between the nuclei, see Fig. 5, left hand side, central SEM-picture). Conducted measurements of the isles revealed a distinct peak at $\omega = 1333$ cm$^{-1}$ and a broad band at around $\omega = 1500$ cm$^{-1}$. This proves the presence of sp$^2$ on the isles, whereas sp$^3$ was measured in the valleys.

4.2. Wear mechanism: adhesion

The wear mechanisms of CVD-D are adhesion, abrasion and surface fatigue [17]. Subsequently, the samples were investigated in order to evaluate a dominant wear mechanism and to evaluate, whether the varied process parameters have an influence on the wear mechanism.

Adhesion occurs at high temperature and pressure, and leads to a deposition of machined material on the cutting edge. Adhesion is prone to be the dominant wear mechanism when machining ductile materials such as aluminium alloys. However, Linke et al. observed adhesion wear in dressing of brittle vitrified bonded corundum grinding wheels [21]. They detected deposits of bond material on the CVD-D dressing tools. EDX measurements of the cutting edges carried out in this investigations show a maximum of 4 wt% aluminium as well as oxygen on the rake face in case of $r_e = 0.3$ mm, $v_{rel} = 15$ m/s. This result is presented in Fig. 6. The detection of gold is caused by the treatment prior to the SEM investigation, in which gold was sputtered on the samples. Enhanced quantity of material was, therefore, not observed. This can be explained by the cutting speed, which is in this investigation...
comparably low. The relative speed of this investigation was in maximum 25 m/s, whereas the cutting speed of the grinding wheel, within the investigation of Linke et al. was 63 m/s. Therefore, adhesion is not a dominant wear mechanism in this study.

4.3. Wear mechanism: abrasion

Another wear mechanism is abrasive wear, which was, e.g., detected by Denkena et al. in a previous study and found to be the dominant wear mechanism of CVD-D [9]. This study includes a comparison of different cutting materials in regard to their wear behaviour when dressing a bronze bonded CBN grinding wheel. However, scratches of the grinding wheels abrasive grains were not found on the cutting edges of the CVD-D inserts in this study, which can be seen exemplarily in Fig. 6. Such scratches on the worn surface of the CVD-D would be evidence for an abrasive wear mechanism, which can, therefore, be excluded. This can be explained by the significantly higher hardness of diamond compared to corundum. The variation of relative speeds, radii as well as CVD-D grades had no influence on the occurrence of the fatigue fracture lines. Subsequently, the dominant wear mechanism is detected as fatigue failure, while other wear mechanisms can be excluded. Thus, a change of wear mechanism is not a reason for the different wear extension.

4.4. Wear mechanism: graphitisation

In order to identify a possible change in carbon modification, Raman spectroscopy was also conducted on the worn surfaces (see Fig. 7). A graphitisation is a change in modification that leads to a reduction in strength. Herein, the grades A and C have local peaks at $\omega = 1545$ cm$^{-1}$ (grade A) and $\omega = 1457$ cm$^{-1}$ (grade C), which are low in intensity and broad over a range of wavenumbers. The value of $\omega$ in case of grade C is rather low to be a G-band. This can be misinterpreted as a peak for nanocrystalline diamond. That however, has
two peaks. One is at $\omega = 1460 \text{ cm}^{-1}$ and a second is at $\omega = 1140 \text{ cm}^{-1}$, which is not observed here. Stresses and defects can have an influence on the position of $\omega$ of the G-band [5,23]. This was investigated already on diamond and $\omega$ values of $\sim 1440 \text{ cm}^{-1}$ were observed and rooted to be sp$^2$ hybridised carbon with defects [11]. Subsequently, the outlined bands show a slight increase in sp$^2$ for grades A and C, which can be explained by graphite related structures of the worn surface. Graphitisation is excluded, however, as a wear mechanism of a major extension, especially as the worn surface appears not as graphitized. This G-band was not observed on grade B, so that the surface of grade B has full sp$^3$ hybridisation. In all cases investigated, the worn surface is, therefore, diamond. An increase in relative speed had no influence on this.

4.5. Wear mechanism: surface fatigue

By SEM micrographs of the samples after the tests, a dominant wear mechanism of surface fatigue was identified. This mechanism is expressed by fatigue fracture lines in the diamond crystals and is consistent over all tested cutting edges and CVD-D grades. Fig. 8 illustrates the worn surfaces of the three grades with the corresponding fatigue fracture lines. The results of 4.2-4.4 reinforce this result, as no other wear mechanism is found to be dominant.

The quantitative wear was measured as a radial reduction of the structuring tool $\Delta r$. The results are shown in Fig. 9. The grade A has overall the highest wear levels. The grade B has the lowest values and reduces the wear by 65% compared to grade A. The results also indicate, that the relative speed has not a significant influence on the wear extension, within the investigated range, as shown in Fig. 9 on the left side. The wear values of grade B and C increase slightly with increased relative speed, while grade A remains on a high level of wear, compared to the other grades. This different behaviour of A however, can be rooted to the high extension of wear, as the depth of cut was 60 $\mu$m. Therefore, the wear extension of grade A is higher than the corresponding depth of cut, which indicates a brittle wear behaviour that causes major-sized fractures.

The corner radius, however, has an influence in that way, that the small radius of 0.1 mm had the highest wear values. By increasing the corner radius, the wear extension was reduced. The samples were all investigated after $N_p = 5000$, independently of the width of one structure, which increases with increasing corner radii. Bigger radii have a higher dressing grain collisional number, as more grains are be machined with increasing width per pattern [20]. Subsequently, the load on the insert is higher. The results indicate that an increased strength of cutting edge is, however, advantageous. The reason for this is the optimised load distribution within the diamond. The influence of the used grade shows, that grade A had the overall highest wear extensions, while grade B had constant low values.

As the wear mechanism surface fatigue is of internal, sub-surface nature, the internal condition of diamond is of relevance, i.e. the texture. The pole figure of grade A shows, that the minor cleavage direction is orientated normal to the surface in a significant extension (see Fig. 4). In the application of patterning, the interaction of CVD-D and the grinding wheel leads to a mechanical load in normal direction to the rake face. Thus, the load is almost in the same direction as the minor cleavage direction of texture of the CVD-D. The direction of load changes, however, as the wear progresses, so that other crystal directions may be loaded as well. Diamond has symmetry equivalent lattice planes, which can be seen in case of grade A, by the circle (see Fig. 4). In this way, a tilted load on the fibre textured grains leads to an increase in wear. The grades B and C have a significantly reduced texturing level compared to grade A. The maximum value is 5.5 MRD (multiples of a random distribution, grade B) and 3.9 MRD (grade C). Grade A has a value of 27.7 MRD. In this way, the grades B and C have less crystals orientated in the preferred cleavage direction [111]. In combination with the quantitative wear extension, the results indicate that a higher level of texture leads to a higher wear. Lower texturing levels have lower wear extensions.

5. Conclusion and outlook

The wear mechanisms of CVD-D in the application of patterning of vitrified corundum grinding wheels was investigated within this paper by an experimental investigation. Therefore, the relative speed of grinding wheel and patterning tool, the radii and the grade of CVD-D was varied. 5000 patterns were machined per sample, which equals an average patterning process of one grinding wheel. The relevant relative speeds in the patterning process were calculated by a scenario method.
Measurements of the samples prior and posterior to the test were conducted with SEM, X-ray diffractometry and Raman spectroscopy. By the SEM measurements it was possible to show the different surface properties of the CVD-D grades and that they do not have an effect on the wear mechanism. The direction of CVD-D growth had also no effect.

Fatigue fracture lines were found on all investigated samples, indicating that the wear mechanism was surface fatigue. As this mechanism is of intergranular nature, the internal orientation of diamond crystals, i.e. the texture was investigated by X-ray diffractometry. A fibre texture was found on all samples, while grade A had a highly distinct texture compared to the lower MRD values of grade B and C. The minor cleavage direction of diamond [110] was normal to the rake face. This was found to be a cause for the high wear values of grade A. Raman measurements underlines the dominance of the wear mechanism surface fatigue, as graphitisation was excluded to be a dominant wear mechanism.

The relative speed was of minor influence on the wear extension. However, the influence of the radius was determined in that way that the bigger the radius the smaller the wear. Smaller radii had smaller mechanical load within the test, as the width of cut was increased with increasing radii, while the number of patterns Np and the depth of cut ap was kept constant. In that way, bigger radii rε had a higher mechanical load. The increased strength, however, was superior.

In further studies, the influence of the patterns on profile creep feed grinding process will be investigated. Initial results can be seen in a first publication [10].

Fig. 8. SEM micrographs of samples with determined wear mechanism of fatigue failure.

Fig. 9. Quantitative wear results of the three CVD-D grades.
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