Self-sharpening-effect of nickel-diamond coatings sprayed by HVOF

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Abstract. The durability of stone working and drilling tools is an increasingly significant requirement in industrial applications. These tools are mainly produced by brazing diamond metal matrix composites inserts to the tool body. These inserts are produced by sintering diamonds and metal powder (e.g. nickel). If the wear is too high, the diamonds will break out of the metal matrix and other diamonds will be uncovered. This effect is called self-sharpening. But diamonds are difficult to handle because of their thermal sensitivity. Due to their high thermal influence, manufacturing costs, and complicate route of manufacturing (first sintering, then brazing), there is a great need for alternative production methods for such tools. One alternative to produce wear-resistant and self-sharpening coatings are thermal spray processes as examined in this paper. An advantage of thermal spray processes is their smaller thermal influence on the diamond, due to the short dwelling time in the flame. To reduce the thermal influence during spraying, nickel coated diamonds were used in the HVOF-process (high velocity oxygen fuel process). The wear resistance was subsequently investigated by means of a standardized ball-on-disc test. Furthermore, a SEM (scanning electron microscope) was used to gain information about the wear-mechanism and the self-sharpening effect of the coating.

1. Introduction
Stone working and stone drilling tools are extremely highly charged during use. Hence, only the hardest materials can be used for this field of application. Generally, diamond impregnated inserts or diamond reinforced tools are used for this purpose as diamonds are the hardest known material. For industrial applications, synthetic diamonds are used due to the costs of such tools. Synthetic diamonds can be produced with different processes such as the high temperature high pressure synthesis (HPHT), which is the most widely used process for this task. HPHT uses high temperatures and high pressures to produce diamonds from a carbon-rich melt. Metals such as Fe, Co, or Ni can be used for this process [1]. Furthermore, thin diamond coatings can be applied by means of CVD (chemical vapour deposition) [2], whereas detonation and ultrasonic methods [3] are more alternative techniques.

To obtain a tool or tool insert that can be used for stone processing, non-coated diamonds are not suitable, due to their high brittleness and the fact that there are no contouring possibilities. Normally, the diamonds are mechanically embedded into a metal matrix. These diamond metal matrix composites (MMC) are used for tools or tool inserts. The production of diamond MMC tools is mainly divided in two process routes. The first route is the production by means of powder metallurgy during which the diamonds are sintered with a metal powder. This method is mainly used for solid diamond MMCs or diamond inserts. The processing of synthetic diamonds is a challenge, because of the thermal sensibility of diamonds [4]. At high temperatures, the diamonds can react with their metal matrix, which leads to graphitization effects that damage the surface of the diamonds [5].
Long sintering times combined with long holding times in the presence of metallic matrix lead to uncontrolled solution reactions, dissociation, or degradation of the diamonds, which subsequently affects the life span of the tools. Because of these effects, fast sintering methods become more interesting [6].

The second main processing route of diamond MMC is based on brazing methods. Brazing pastes, impregnated with diamonds, can be applied on large components to form a closed, diamond impregnated coating. Furthermore, pick-and-place techniques allow to braze diamonds onto defined positions. For this purpose, active elements have to be used to achieve a wettable surface [7]. The yielded temperature has to be controlled as well to reduce thermally induced damages of the diamonds during brazing.

The deposition of diamond reinforced coatings by means of different thermal spraying processes has already been investigated in numerous studies [8-10]. Especially, thermal spray processes that use moderate to high kinetic energies and low to moderate thermal energies were used. The aim was to minimize the thermal influence during the coating process. Two processes are particularly suitable: The detonation spraying process (CD-gun) provides for large diamonds within a softer matrix such as aluminium or bronze [8]. The high velocity oxygen fuel (HVOF) process proves to be the suitable process for fine diamonds with a thin metallic coating (e.g. nickel) [11]. Additionally, the tribological wear behavior was investigated. Diamond reinforced coatings, deposited by means of flame spraying and detonation spraying process, were applied to improve the wear behavior [8] [12].

This paper scrutinizes the wear mechanisms of diamond reinforced coatings, produced by means of HVOF. Especially the self-sharpening effect of the coating that occurs when worn out diamonds break out and new sharp diamonds are exposed or which result from a partial breaking or cracking of the diamond [13], is investigated.

2. Experimental

2.1 Thermal spray processes
For this study, round specimens (diameter 40 mm, thickness 8 mm) made from 1.2249 (45CrSiV6) serve as substrates. The preparation was conducted with corundum (type EKF 100) with a grain size of 100 – 150 µm. The blasting parameters are a distance of 100 mm with an angle of 45° and a pressure of 4 bar.

The spray equipment used for the experiments was a high velocity oxygen fuel (HVOF) system type CJS K5.2 by Thermico GmbH & Co KG (Dortmund, Germany). This system uses the energy of a continuous combustion of an oxygen-fuel mixture to melt the powder feedstock material. The powder is injected behind the combustion chamber by a powder feeder (Thermico GmbH & CO. KG, type CPF 2). Table 1 summarizes the spray parameters. The parameters are composed of optimized parameters for nickel coatings, generated during former investigations. The parameters for the application of diamond reinforced coatings were tested in former research projects [14].

| Parameters               | Value         |
|--------------------------|---------------|
| Oxygen                   | 800 l/min     |
| Hydrogen                 | 60 l/min      |
| Kerosene                 | 14 l/h        |
| Feeder gas (Nitrogen)    | 10 l/min      |
| Feed rate                | 50 g/min      |
| Gun movement             | 17.500 mm/min |
| Stand-off distance       | 250 mm        |
| Distance between each path | 5 mm         |
The spray gun was handled by a 6 axis robot type IRB 4600 2.05 m (ABB Automation GmbH, Zürich, Switzerland).

![SEM image of an embedded diamond in a nickel matrix](image.png)

**Figure 1.** SEM image of an embedded diamond in a nickel matrix [14].

For this study, monocrystalline nickel coated synthetic diamonds type CM-M Ni 60 supplied by Ceratonia GmbH & Co. KG (Eltmann, Germany) were used to produce the diamond reinforced coatings. Figure 1 shows a SEM image of Ni-coated diamonds that serve as feedstock. For this study, blocky-shaped diamonds were used. The diamonds exhibit an average grain size of 10 µm (8 µm to 12 µm). The feedstock is composed of 60 wt. % of Ni.

### 2.2 Wear resistance tests

To obtain information about the wear-mechanism of the produced diamond reinforced coatings, a standardized ball-on-disc test was used (ASTM G99 [14]). A tribometer (Pin-Disc Machine) by CSEM Industries (Neuchâtel, Switzerland) was used to conduct tests with a constant radius of 15 mm. The parameters of the ball-on-disc test are summarized in table 2.

| Parameters     | Value     |
|----------------|-----------|
| Rotation       | 120,000 U |
| Counter body   | Al2O3     |
| Load           | 10 N      |

**Table 2.** Parameters of the ball-on-disc tests.

To gather information about the wear coefficient, the volume of the wear track was measured. The wear coefficient ($k_{wear\,track}$) results from the volume of the wear track ($V_{wear\,track}$) divided by the load (F) used for this test, multiplied by the total distance of the rotation (s). The volume of the wear track was measured with a 3D-profilometer type InfiniteFocus (Alicona Imaging GmbH, Graz, Austria). The InfiniteFocus is able to visualize the surface of the specimen in a 3D model.
The volume of the wear track ($V_{wear\ track}$) results in an area of wear, multiplied by the circumference ($u_{wear\ track}$).

$$V_{wear\ track} = A_{wear} * u_{wear\ track}$$

Furthermore, the ball (counterpart) was investigated and a 3D image of the ball was created to visualize the wear of the ball. This image was used to determine the volume of the worn out parts of the ball ($V_{wear\ ball}$), which results in:

$$V_{wear\ ball} = \frac{\pi * h_{wear\ ball}^2}{3} * (3 * r_{ball} - h_{wear\ ball})$$

The height of the worn out part of the counterpart $h_{wear\ ball}$ is determined by

$$h_{ball} = r_{ball} - (r_{ball}^2 - r_{wear\ ball}^2)^{1/2}$$

The wear coefficient of the counterpart ($\kappa_{wear\ ball}$) is calculated similarly to the wear coefficient of the track, by the volume of the wear of the ball ($V_{wear\ ball}$) divided by the load (F) used for the test, multiplied by the total distance (s).

$$\kappa_{wear\ ball} = \frac{V_{wear\ counterpart\ [mm^3]}}{F\ [N] * s\ [m]}$$

2.3 Surface analysis

One of the main objectives of this study is the analysis of the wear mechanism of the diamond reinforced coating, with a special focus on the self-sharpening effect of the coating. Therefore, the wear track was investigated in the SEM (scanning electron microscope) after the wear tests. For this study, a SEM type JSM 70 1F (Jeol GmbH, Freising, Germany) was used. A 3D model was created to receive a more precise image of the surface of the specimen. This model was created by taking three images with a slightly different angle (0° and +/- 5°) that were subsequently interpolated to a 3D model with the help of the software InfiniteFocus.

3. Results and discussion

3.1 Wear resistance tests

Figure 2 shows a cross-section image of the diamond reinforced coating. It shows the substrate, made of 1.2249, the coating, and the embedding resin in the upper section of the image. The diamonds are spread homogeneously in the coating. The image also shows an average coating thickness of 230 µm. The interface exhibits no slots between the coating and the substrate, which indicates a good bounding of the coating to the substrate.
Ball-on-disc wear tests were applied to the coating of the substrate. Table 3 summarizes the comparison of the wear coefficients of two different coating systems compared to the substrate without any coating. For the comparison a WCCo 88/12 coating, deposited by means of HVOF was used. As WCCo is a standard coating used for wear protection [8] it was used for the comparison with the diamond reinforced coating.

Table 3. Wear coefficients of the specimens.

| Specimen                        | Wear coefficient $\kappa_{wear\ track}$ | Wear coefficient counterpart $\kappa_{wear\ ball}$ |
|---------------------------------|-----------------------------------------|--------------------------------------------------|
| Substrate 1.2249                | $3.56\times10^{-3}$ mm$^3/(N*m)$        | Not measurable                                   |
| Diamond reinforced coating      | $1.668\times10^{-5}$ mm$^3/(N*m)$        | $1.809\times10^{-6}$ mm$^3/(N*m)$                |
| WCCo coating                    | $0.1614\times10^{-5}$ mm$^3/(N*m)$       | $0.01861\times10^{-6}$ mm$^3/(N*m)$              |

The results are averages from three different measurements. Table 3 shows that the diamond reinforced coatings increase the wear resistance when compared to the substrate and the wear coefficient gets close to regions of WCCo 88/12 coatings. The wear coefficient of WCCo coatings is the lowest in this comparison. This could be explained by the smaller carbides of the WCCo coatings, which are finely spread in the coating. The matrix material cobalt, is harder when compared to nickel, the matrix material of the diamond reinforced coatings. Whereas the matrix material of the diamond reinforced coating will wear out faster than the matrix material of the WCCo coating.

Table 3 also shows the wear coefficients of the counter body. The ball, used for the wear test of the substrate, indicates no wear. The comparison of the coefficients of the two different coatings reveals some differences. The wear coefficient of the diamond reinforced coating is higher than the coefficient of the WCCo coating. Due to the lower hardness of the counterpart made of Al2O3 (about 1800HV [16]), the counterpart wears out fist. The harder diamonds cause a high mass loss on the counterpart by cutting the Al2O3 from the ball. This can be seen as a first evidence for an outstanding abrasive behavior of the coating.
3.2 SEM analysis
The SEM was used to investigate the wear mechanism of the diamond reinforced coating. It was the aim to investigate if a self-sharpening effect of the coating does exist.

Figure 3. SEM image of the diamond reinforced coating.

Figure 3 shows the worn surface of the diamond reinforced coating after the wear test. Several diamonds stick out the surface. These diamonds were located in the track of the ball-on-disc test. Besides two almost uncovered diamonds, a third diamond is visible. This diamond is almost completely covered by a nickel coating. This observation can be seen as another evidence for the self-sharpening effect of the coating. A 3D model was generated to gain more information about the topography of the surface and the diamonds in the coating.

Figure 4. 3D-model of the diamond coating.

Figure 4 shows a SEM 3D model of the wear track with some exposed diamonds on the surface. The diamonds stick out the surface and cause, despite the high hardness of the Al2O3, a high abrasive wear on the surface of the ball. The ball further causes wear on the surface of the coating. It can be seen that the matrix metal is worn out and diamonds can be found in different depths. If the wear is high, the nickel matrix will first dig out. The initial state of this mechanism is visible in Figure 4. Between the diamonds, trenches are formed. Consequently, some diamonds will drop out or break out of the
surface. This effect exposes new diamonds with a new sharp contour. The new, sharp diamonds verify the initial hypothesis of the self-sharpening effect of diamond reinforced coatings.

4. Conclusion
HVOF-sprayed, diamond reinforced coatings were tested with a ball-on-disc device according to ASTM G99. Subsequently, the volume loss was measured and the wear coefficient was calculated. The results show that the wear coefficient of the coating is extremely low in comparison to that of the uncoated specimen. However, the Al2O3 counterpart shows a higher wear coefficient compared to that of other coatings. It was shown that the matrix metal is removed and that the diamonds stick out of the surface. Consequently, this effect will lead to a drop out of diamonds and new diamonds are exposed. This effect can be labelled a self-sharpening effect of the diamond metal matrix coating. To obtain more information about the wear mechanism and the self-sharpening effect, the experiments should be further expanded. Therefore, experiments with a tribometer in a great chamber SEM are planned. This method allows an in-situ observation of the occurring mechanisms.

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