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Diamond-Bronze Coatings for Grinding Applications

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Grinding applications for the machining of stone and concrete require composite tools where large diamonds are perfectly embedded into a metallic matrix. With the detonation flame spraying process, it is possible to manufacture these super abrasive composites. Excellent embedment of the voluminous super abrasive particles into the matrix coating material can be realized to produce high quality composite layers for grinding applications of stone and concrete. In this paper, different diamond gradings as well as different volume contents of diamond in matrix are compared. Especially, the influence of particle size on its implantation efficiency is investigated and the influence of process and substrate temperature is analyzed. The thermal sprayed grinding tools are evaluated with respect to their microstructure as well as their grinding abilities. Compared to sintered diamond-bronze samples, the results of an adaptively designed grinding test for the machining of concrete are presented and analyzed.

Keywords detonation spraying, diamond-bronze, grinding tool, superabrasive composite, substrate preheating

1. Introduction

Diamond-based grinding tools are typically used for the machining of stone or concrete. Due to the high hardness and abrasiveness of the machined minerals, metal-bonded composites provide the best performance. Sintering, brazing, and electroplating are the main technologies for the industrial production of these metal-bonded diamond tools (Ref 1-4).

But sintering as well as brazing is characterized by a high procedural effort and a lot of production steps (Ref 5). Complex component geometries cannot be accomplished and the repairing of worn out grinding tools is usually neither possible nor economically justifiable. Detrimental effects on the environment mainly restrict the electroplating process (Ref 6).

Thermal spraying as an alternative production method has not yet been established. But the possibility to produce complex-shaped tools and to repair damaged surfaces is of high technological interest. Minor procedural complexity and fewer production steps characterize the coating process. Furthermore, it allows a production of the tool under atmospheric environmental conditions. Additionally, the spraying process is fast and custom-made products can be produced easily. No additional production-tool costs (e.g., pressing molds) are necessary to change the grinding tools design. Summarized, detonation flame spraying has an interesting potential for producing these super abrasive coatings.

However, the manufacturing of diamond composite layers by means of thermal spraying presents some challenges which need to be scientifically investigated. For example, diamonds are quite temperature-sensitive. In oxygen atmosphere, they react at elevated temperatures to graphite, carbon monoxide, and carbon dioxide (Ref 7-12). Therefore, the coating process has to ensure a low thermal influence induced into the sprayed diamonds.

If grinding tools for the machining of mineral materials are supposed to be produced by thermal spraying, the desired hard material has to be perfectly embedded in the metallic matrix. Additionally, it is to be assured that the diamond is distributed homogeneously within the functional layer to achieve afterward a constant cutting performance during the grinding. Moreover, the manufacturing process needs to guarantee the production of dense composites without oxidizing the matrix metal and decreasing the MMC ductility.

The main challenge for the production of grinding tools by thermal spraying is the voluminous diamond particle size. A good stone grinding performance requires the embedding of diamonds with a large grain size. Depending on the grinding task and the mineral material 150-400 μm diamonds are used for sawing, cutting and coarse grinding applications (Ref 4, 12).

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Hence, the diamonds are not plastically forming or fusing with the matrix bronze form fit joints are the exclusive bonding mechanism. Form fits are generated by the injection of the diamonds displacing the matrix metal during the impact. A successful implantation of the voluminous diamonds demands the movement of a high amount of matrix material. More than half of the diamond volume is needed to be fixed after the impact.

Due to the requirements mentioned above the diamond impregnation by means of thermal spraying can only be carried out at high particle velocity and moderate spraying temperatures. Detonation flame spraying is well-suited for the application of the MMC-layers.

2. Experimental

2.1 Base Materials

Diamond and CuSn 85/15 were applied as base materials to produce composite coatings by detonation flame spraying. In order to fulfill the cutting demands for the grinding of concrete or stone the diamonds must have a certain size. Different grain sizes were investigated regarding spraying efficiency and grinding abilities (Table 1).

The diamond quality SDB 1055 (Element Six GmbH, Hanau, Germany) is commonly employed in grinding and sawing tool production. Fine nickel alloy inclusions are distributed throughout the cubo-octahedral particle due to the catalytic synthesis manufacturing process (Ref 12). Bronze powder with a grain-size of 45-90 µm (GTV GmbH, Betzdorf, Germany) was used as matrix material. SE-micrographs of a 240 µm diamond and the bronze powder are given in Fig. 1.

Table 1 Used diamond gradings (SDB 1055)

µm	U.S.-Mesh
300-420	40-50
250-300	50-60
210-250	60-70
180-210	70-80
150-180	80-100

Cylindrical C45 steel billets (1.0503) with a diameter of 16 mm and a length of 40 mm were taken as substrate. They were coated at their grid blasted tip.

In grinding tests CEM III A 42.5 N cement disks with a diameter of 105 mm and a thickness of 10 mm were machined, which were produced at the Department of Building Materials (TU Dortmund University, Germany).

To verify the results of the grinding test, sintered diamond-bronze tools of the same geometry were compared with the thermally sprayed tools. Detailed information for the production of the sintered tools is given in Ref 5.

2.2 Spraying of Diamond-Bronze Superabrasives

The investigations were carried out using a detonation flame spraying equipment (Surface Advanced Technology Inc., Warsaw, Poland). Two different powder-feeders (Elektroplasma Inc., CA, USA; Single-10C, Plasma-Technik AG, Switzerland) were used to insert super abrasives and matrix material independently. The detailed setup is described in Ref 13.

C45 substrates were grit blasted with Al_2O_3 with a grain size of 1180-1700 µm before coating. Three bar blasting pressure and a blasting distance of 100 mm in an angle of 70° result in a substrate roughness of $Rz = 73.5 \pm 8.7$ µm and $Ra = 14.4 \pm 0.9$ µm.

Before coating the substrates were heated by induction. The induction equipment (HG 3002, Himmelwerk GmbH, Tübingen, Germany) worked with a frequency of 2 MHz and a maximum power of 3 kW. The induction coil was designed with seven windings and an inner diameter of 28 mm.

With this configuration, preheating of the cylindrical steel substrates could be rapidly achieved. A temperature of 923 K (650 °C) at the substrate tip was reached in 2 min. The temperature before and during the coating process was controlled by a thermocouple, which was fixed at the tip of the steel sample right under the coated surface.

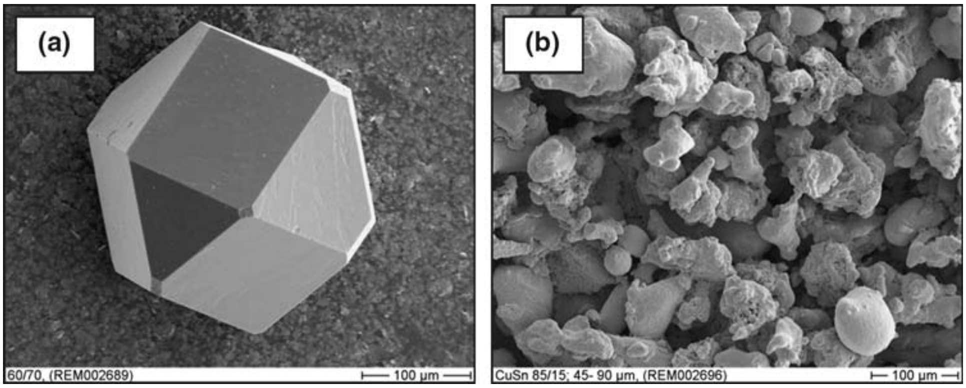

Fig. 1 SE-micrographs. (a) 240 µm diamond (SDB 1055). (b) 45-90 µm CuSn 85/15 matrix powder

It was determined, that the sample temperature deviates max. 10% during the process. Starting with 923 K, it was 863 K after coating.

2.3 Coating Characterization

Vickers hardness was measured on an universal hardness tester (Wolpert, Hahnkolb GmbH, Stuttgart, Germany) relating DIN EN ISO 6507-1. Warm hardness tests were carried out on the self-designed Vickers vacuum hardness tester of the Chair of Materials Technology (University of Bochum, Germany).

Optical microscopy (Axiophot, Zeiss, Germany) with analytic module (KS 300, Zeiss, Germany) was used to characterize the coating morphology and hard-particle content and distribution. Additionally, SEM analyses were conducted (JXA-840, Jeol GmbH, Japan).

Roughness and wear measurements on grinding pins and cement disks were carried out by 3D analysis. They were realized on an Alicona Infinitive Focus optical surface measurement system (Infinitive Focus, Alicona Imaging GmbH, Austria). Additionally, the implantation of 180-210 μm and 300-420 μm sized diamonds into metal materials with different hardness was investigated by means of 3D surface analysis. After detonation spraying, the diamonds without matrix feedstock into Pb, Al, AlMgLi, AlMg, Cu, and CuZn the diamonds were mechanically removed out of the surface. By gauging minimal 10 indentations sinks per sample the average diamond implantation depth and the volume of the displaced material was measured.

2.4 Grinding Performance Test

A grinding test was built up which assured controlled and comparable grinding parameters and results. The assembly is given in Fig. 2.

The concrete disk was rotating with 60 rpm. The pin was pressed on with a contact force of 20 N without using a lubricant or additional cooling. Grinding dust was continuously removed by an external vacuum device.

The weight loss of pin and disk was measured after a running distance of 2500, 5000, 7500, 20,000, and 35,000 m.

3. Results and Discussion

3.1 Substrate Heating

It was shown in previous works (Ref 5, 13, 14) that the implantation efficiency of impacting hard particles could be affected positively by heating the substrate material during the spraying process. For copper as matrix material, an optimum was confirmed at 623 K (350 °C). Without significantly oxidizing, the copper it was softening the layer.

Compared to pure copper the oxidation affinity of CuSn 85/15 is much lower. Respectively, the oxidation velocity at higher temperatures is decelerated. Higher process and substrate temperatures are possible without sensibly oxidizing the matrix material.

Even though the oxidation affinity of bronze allows higher temperatures, the spraying of the diamond-bronze composite is additionally affected by the temperature sensitiveness of the diamond. Mostly the diamond deterioration is induced through high process temperatures. For example, diamond reacts under high temperature in oxidizing conditions to CO_2. However, the temperature range for this deterioration varies in literature sources depending on the investigated diamond size and quality. Under atmospheric conditions the deterioration temperature of diamond differs from 773 K (500 °C) to 1273 K (1000 °C) (Ref 7-12). However, the literature sources confirm a low deterioration velocity up to temperatures of 1023 K (750 °C) (Ref 10, 15).

The durability of SDB 1055 diamonds at elevated temperatures is only known under inert conditions. Element six guarantees a thermal resistance of SDB 1055 of min. 1373 K (1100 °C) with a small reduction in the diamonds strength (Ref 12).

Although, the behavior of SDB 1055 in oxidizing atmospheres is only partially investigated no affecting

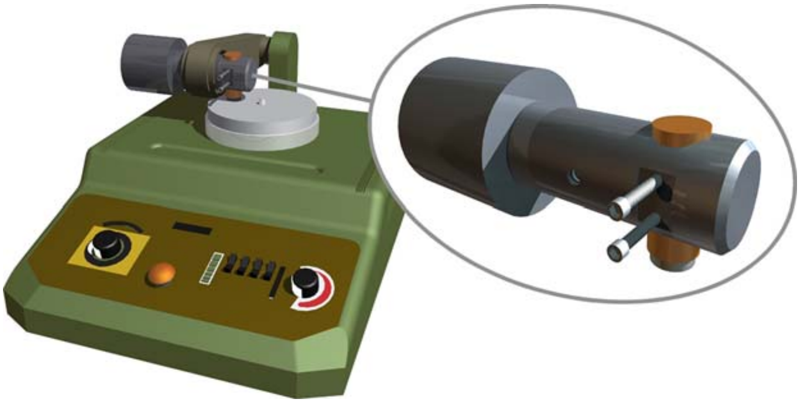

Fig. 2 Grinding test setup

deterioration can be assumed at temperatures below 1023 K (Ref 10, 15) regarding to the short thermal spraying time.

3.2 Spraying Parameter Optimization

The spraying parameters of the diamond-bronze composites were optimized by variation the oxygen and propane flow rate, ignition frequency, powder feed rates, spray distance, and preheating of substrate.

The value range is given in Table 2. Additionally, the optimal detonation flame spraying parameters are specified.

The experiments have shown that compared to copper (Ref 13), the diamond-bronze layer could be sprayed at much higher temperatures without sensibly oxidizing the matrix material. Due to higher process temperatures, the bronze-layer hardness is reduced. Hence, the implantation of the diamond particles is improving.

But if the spraying temperatures are too high, the bronze layer quality is getting affected negatively. High porosity, oxidation, and poor bonding were detected by choosing spraying parameters which are typically used for spraying ceramic materials ($O_2 = 72$ L/min, $C_3H_8 = 4.2$ L/min, $f_{\text{det}} = 2$ Hz). Furthermore, some diamond particles deteriorate and crack regarding the strong thermal influence and the shock wave of the detonation (Fig. 3).

A much better independent variable was confirmed by substrate heating and colder spraying conditions. Induction heating permitted high temperatures of 923 K (650 °C) during the spraying process. A short preheating period of 2 min reduced the oxidation of the sample. The continuous impact of matrix and diamond particles through the spraying process predominantly avoided the oxidation of the layer.

Table 2 Detonation spraying parameters for the diamond-CuSn 85/15 composites

	Parameter range	Optimized parameters
Substrate		
Material	1.0503	
Dimension, mm	Ø 16 × 40	
Sprayed material (1)		
Analysis	CuSn 85/15	
Size, µm	45-90	
Feed-rate, g/min	10-30	15
Sprayed material (2)		
Analysis	Diamond SDB 1055	
Size, µm	150-420	
Feed-rate, g/min	0.2-10	0.2
Spraying parameters		
O_2, L/min	29-72	58
C_3H_8, L/min	1.7-4.2	2.6
Deton. frequency, Hz	2-4	2
Distance, mm	100-220	100
Substrate temperature		
Pre-heating	20-650	650
During spraying	80-600	600
Others		
Layer thickness, µm	380-2200	~1300

3.3 Microstructure

The microstructure of the optimized detonation flame sprayed diamond-bronze composite is given in Fig. 4. In the cross section, it is visible that the diamonds are well embedded. Almost no voids in the layer or in the interface between the substrate and coating lead to a good bonding and durability of the composite. Further, the bronze oxidation is very low. Only few oxides were found on the bronze grain boundaries. The low porosity and homogeneity of the layer as well as the perfect mechanical embedment is more obvious in the SE-micrograph (Fig. 5). The picture shows the same section of the sample.

Even though, diamond deterioration and cracking were observed by spraying with "strong" conditions ($O_2 = 72$ L/min, $C_3H_8 = 4.2$ L/min, $f_{\text{det}} = 2$ Hz, Fig. 3) no diamond damage was detected in the coatings with optimized spraying parameters. Considering the results of previous spraying experiments with Al_2O_3-Cu and SiC-Cu (Ref 13), it was assumed that diamond cracking cannot be avoided completely due to the high pressure during the detonation

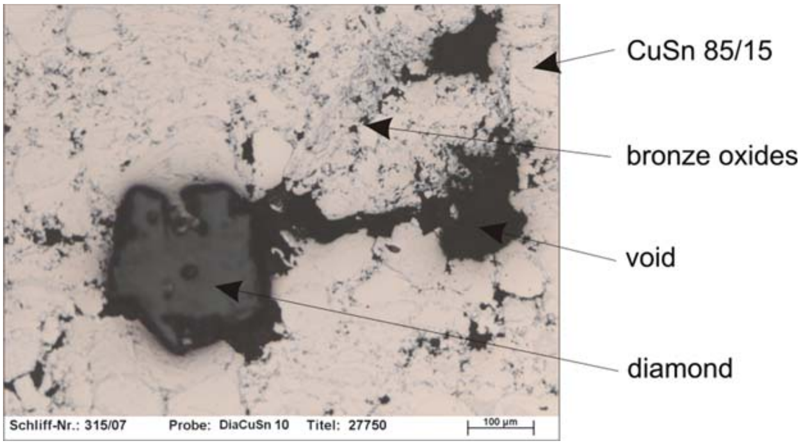

Fig. 3 Diamond-CuSn 85/15 layer before optimization

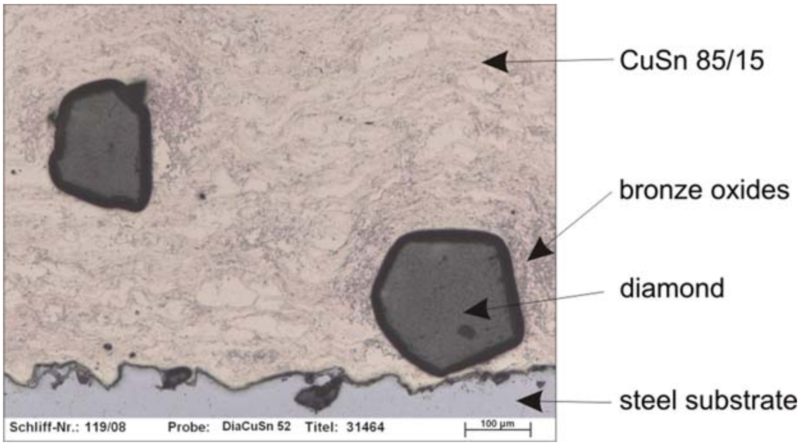

Fig. 4 Optical micrograph of detonation sprayed diamond-bronze composite after process optimization

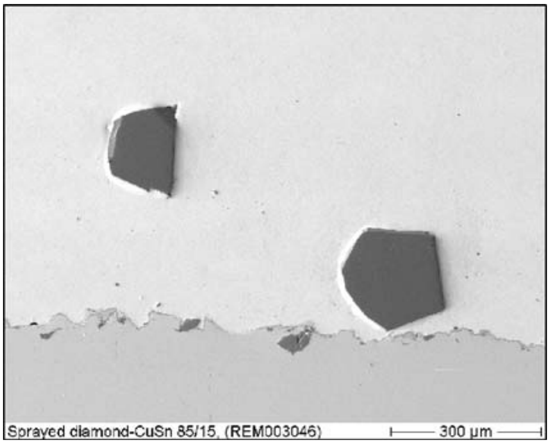

Fig. 5 SEM of detonation sprayed diamond-bronze layer

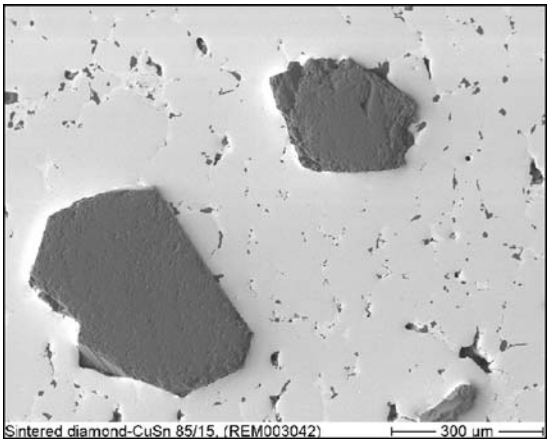

Fig. 6 SEM of sintered diamond-bronze segment

or the impact on the substrate. But due to the diamonds' higher fracture toughness compared to Al_2O_3 and SiC, smooth surface (lower notch effect), optimized spraying conditions, and substrate heating no cracking was observed in all layer cross sections.

3.4 Comparison to Sintered Composite

To evaluate the layer morphology of the sprayed composite a cross section of a sintered diamond-CuSn 85/15 segment is added (Fig. 6).

Related to the sprayed composite the sintered compound shows a higher porosity. A dense structure is useful for a good grinding performance because it provides mechanical stability. Furthermore, a low porosity increases the wear resistance and durability of the tool. In this case, the detonation sprayed composite quality is indeed better. The embedding quality of the diamond into the bronze matrix is nearly identical in both cases. No diamond deterioration or cracking was detected.

3.5 Deposition and Implantation Efficiency

High deposition efficiency (DE) is an aim of thermal spraying to reduce costs and attain economical profit. DE is strongly affected by the spraying parameters such as powder materials, particle sizes, spraying velocity, particle temperature, substrate geometry, and the substrate temperature.

3.5.1 Bronze Deposition Efficiency. Typically kinetic spraying processes show deposition rates of about 35-55% for Al, Zn, Cu, CuSn, and Ni (Ref 16-20). For the cold spraying of bronze powder, Shin et al. determined a DE of 40% (Ref 16).

Compared to cold spraying, detonation flame spraying offers analogical process velocities in a wider range of possible particle temperatures.

Without preheating the substrate material, DE for the bronze powder was verified to 47% in our experiments. With the same optimized spraying parameters (Table 2) and heating the substrate to 923 K (650 °C) during the spraying process, the DE was slightly increased to 56%.

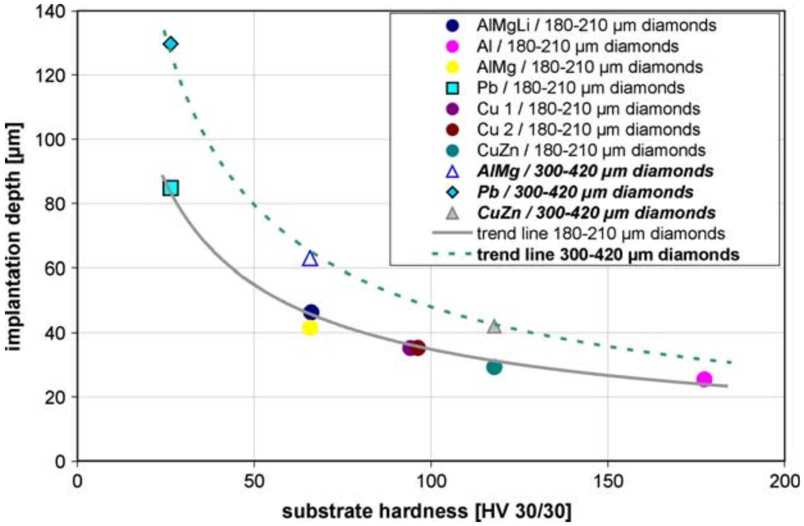

Fig. 7 Measured implantation depth of detonation sprayed diamonds into different substrate materials with dissimilar hardness

3.5.2 Diamond Implantation Efficiency. In the case of MMCs, the bonding mechanism of the hard material is entirely different to the metal matrix powder. When the process gases, propane and oxygen, are ignited in the spraying gun, the simultaneously fed bronze and diamond powders are heated and accelerated to high velocities.

During the impact of the bronze and diamond powder on the sample surface, their kinetic energy is transformed to heat and deformation of the matrix layer. Clamped bronze splats are building up the layer, whereas the hard and strong diamonds inject into it. Displacing the weaker metallic matrix, they build up form fit joints in the material. Plastic deformations of the diamonds are missing in this case. The DE of the diamonds is mainly dependent on the grain size, shape, velocity, and mass of the hard particle as well as the hardness of the matrix layer. Shin et al. confirmed a DE of max. 20% for kinetically sprayed diamond particles (5 µm) into a bronze matrix (Ref 16). Kim et al. specified the DE of uncoated diamonds with a size of 28-35 µm kinetically sprayed into Fe with 46%. For Ti-coated diamonds (53-63 µm), they determined a DE of 24% (Ref 21).

For significantly larger diamond particles, the DE is much lower. In the spraying experiments, it was identified that effective form fit joints of the cubo-octahedral diamond require the implantation of approximately half of the diamond volume. Because the surface of the diamond is very smooth, the DE decreases by an implantation depth of less than the half grain size. Under a critical injection depth of a quarter of the grain size the DE comes to zero. Impacted diamonds rebound from the substrate or are rejected during the next shock wave of the detonation.

With constant spraying parameters and diamond grain size, the depth of diamond implantation is only influenced by the hardness and elasticity of the substrate/matrix material. Figure 7 shows the implantation of SDB 1055 diamonds with a grain size of 180-210 µm and 300-420 µm diamonds into materials with different hardness. They were sprayed without substrate preheating and without bronze powder (additional parameters, see Table 2).

The experimental approach, relating the matrix hardness to the diamond implantation depth, underlines the challenge in realizing diamond-bronze composites (Fig. 7).

With a bronze hardness of 206 HV0.025/30 at room temperature the corresponding implantation depth of a 200 µm SDB1055 diamond is about 20 µm. As it was shown in the spraying experiments, it is not bonded to the matrix. Relating to the smooth surface of the diamond, the rebound rate was quantified to 100%.

By heating the sample to 923 K during the spraying process, the bronze matrix is getting significantly softer.

Because of the short time of the spraying and the high temperatures, the exact hardness for the sprayed bronze matrix could not be determined during the coating process. However, the layer hardness was measured afterward through vacuum warm hardness tests. At a temperature of 923 K, a hardness of 17 HV0.1/20 was determined.

Because of a much lower heating rate of 5 K/min in the vacuum chamber and a dwell-time of 60 min during the hardness measurements, the exposure time at high temperatures is much longer than in the real thermal spraying process. It can be assumed that reduced soft-annealing effects during the spraying lead to a bronze layer hardness of approximately 50 HV, which was deduced from the implantation results.

For sawing, cutting and coarse grinding of hard concrete material a diamond volume fraction of 10-20 vol.% in the layer is needed (Ref 4, 12, 22). But this concentration could not be achieved in our spraying experiments. By applying the optimized parameters with a 923 K heated substrate (Table 2) and a diamond powder feedstock of 0.2 g per spraying experiment, ~5 vol.% was the highest reached diamond concentration for diamonds with a grain size of 150-180 µm. The DE was confirmed to be ~3.6%.

Coherent to the implantation results given in Fig. 7, the DE and volume concentration in the layer reduced by employing diamond with larger size. For 180-210 µm diamonds, a concentration of ~2.7 vol.% was verified in the layer. With a feedstock of 0.2 g diamonds, the DE was calculated to be ~1.7%.

For 250-300 µm diamonds, a volume concentration of ~1.6% and a DE of ~0.9% were determined. Even with optimized detonation spraying parameters (Table 2) and sample heating of 923 K, the diamond implantation was limited to the size of 300 µm. For the larger grading of 300-420 µm only a small amount of diamonds could be detected in the coating.

Experiments with a diamond feedstock of 1 g showed nearly the same diamond quantity in the layer. For instance the volume concentration of diamonds in the coating was confirmed to be 3 vol.% for 180-210 µm diamonds. Due to the higher amount of feedstock material the DE was ~75% lower in this case.

3.6 Grinding Tests

The grinding performance of the diamond-bronze layers was verified in grinding tests. Detonation sprayed diamond-bronze composites with diamond gradings of 180-210 µm and 250-300 µm were compared to a detonation sprayed pure bronze layers and to sintered diamond-CuSn 85/15 tools (diamond size, 300-420 µm, Ref 5, Fig. 8).

As expected, the pure bronze layers had no grinding abilities (Fig. 8a). Hence, the wear of the CuSn 85/15 coated pin is much higher than the wear of the concrete disk.

With a diamond content of 2 vol.%, the grinding performance was improved (Fig. 8b). The mass loss at the sprayed composite layer reduces to more than 50% compared to the bronze layer without reinforcement.

By employing 3 vol.% diamonds, the grinding pin wear was further reduced (Fig. 8c). Although diamonds with smaller sizes (180-250 µm) were used in these tests, the concrete disk wear remains almost the same.

In Fig. 8(d), the grinding result of the sintered pin is exposed (Ref 5). A typical grinding composite with 10 vol.% SDB 1055 diamonds of 300-420 µm in CuSn 85/15 was used.

The higher amount of diamonds results in significant lower wear rates of the grinding tool. But in relation to the sprayed grinding tools, the machining performance on cement remained almost the same.

4. Conclusion

In this research work, it was confirmed that the hardness of the matrix material has a big influence on the

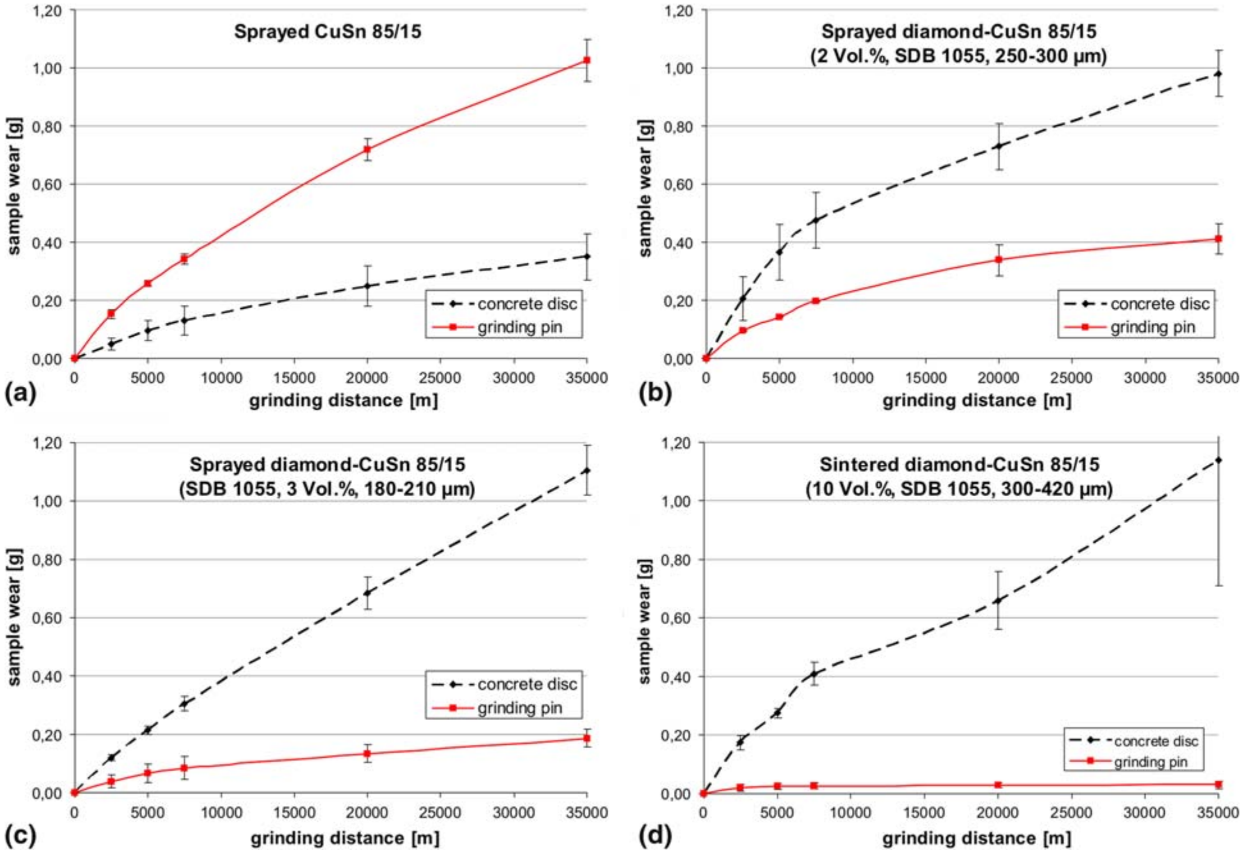

Fig. 8 Results of cement grinding. (a) Detonation sprayed CuSn 85/15 (Ref 5). (b) Detonation sprayed CuSn 85/15 with 2 vol.% diamonds (250-300 µm) (Ref 5). (c) Detonation sprayed CuSn 85/15 with 3 vol.% diamonds (180-210 µm). (d) Sintered CuSn 85/15 with 10 vol.% diamonds (300-420 µm) (Ref 5)

implantation rate of impacted diamonds. Substrate heating during the spraying process is necessary to soften the matrix material and to increase the implanting efficiency. The optimal substrate and matrix material temperature is therefore a compromise of bronze oxidation velocity and rate, as well as of diamond deterioration temperature. For this spraying setup, a substrate temperature of 923 K (650 °C) provided the best conditions.

With the employed experimental setup and substrate preheating diamond implantation was successful for particle sizes of 150-300 μm. The highest DE was reached with the smallest diamond grading (150-180 μm), which was determined to ~3.6%. It was figured out, that the DE decreases significantly for larger diamond sizes. Even with a diamond size of 180-210 μm the DE reduces to ~2.7%. Above a critical diamond size of 300 μm, the implantation into CuSn 85/15 was not possible. Additionally, it was observed that nearly the same amount of diamonds was implanted no matter whether a diamond feedstock of 0.2 or 1 g was used. This effect indicates the interaction of the diamonds during spraying. Impacting diamonds collide with injected diamonds on the tools surface and rebound or partially dissolve implanted particles.

The sprayed layers showed a dense structure. Excellent embedment of the voluminous diamonds into a bronze matrix was achieved leading to high quality composite layers. Furthermore, diamonds are not damaging during the detonation spraying process or in the heated layer.

Compared to sintered diamond-CuSn 85/15, the microstructure of the sprayed composites gave comparable results in diamond bonding quality and composite density. Only the bronze oxidation was slightly higher in the sprayed layers. The convenience and flexibility of the detonation spraying process coupled with the excellent layer microstructure and promising machining performance results indicate the future potential of sprayed diamond-bronze grinding tools.

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