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ORIGINAL PAPER

Experimental study on manufacturing of vacuum-brazed grinding tools with diamond grains

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Abstract
This work provides an experimental study on manufacturing methods for vacuum-brazed diamond grinding for edge machining of carbon fiber-reinforced polymers (CFRP). Therefore, various methods for applying active brazing alloys and diamond grains were investigated. The application methods were evaluated regarding practicability and the possibility of automation. Additionally, the samples were examined after vacuum brazing and brazing results were compared concerning method, amount and type of brazing alloy, diamond grains and binding agent. It was found that the best results could be achieved by using fluidized bed coating for diamond application and a brazing alloy containing a 15% binding agent. The method and brazing alloy were then used to produce cylindrical mounted points for grinding tests. It was possible to show that vacuum-brazed tools performed as good as commercially available electroplated tools.

Keywords Vacuum brazing · Cutting tools · CFRP · Carbon fiber-reinforced polymers · Brazing diamond · Grinding

1 Introduction

Although carbon fiber-reinforced polymer (CFRP) components are ideally manufactured with near-net-shape geometry, machining processes are typically used for post-processing. An essential process is trimming, where burrs and protruding fibers are removed from the edges to provide the defined shape of the workpiece [1]. In edge machining, diamond abrasive cutter [2] or mounted points for grinding are often employed. Currently, these cutters are produced using electroplating processes [3]. However, these methods are no longer desirable due to their high environmental impact and the risk to workers caused by aggressive chemicals. Another disadvantage electroplating faces is that a grain protrusion of only 40–50% of theaverage grain size can be manufactured, leading to a small grain volume that can be used for cutting [4]. Therefore, alternative processes need to be established to produce these tools. Vacuum brazing is a viable option that could enable an environmentally friendly manufacturing process. The brazing of diamond tools is especially possible since undesired graphitizing of the diamond at high temperatures can be significantly reduced by using a vacuum. Poor wetting characteristics of diamonds can be addressed by using active brazing alloys [5]. A challenge this new manufacturing process encounters is finding a way to automate the application of filler metal as well as the cutting material. Currently, this is done by hand. Even though there have already been investigations on vacuum brazing of diamond tools [6], they rarely focused on applying filler metal and cutting material. Only Burkhard et al. investigated such methods and invented a process using micro-dosing of adhesive for the exact distribution of diamond particles [7]. However, the method is expensive and slow because each drop is applied individually and thus is not suited for a large number of tools. Therefore, this is still an immense research gap since correct application, on the one hand, and suitable methods for automation, on the other hand, are the enabling factors for the breakthrough of this technology.

This paper shows an experimental study on preparing diamond mounted points for grinding CFRP. The study's objective was to identify a suitable method for the application of brazing alloy and cutting material that can be applied in an automated manufacturing process. Therefore, experiments were carried out using different methods for applying the filler metal and diamond grain. Additionally, the

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type and amount of filler metal, diamond grain size, cutting material, and tool body material varied. The most promising method was used to manufacture samples for conducting grinding tests. The results were compared with commercially available tools.

At the end of this paper, the following questions will be answered:

- *Which method is generally suitable for applying filler metal and cutting material to the tool body and can easily be automated?*
- *Which application method shows the best results after vacuum brazing, and what are the influencing factors (filler metal composition, grain size, application method)?*
- *What are the differences between vacuum-brazed and electroplated tools regarding the workpiece's tool life and surface quality?*

2 State of the art

The grinding of CFRP is a highly investigated topic in engineering. Wang et al. investigated, what are the main influences of grinding CFRP with an industrial robot. They showed that the main influences are the rotation speed, the direction, and the mesh size of the grinding heads. The surface quality will decrease if the grain size is unsuitable for the process. However, in general, the tests showed that high-speed grinding of CFRP is suitable to improve the surface quality of the workpieces [8]. However, some things could still be improved in the grinding of CFRP. This material is considered difficult to machine [9]. Damages in cutting CFRP have a wide range of possibilities. It starts with the fibers with only partially cut fibers and goes further to breakage and fracture of carbon fibers or a fiber pullout. However, it is also possible that the matrix gets flowed, cracked, or softened [10]. Also, a challenge is the significant tool wear. Gao et al. reviewed different ways and promising technologies to reduce tool wear. There are different possibilities with ultrasonic vibration-assisted machining and different cooling concepts with cryogenic cooling and minimum quantity lubrication. They concluded that ultrasonic vibration reduces the tool forces the most while cryogenic cooling reduces the temperature the most. Another way to improve the quality of the cutting area is with the help of an improved tool [11]. This approach was conducted in this paper. Tools for trimming CFRP workpieces are usually electroplated mounted points. Due to good heat dissipation, those tools use diamonds as cutting material and nickel-based galvanic bonds [3]. As stated in the introduction, this kind of mounted point is limited in grain protrusion. Therefore, research for the brazing of diamond tools has been ongoing.

Due to the poor wettability of diamonds, solders for diamond brazing usually include active elements such as titanium, chromium, or zirconium [12]. The active elements form carbides with the diamond's carbon [13]. The most common brazing alloys for diamond brazing are Cu-Sn-Ti, Ag-Cu-Ti, [14] and Ni-Cr [15]. Because of the high reactivity of the active elements, brazing can only take place in a high vacuum. Ni-based alloys were the first brazing alloys to be investigated for diamond brazing. Liu et al. used Ni-Cr-P-Si active filler alloy to braze diamonds in a vacuum. They found that in the interface between the diamond and the filler alloy mainly Cr_7C_3 and Cr_3C_2 were formed during vacuum brazing. The tools they fabricated were suitable for grinding ferrous metals. [16] Lu et al. compared Cu-Sn-Ni-Cr and Cu-Sn-Cr brazing alloys. They found that when brazing diamonds, the Cu-Sn-Ni-Cr-alloy showed a better wettability of the diamonds. However, the diamonds brazed with Cu-Sn-Cr-alloy showed better compressive strength and toughness index. This is mainly due to the disadvantage Ni-based brazing alloys encounter compared to Cu- and Ag-alloys. Nickel strongly acts like a catalyst and dissolves the diamond's carbon, which leads to the dissolution of the diamond. For Cu and Ag as matrix elements, the catalyst character is minor. Therefore, the solution of carbon in Cu and Ag is less. [17] Chen et al. compared a Ni-Cr alloy to an Ag-Cu-Ti, finding that the latter led to graphitization, microcracking, and fracturing of the diamonds [18]. Ti is usually used as the active element in Cu- or Ag-based brazing alloys, while Cr is rather used for Ni-based alloys. Sn is often added to reduce the melting point since brazing at low temperatures is crucial for avoiding the graphitization of the diamond. [17] Ag-based baring alloys show excellent ductility and a low melting point. However, they have poor abrasion resistance. Therefore, Cu is added to the filler metal. Ti, as the active element, reacts with the diamond and forms Ti-carbide, while Cu interacts with the Ti. Finally, Ag wets the Cu, forming a firm bond between the brazing alloy and diamond. [19]

As stated in the introduction, more research is needed on applying methods for vacuum-brazed tools. Burkhard et al. did extensive research and experiments on that topic. They used two methods for applications. In the first one, they first applied the filler metal to the tool body. Afterward, they used micro-dosing to apply adhesive dots on the tool body covered with filler metal. Finally, they applied diamond grains through a vibration plate or electrostatic sprinkling machine. The second method they used was micro-dosing adhesive dots, applying diamonds and finally wetting the diamonds with a soldering paste using an airbrush. They found the second method more suitable for vacuum brazing because when they applied the adhesive to the filler metal, the dry filler metal absorbed parts of it. This resulted in reduced adhesion of cutting material grains [20]. Li et al. also applied cutting material to the tool body first and subsequently spread filler alloy over it. However, they used cubic boron nitride (cBN) instead of diamond as cutting material [21]. Another method Boretius et al. used is applying filler metal and cutting material to the body using two types of tape. The first tape consists of the cutting material grouted into a polymer binder. It is applied to the body material. Afterward, a filler metal tape is applied on top. During brazing, the polymer binder decomposes residue-free, while the filler metal binds the cutting material to the body material [22]. In general, researchers try to achieve a filler metal layer that is around 30% of the cutting material's grain diameter [23]. Andrews et al. filed a patent for the bonding of abrasive tools. They used a perforated sheet, which was placed on top of the body material to apply an active brazing alloy on the exposed surface. Next, diamonds were sprinkled on the brazing alloy. After the removal of the perforated sheet, brazing alloy dots with diamonds on top were left [24]. Even though the method allows a uniform distribution of diamonds on plane surfaces, it is not suitable for the manufacturing of cylindrical abrasive tools. Sung filed a similar patent: Instead of directly applying the brazing alloy to the body material, a tape was fabricated. The tape consists of a paste-like filler metal, which is applied to a substrate and rolled out to a thickness that matches the grain diameter. Afterward, a perforated sheet is used to distribute the abrasive grains uniformly on the filler metal. The grains are bonded to the filler metal by pressing them into the paste using another sheet. Subsequently, the sheets are removed, leaving a tape consisting of abrasive grains and filler metal, which can be applied to a tool body. This method is suitable for abrasive materials with a grain size of 427 µm and bigger [25]. Chen et al. investigated the diamond distribution using electrostatic spray deposition (ESD) for fabricating grinding or polishing tools. Therefore, they mixed diamond particles with an electrostatic liquid and pressed the mixture through a nozzle with a negative electrode. As a positive electrode, a copper ring was used, which was set up beneath the nozzle. The high electrostatic field that was generated between the electrodes made the liquid-diamond mixture stretch out and distribute uniformly on the substrate. The application of this method is limited to ultrafine particles. The authors used diamond particles with a size of 10 µm, 2 µm, and 0.5 µm [26]. Although there are a few methods for applying filler metal and abrasive particles to a tool body, they are not suited for the fabrication of grinding tools for CFRP. Either the method cannot be used for cylindrical-shaped tool bodies, the abrasive grains that can be applied are too small or too big, or it is not a good fit for automation.

Fluidized bed coating technology is a method where particles are suspended in a bed. By using air flowing vertically through a filter, the particles act like a fluid [27]. The method can be used for particle coating when sprayed with a coating fluid. There are different designs for fluidized bed coating, including bottom spray, top spray, and rotor spray [28]. This technology is commonly used in the pharmaceutical industry [29] and offers advantages such as direct particle coating, minimal material loss, and a quick and easy process [30]. The method can also be used the other way around: A workpiece is dipped into a fluidized bed of coating particles. This technique is widely used for polymer coating of metal parts [31]. The metal parts are pre-heated, dipped into the fluidized polymer bed and, thereby coated with a homogenous polymer layer [32]. Afterward, the parts are sintered again. The process is simple, easy to automate and fast [33]. Additionally, it is environmentally friendly since it does not use any solvents, nearly no spare substances occur, and the material is almost entirely utilized [34].

3 Methodology

For vacuum brazing of diamond grinding tools, applying filler material and the cutting material is the most crucial challenge to overcome. Contrary to electroplating processes, the diamond grain is not deposited on the tool body electro-chemically but has to be applied mechanically. This also holds true for the filler material. Therefore, various application methods have been investigated. In recent literature, if mentioned at all, the cutting material was manually placed on the tool body, which had been covered in filler metal before. Based on this, application methods for the experiments were chosen. The methods are schematically presented in Fig. 1.

For the first application method, paste-like filler metal was used and mixed with diamond grains. Subsequently, the mix was applied to the tool body using a spatula (cf. Figure 1I). Similar to the first method, powdery filler metal, binding agent, and diamond grains were blended as a second application method (cf. Figure 1II). The mixture was applied to the tool body in the same manner as the first method. The third and fourth application methods involved the application of filler metal in combination with a binding agent and paste-like filler metal, respectively, to the tool body. Afterwards, diamond grain was sprinkled on the tool body (cf. Figure 1III and IV). The fifth application method entailed applying the paste-like filler metal and then dipping the covered tool body into a filter crucible filled with diamond grain (cf. Figure 1V). Since the method utilises

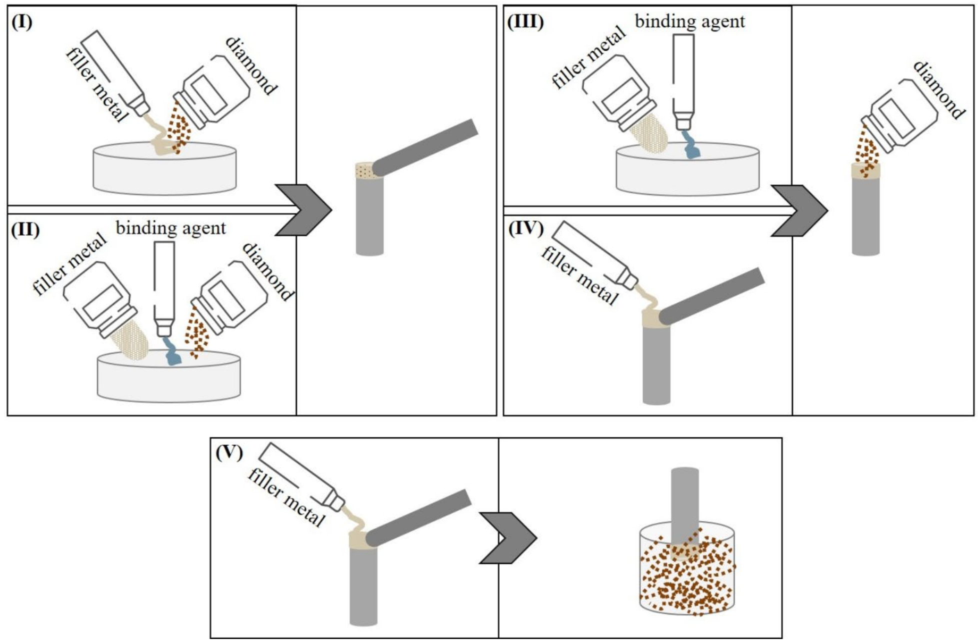

Fig. 1 Schematic presentation of application methods used for the experiments

Table 1 Filler metals used for the experiments

Filler metal	Composition	Type	Ratio binding agent
APA 5 (F1)	Ag (63%), Cu (35.25%), Ti (1.75%)	Powder	-
APA 16 (F2)	Ag (18%), Cu (63%), Sn (11%), Ti (8%)	Powder	-
APA 5 (F3)	Ag (63%), Cu (35.25%), Ti (1.75%)	Paste	11%
APA 16 – 11 (F4)	Ag (18%), Cu (63%), Sn (11%), Ti (8%)	Paste	11%
APA 16 – 15 (F5)	Ag (18%), Cu (63%), Sn (11%), Ti (8%)	Paste	15%
APA 8 (F6)	Ag (60.3%), Cu (23%), In (14.7%), Ti (2%)	Paste	15%

fluidized bed coating, it will be referred to as the FBC method in the following.

After applying filler metal, diamond grains and, if necessary, a binding agent, the samples were brazed in a vacuum brazing machine with filler metal specific parameters. The samples were optically examined, and the most promising method was used to manufacture mounted points. One of the tools was used for the grinding tests on CFRP sheets. Afterwards, the tool and the sheets were inspected in terms of wear and quality.

4 Material, machines, and methods

Six commercially available active brazing alloys were purchased from the company LOT-TEK GmbH (Erlangen, Germany) to conduct the experiments. They are composed of Ag, Cu and Ti; Cu, Ag, Sn and Ti; and Ag, Cu, In and Ti. Two powdery and four paste-like filler metals were used. The paste-like filler metals varied in binding agent ratio. Table 1 gives an overview of the filler metals used for the experiments. Additionally, a water based binding agent was used to compose a paste out of the powdery filler metal, and an isopropanol based binding agent diluted with acetone was used as an adhesion-promoting agent between the tool body and the filler metal paste.

Three different types of diamond grains from DURATEC Hartstoffe GmbH (Wermelskirchen, Germany) were used as cutting material. Two had an average grain size of 251 µm and differed in impact strength (C1 with medium impact strength and C2 with hardest impact strength). The third cutting material was diamond with a 426 µm average grain size (C3).

The tool body was a cylindrical pin with a diameter of 10.2 mm, a total height of 20 mm and a height of 5 mm for applying filler alloy and cutting material. The experiments were conducted with tool bodies out of steel (42CrMoS4) and carbide (AF KF 40 UF) from Arno Friedrichs Hartmetall CmbH & Co. KG in Mainleus, Germany.

The paste-like brazing alloys were applied with a pneumatic dosing system from a 30 ml cartridge and dispersed using a spatula. The automated vacuum brazing system VVBM 200 from the company IEW Induktive Erwärmungsanlagen GmbH (Gumpoldskirchen, Austria) was used for

Table 2 Overview of combination of method, cutting material, brazing alloy and tool body for the experiments

Sample number	Method	Cutting material	Brazing alloy	Tool body
1	(I)	C2	F3	steel
2	(I)	C1	F4	steel
3	(I)	C1	F4	carbide
4	(II)	C2	F2	steel
5	(II)	C1	F1	steel
6	(II)	C2	F1	carbide
7	(III)	C2	F2	carbide
8	(III)	C1	F1	steel
9	(III)	C3	F1	carbide
10	(IV)	C1	F4	carbide
11	(IV)	C3	F4	steel
12	(IV)	C2	F3	steel
13	(V)	C1	F6	steel
14	(V)	C1	F5	steel
15	(V)	C1	F5	steel

vacuum brazing. Brazing parameters were harmonized with the particular brazing alloy. For example, samples manufactured with filler metal F2, F4 and F5 were brazed using three heating ramps with respective holding times: 600 °C for 15 min, 700 °C for 10 min and finally 885 °C for 5 min.

A Kern precision balance and a Keyence VHX-7000 digital microscope were used for weight measuring and inspection, respectively.

The experiments were conducted according to the following procedure: The tool body was degreased with acetone, blasted with white corundum and degreased again. Afterwards, the brazing alloy and the cutting material were weighed and prepared for application. The required quantity was taken from recent literature and pre-experiments. It was further adapted in the course of the experiments. Filler metal, diamonds and, if necessary, binding agent were applied according to the application methods shown in Fig. 1. After ventilating the samples, they were optically examined with the digital microscope. Subsequently, the samples were brazed in the vacuum brazing machine with brazing alloy-specific parameters and optically examined again. The combination of cutting material, brazing alloy and tool body used for each method is summarized in Table 2. The combinations were chosen randomly, with the goal of combining various brazing alloys with different diamond grains. Additionally, the tool body material (steel and carbide) was varied to examine whether the tool body's surface affected application behaviour. Since this could not be observed, only steel was used for the last method.

Since it was found that brazing alloys with higher binding agent ratios could be applied more easily, two new brazing alloys were used for method (V) and the method was not carried out with paste-like filler metals with only 11% binding agent. After performing the experiments, samples for conducting grinding tests were manufactured using the combination, which was found to be best. This was steel as tool body, filler metal F5, method (V) and cutting material C1.

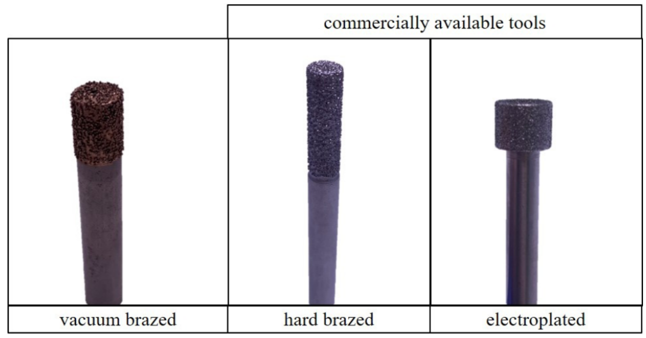

Fig. 2 Tools used for grinding tests

Table 3 Overview over the performed cutting tests

Test number	Cutting depth	Repetition	Cutting volume
1	0.02 mm	28	308 mm³
2	0.04 mm	25	550 mm³
3	0.04 mm	125	2750 mm³
4	0.1 mm	25	1375 mm³

For grinding tests, a tool body with a height of 60 mm and CFRP sheets with a size of 100 mm x 250 mm x 5.5 mm (width x depth x height) were used. The sheets were prepreg semi-finished parts with an epoxy system as matrix material and unidirectional angle (0°/90°). They were purchased from Carbon-Werke Weißgerber GmbH & Co. KG (Wallerstein, Germany). Additionally, two commercially available tools were used to compare the grinding results. The first one was a hard-brazed diamond grinding point with an 8 mm tool diameter and an average grain size of 427 µm (Hoffman SE, Munich, Germany), and the second one was an electroplated diamond grinding point with a tool diameter of 10 mm and an average grain size of 181 µm (August Rüggeberg GmbH & Co. KG, Marienheide, Germany). Different grain sizes were compared to determine the influence on the workpiece quality. The tools are depicted in Fig. 2.

An HSC machining center from the company DMG Mori (Winterthur, Switzerland) was used to conduct the grinding experiments. All the tools were tested with a cutting speed of 11.73 m/s resulting from a rotational speed of 22,400 rpm for 10 mm tool diameters and 22,800 rpm for 8 mm tool diameters. The feed was 400 mm/min for all tools and sets. The cutting depth was increased from 0.02 mm to 0.04 mm to 0.1 mm. A water-miscible lubricant was used for all grinding experiments. Table 3 gives an overview of the performed tests. The experimental setup and a schematic presentation of the grinding tests are shown in Fig. 3.

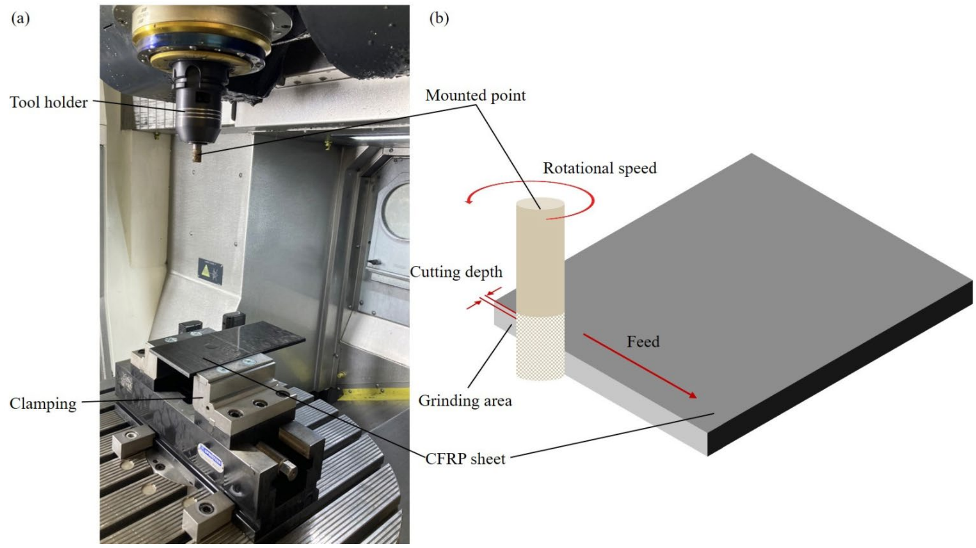

Fig. 3 Experimental setup (**a**) and schematic representation of grinding tests (**b**)

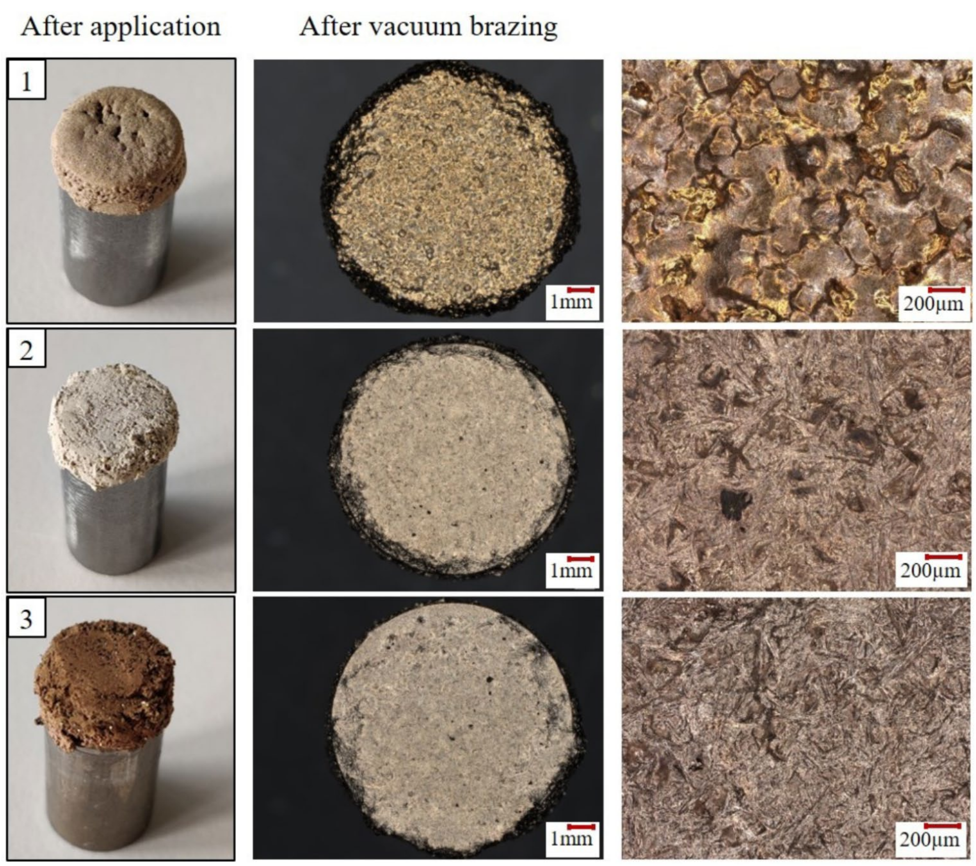

Fig. 4 Results after application and after vacuum brazing for method (I)

5 Results

The samples were optically examined before and after brazing and during grinding tests. The following results are divided into investigations of the application method and vacuum brazing results and results of the grinding tests.

5.1 Results of application method and vacuum brazing

The following figures show the images of the sample before and after vacuum brazing for all methods and varied parameters.

Figure 4 illustrates the samples manufactured by applying paste-like brazing alloys mixed with diamond before and after brazing. It can be seen that the mixture could not be applied homogeneously to either of the samples. For samples 2 and 3, the diamond grains were visible after application, while for sample 1, the brazing alloy covered all of the diamond. After vacuum brazing, samples 2 and 3 show a bulk of brazing alloy in the middle of the tools' diameters, whereas the tools' edges are barely covered. Additionally, diamond grains can be seen only for samples 1 and 2 in the close-up. The surface of sample 1 looks more homogeneous. It does not show less material at the edge of the tool. The distribution of the diamonds can be seen in the close-up. However, they are coated with brazing alloy and thus do not show any grain protrusion. This indicates that the tools are not suitable for grinding.

The results of using filler metal, binding agent and diamond grains and applying the mix to the body material are depicted in Fig. 5. Again, the applied material looks rather inhomogeneous. A few diamond grains can be seen in sample 4 after application. Samples 5 and 6 show rather pores than diamond grains before brazing. After vacuum brazing, both brazing alloys (F1 and F2) have pulled back from the edges of the body material. This especially holds true for brazing alloy F2 on sample 4, where an actual ring has formed around the bulk out of brazing alloy and cutting material in the middle of the sample surface. Samples 5 and 6 also tended to form a ring; however, it is rather formed by the cutting material. The brazing alloy used for samples 5 and 6 shows a better distribution on the samples' surfaces while brazing alloy F2 accumulated in the middle. After brazing, the diamond grains can barely be seen for sample 4. The close-up shows a couple of diamonds coated by a thick layer of brazing alloy. In samples 5 and 6, the diamond grains can be seen clearly, but they are coated with brazing alloy so that no grain protrusion can be observed. On the surface of sample 5, the body material shines through the brazing alloy in some areas at the edge and in the middle of the sample.

For manufacturing the samples in Fig. 6, filler metal was mixed with a binding agent, applied to the body material and sprinkled with diamond grains. Sample 8 shows a uniform distribution of diamond grains after application, whereas samples 7 and 9 show minor irregularities. For sample 9, this applies especially to the edges of the body material. Even though the diamond grains in sample 7 were applied on top of the brazing alloy after vacuum brazing the cutting material is coated with filler metal. For samples 8 and 9, the diamond grains show a grain protrusion after vacuum brazing. Neither of the brazed sample show an accumulation of brazing alloy and cutting material in the middle of the surface.

Nevertheless, some gaps in the cutting material layer can be seen at the edge of the samples. The irregularities in

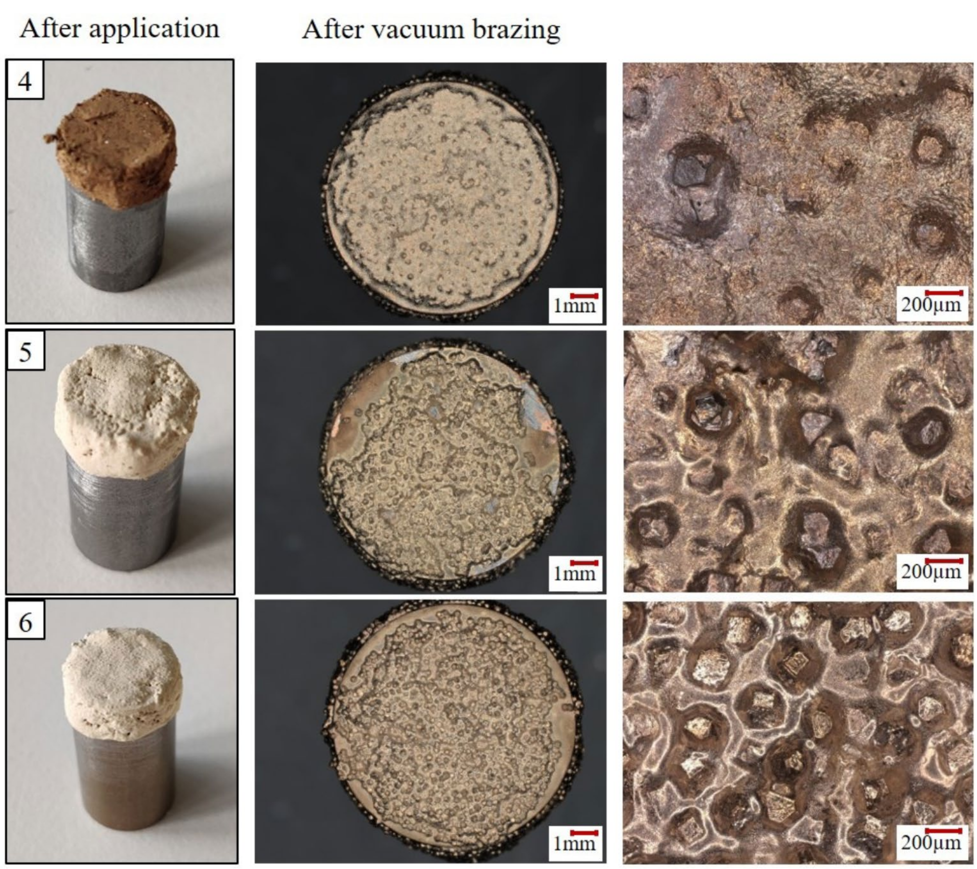

Fig. 5 Results after application and after vacuum brazing for method (II)

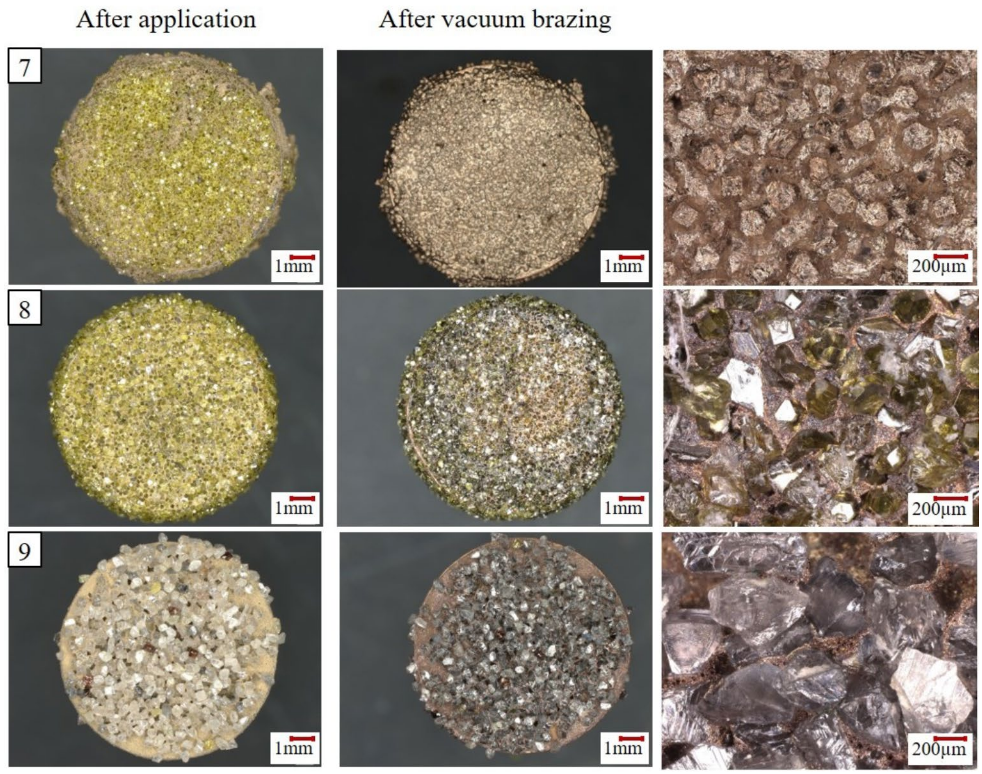

Fig. 6 Results after application and after vacuum brazing for method (III)

grain distribution seen in samples 7 and 9 after application stayed the same after vacuum brazing. For samples 8 and 9, the diamond grains have changed their colour after vacuum brazing.

As the fourth application method, the authors applied paste-like filler metal to the body material and sprinkled diamond grain on top of it. The results after application and after vacuum brazing are shown in Fig. 7. The distribution of the brazing alloy and that of the diamond grains looks inhomogeneous for all three samples. In all samples, the cutting material does not cover the complete contour of the edge. The material body can also be seen through the brazing alloy in sample 12. After the application, the diamond grains for all samples are visibly present on the sample's surface, and no grains are coated with filler metal. However, only a few grains show on the surface for sample 10 after vacuum brazing. The close-up of sample 10 shows diamond grains completely covered with brazing alloy and some grains that show on the surface. For samples 11 and 12, neither the images taken after brazing nor the close-ups show visible diamond grains. Additionally, the diamonds used for the samples changed their colour during brazing.

The last application method tested within the experiments was the FBC method. The results after application and after vacuum brazing are shown in Fig. 8. After the application, the grain distribution for all samples is very homogenous. No gaps or accumulations can be seen in the images. The edges of the samples are uniformly covered with filler metal and cutting material. After vacuum brazing, it can be seen that the colour of the diamond grains has changed. Still, filler metal and cutting material distribution is homogenous across the entire surface. Looking at the close-ups, the diamond grain distance of sample 13 is shorter than that of samples 14 and 15. However, all three samples show diamond grains that protrude from the brazing alloy after vacuum brazing. No grains that are entirely covered in filler metal can be seen.

5.2 Results of grinding tests

Since the FBC method was the best method for the automated application of diamond grains to the tool body, it was used to manufacture cutting tools for grinding tests. An image of the new tool is depicted on the left in Fig. 9. It can be seen that the diamond grains are uniformly distributed across the surface. The grains protrude from the brazing alloy, and none is completely covered.

On the right hand side, the same tool is shown after cutting 5000 mm³ of material. In direct comparison, no wear can be seen on the used tool. Looking at the close-up on the right, the diamond grains can be seen more closely. No disruptions or missing grains can be seen. All grains show a grain protrusion and seem to be firmly joined to the tool body.

A close-up view of a diamond grain of the new tool and the tool after grinding tests is shown in Fig. 10 (a) and (b),

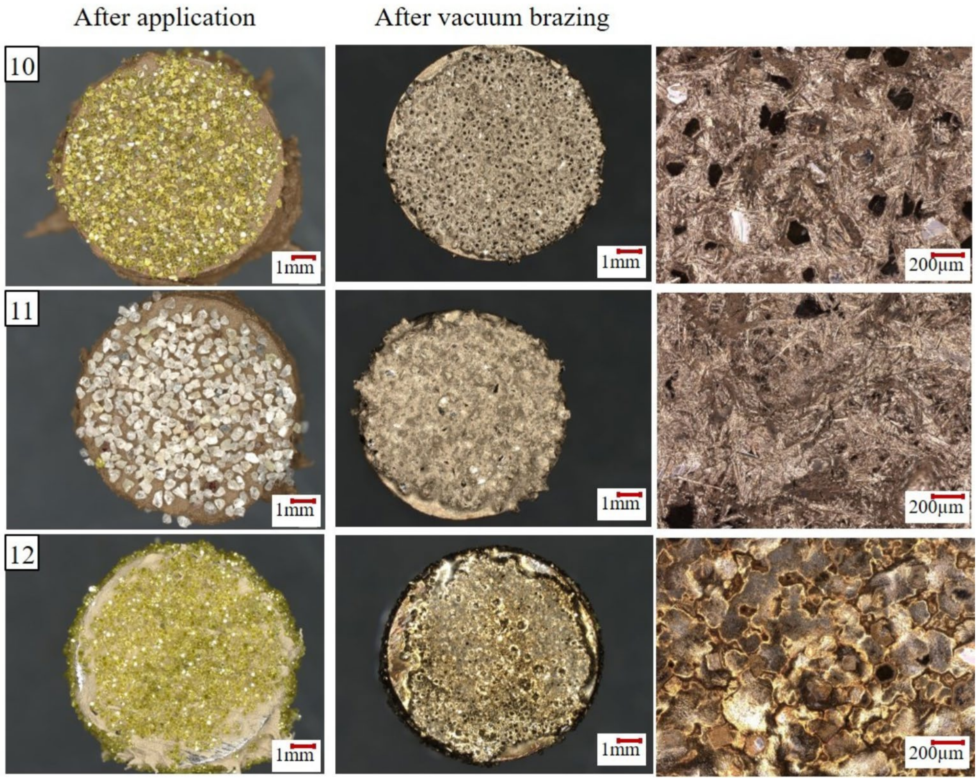

Fig. 7 Results after application and after vacuum brazing for method (IV)

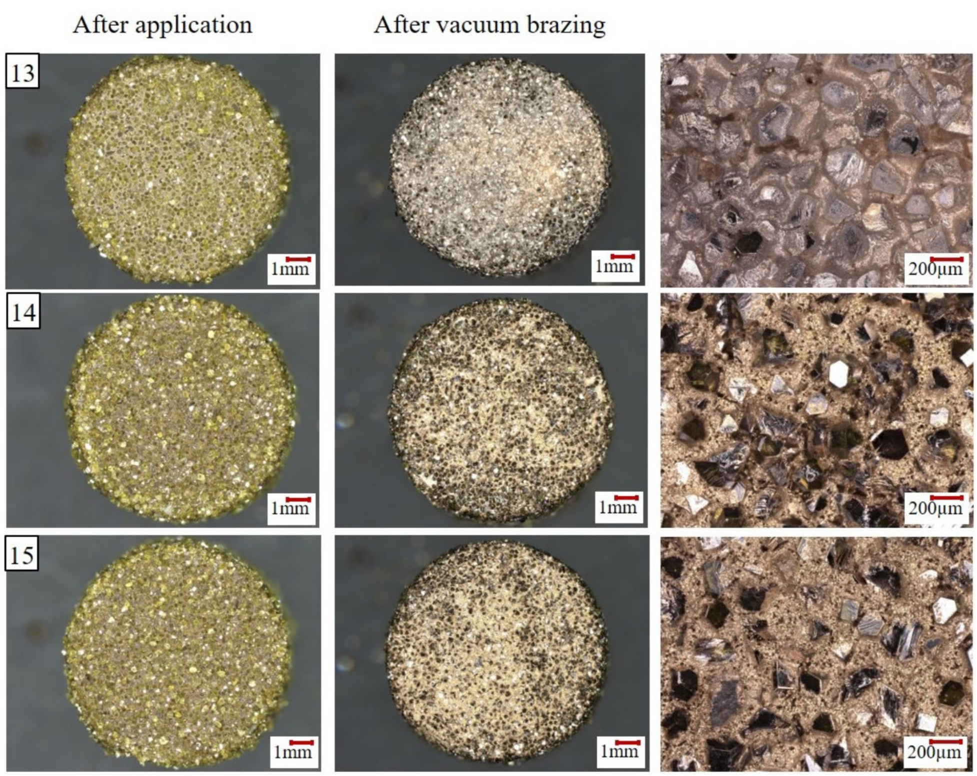

Fig. 8 Results after application and after vacuum brazing for method (V)

respectively. Both grains show suitable grain protrusion and good wetting on the bottom of the grains. The brazing alloy does not show any pores or cracks in either of the images. Furthermore, the diamond grain, after grinding tests, does not show any disruptions, cracks or any other signs of wear. Both grains show sharp edges at the top.

Figure 11 shows the edge of the workpiece after grinding tests with the vacuum-brazed tool. Images (b), (c) and

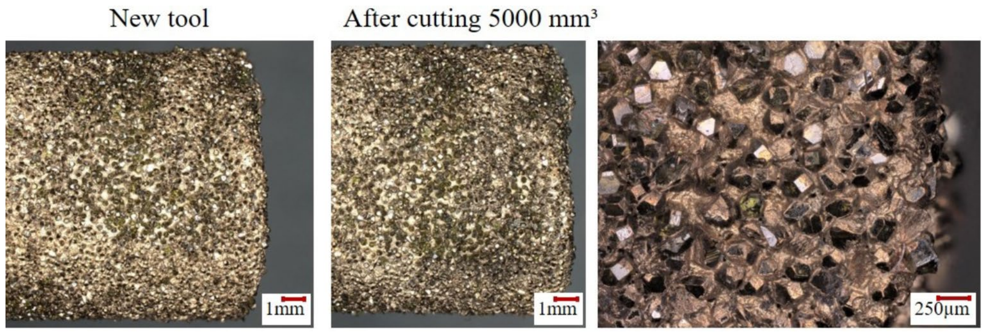

Fig. 9 Comparison of a new and used vacuum brazed cutting tool

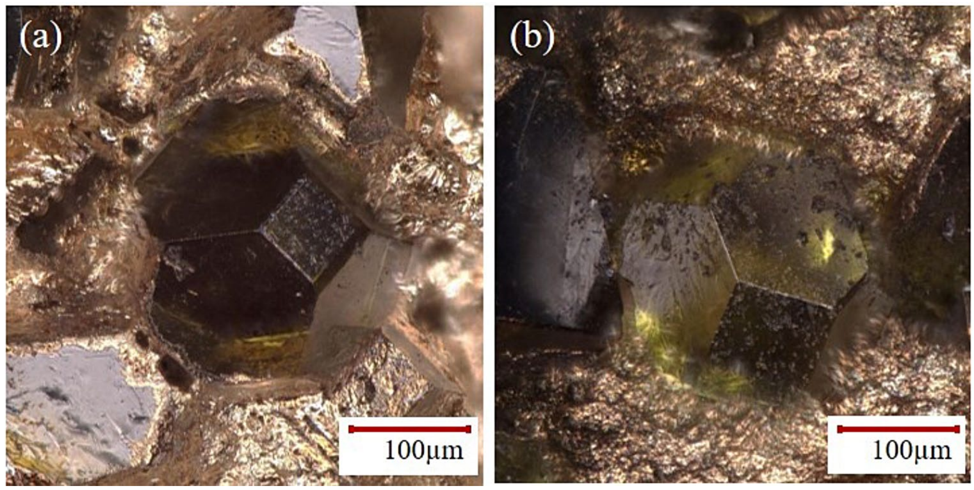

Fig. 10 Diamond grain of a new tool (**a**) and diamond grain of a tool after grinding tests (**b**)

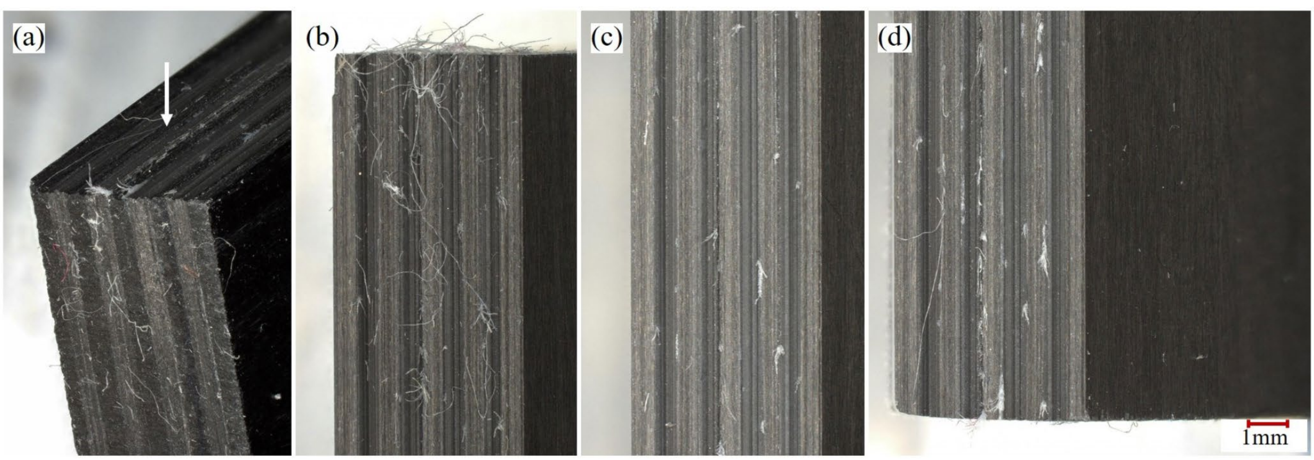

Fig. 11 Edge of CFRP after processing with vacuum brazed tool

(d) show the edge of the CFRP sheet from the front, while image (a) shows a tilted picture to get an impression of the surface topology of the machined edge. The machined surface is indicated with an arrow.

It can be seen that various fibres have been ripped out of the matrix material. Other than that, looking at image (a), it can be observed that the surface after machining is marginally chequered. Compared to the sawn surface, which can be seen at the bottom of image (a), the surface machined by grinding using the vacuum-brazed tool is slightly rougher.

A comparison between the new and the used hard-brazed tool is shown in Fig. 12. Looking at the image of the new tool, it can be noticed that almost all the diamond grains are coated with brazing alloy. After the grinding tests, more grains appeared on the brazing alloy's surface. The grains visible at the surface in the close-up show a suitable grain

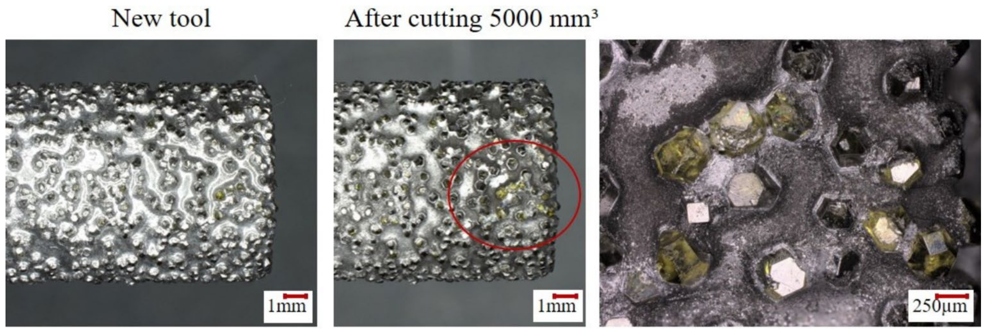

Fig. 12 Comparison of a new and used hard-brazed cutting tool

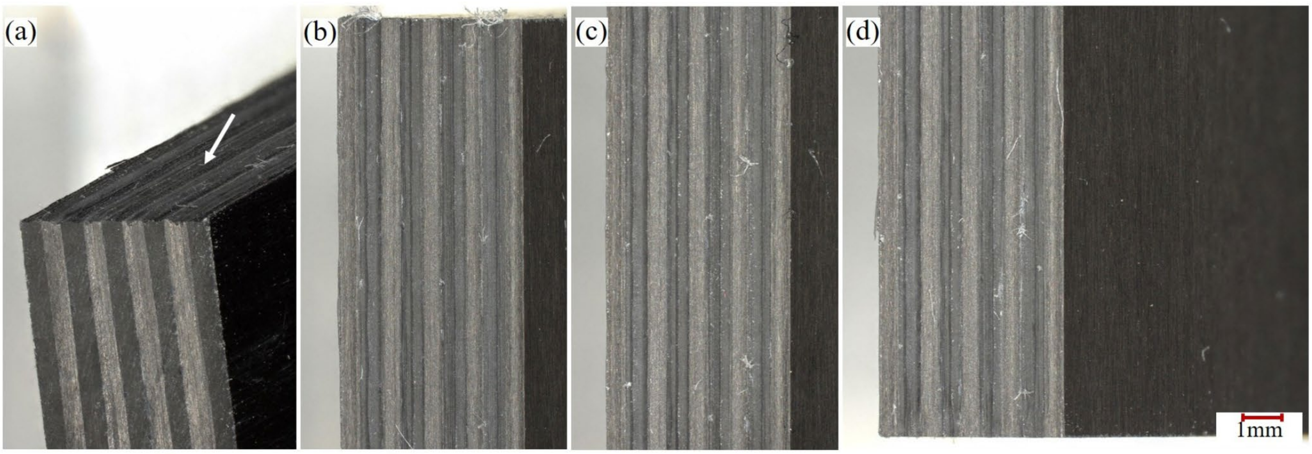

Fig. 13 Edge of CFRP after processing with hard-brazed tool

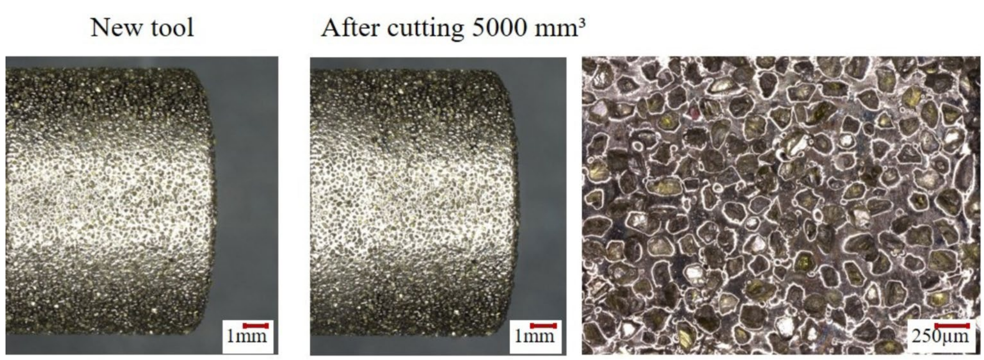

Fig. 14 Comparison of a new and used electroplated cutting tool

protrusion. There are no traces of cracks or disruptions in the grains.

The edge of the workpiece after grinding tests using the hard-brazed tool is illustrated in Fig. 13. Aside from the beginning of the machined edge in image (b), no fibres are coming out of the matrix material. However, in image (a), looking at the edge between the sawn and the ground edge (indicated with an arrow), it can be seen that the machined surface is significantly chequered. Moreover, there is a visible disruption in material, which can be seen in image (a) and (d).

Finally, the grinding tests were conducted with a commercially available electroplated cutting tool. Figure 14 shows an image of the new tool and the tool after cutting tests and a close-up of the diamond grains.

There is no visible trace of wear in the complete image or the close-up. The diamond grains are uniformly distributed on the surface and neither show cracks, pores or disruptions. No adhesions of material can be seen.

The result of the grinding test on the workpiece is presented in Fig. 15. Again, image (a) shows the tilted edge that has been machined with the electroplated tool, whereas images (b), (c) and (d) show the entire edge from the front.

No large fibres are coming out of the matrix material. As can be seen in image (a), there is no chequered part of the surface. The machined surface is very even.

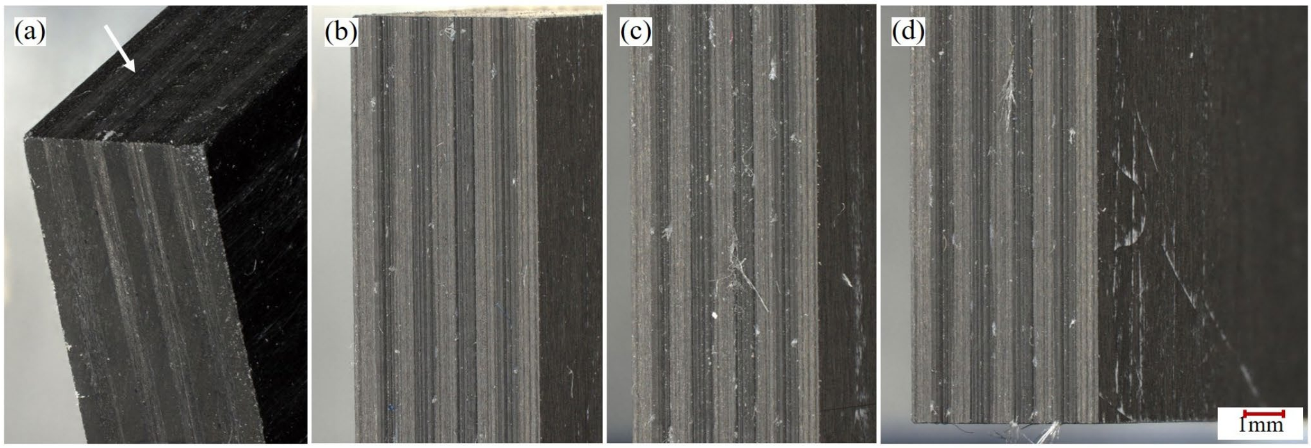

Fig. 15 Edge of CFRP after processing with electroplated tool

6 Discussion

6.1 Application method

Five different application methods were used for this study. Two entailed combining the brazing alloy and a binding agent with diamond grains. In contrast, for the others, the brazing alloy was applied to the tool body first, and diamond grains were subsequently sprinkled or applied using FBC.

For method (I), homogenous mixing of the paste-like filler metal and the diamond grains was crucial. It was conducted manually in this study. However, obtaining the distribution of diamond grains in the mixture was difficult. Since the paste-like filler metal was quite dense, the diamonds could not be seen while mixing, which made it impossible to ensure a proper distribution. This can also be applied to the samples before brazing: A bulk of brazing alloy is on top of the tool body, while diamond grains are not visible. Additionally, when using brazing alloy with an 11% binding agent, an even application of the mixture to the tool body was not possible either. As shown in Fig. 4, the applied brazing alloy shows pores and an uneven surface structure after application. Furthermore, the mixture was too viscous for dipping the tool body into it to achieve a homogenous layer. The method would be suitable for automation when homogenous mixing can be implemented, e.g., using a dynamic mixer. However, a problem with an automated mixer could be a high wear of the components because of the metal filler and hard diamonds. This scenario has to be excluded. Otherwise, the mixer is not economical. For automated applications, the filler metal paste has to be more fluid so that the tool body can be wetted easily by dipping it into the mixture.

Applying the brazing alloy-diamond mixture using method (II) was less problematic than method (I). For samples 4 and 5, the same amount of brazing alloy and diamond was used; however, by using twice as much binding agent, the viscosity of the mix was significantly lower. Therefore, dipping the tool body into the mix was possible. The applied layer's surface still shows inhomogeneity and pores for samples 4 and 5. For sample 6, less filler metal was used while maintaining the amount of diamond and binding agent used. It shows a more uniform surface. Some diamond grains are visible for sample 4; however, this is mainly due to the color of the brazing alloy. When using the water-based binding agent, it was possible to produce a homogenous mixture of brazing alloy and diamond grains. A dense compound was created after applying the blend to the tool body and ventilating the binding agent. Due to the fact that it is possible to submerge the tool body into the brazing alloy-diamond-mix for application, this method is suitable for automation. The advantage of methods (I) and (II) is the ability to precisely adjust the amount of brazing alloy and diamond used to produce the tools.

For methods (III) and (IV), the diamond grains on the tool body before brazing can be seen. Both methods were two-stage: first, the brazing alloy was applied, and second, the diamond grains were sprinkled on top of the brazing alloy. Regarding the coating with the brazing alloy, even without the diamonds, it was much easier to apply the powdery brazing alloy blended with the water-based binding agent than applying the paste-like brazing alloy. When using the water-based binding agent, it was possible to adjust the viscosity of the blend, leading to a uniform coating of the tool body. Another advantage of the water-based binding agent is its adhesiveness. The diamonds were sprinkled on the tool body, which was turned over afterward to lose all the grains that did not stick to the brazing alloy. By weighing the ventilated tool, it was found that almost as many diamonds adhered to the brazing alloy as were used for methods (I) and (II), respectively. On the contrary, the filler metal with an 11% binding agent could not hold many diamonds. It was found that only a third of the diamonds that adhered to the water-based binding agent tool stuck to the paste-like filler metal. Therefore, it can be concluded that paste-like brazing alloys with a small percentage of binding agent lead to poor adhesion of diamond grains when sprinkled on the tool body. The results show that samples with brazing alloys F3 and F4 have considerably fewer diamonds than those with brazing alloys F1 and F2, mixed with a significantly higher portion of more binding agent. A disadvantage the sprinkling methods encounter is obtaining a uniform distribution of diamond grains. This is mainly dependent on how the diamonds are sprinkled on the tool. Regarding automation and sustainability, there are some issues, too. A significant portion of diamonds do not adhere to the coated tool body. Therefore, they need to be caught in a collecting container. However, it can not be excluded that the brazing alloy or binding agent contaminates the diamonds. Thus, they would need to be cleaned again. Additionally, a large amount of diamonds would be needed, leading to high costs for manufacturers.

The authors used paste-like brazing alloys with a 15% binding agent to produce grinding tools using fluidized bed coating because of their experiences with brazing alloys F3 and F4. The new brazing alloys could be applied homogenously to the tool body. When using fluidized bed coating, even more diamonds adhered to the coated tool than with method (III), and a uniform distribution of diamonds could be achieved. The most crucial factor for a uniform distribution is an even coating with paste-like brazing alloy. This can be automated with either a dosing system or using spray coating. However, further research regarding the even distribution of the filler metal is needed. Applying cutting material to cylindrical tools using the FBC is easy to automate with a robot. The robot can take over the handling as well as the dipping of the tool body into the fluidized bed. Depending on the gripper and the shape of the cutting material container, several tools, even with various geometries, can be coated simultaneously. Nevertheless, it needs to be examined if diamond grains that do not stick to the tool body and stay in the filter crucible bind the brazing alloy with time. Additionally, how long the abrasive can remain in the container until it needs to be replaced needs to be investigated. Still, much less material is needed than for the sprinkling methods.

Which method is generally suitable for applying filler metal and cutting material to the tool body and can easily be automated?

In general, all of the methods employed can be used for applying brazing alloy and cutting material to a tool body. Especially methods (I) and (II) can be easily automated. However, using those methods requires adjustments regarding the type of brazing alloy, ratio of binding agent, and amount of diamond grains. Also, the wear in the automated dosing system would be very high because of the diamond grains. For all methods that apply a blend to the tool body, dressing of the tool is likely necessary. Therefore, a two-stage method is considered the best application method. Due to the high automation option of fluidized bed coating, method (V) was found to be a proper method for producing diamond-mounted points. Consequently, further research needs to be done regarding process parameters, setup, and possible grain contamination.

6.2 Vacuum brazing

When looking at the results of method (I) after vacuum brazing, it becomes clear that the tools are unsuitable for grinding. Not only are the diamond grains covered in the brazing alloy, but they also are not even visible. Therefore, dressing does not lead to usable tools either. Additionally, for samples 2 and 3, the filler metal, after brazing, looks dry and brittle and agglomerates in the middle of the tool. Samples 10 and 11, also brazed with an 11% binding agent-brazing alloy (F3 and F4), show similar dry and brittle results. Interestingly, when comparing the diamond-brazing alloy ratio, it stands out that significantly fewer diamonds were used for all four samples. Samples that show good results after vacuum brazing (8, 9, 13, 14, and 15) have a considerably higher diamond-brazing alloy ratio. Therefore, the ratio is a crucial influencing factor for vacuum brazing of diamond-mounted points. It is also noticeable that the samples, which show very poor results after brazing, were manufactured with one of the 11% binding agent brazing alloys. Due to the fact that those brazing alloys did not spread well on the tool body, too much brazing alloy was used. This is another reason for the poor results. For samples 10–12, in addition to this, the diamond grains did not adhere well to the brazing alloy. Even more grains could have gotten lost during the handling between application (when the number of grains was determined) and vacuum brazing, leading to an even smaller diamond-brazing alloy ratio. Consequently, using paste-like filler alloys with an 11% binding agent is not considered an exemplary method for vacuum brazing of this type of mounted points.

For blending method (II), diamonds are visible after brazing but covered in brazing alloy. The brazing alloy has also contracted, leaving the edges either completely uncovered or without diamonds. Since active brazing alloys contain specific active elements, titanium in this case, to wet the diamonds, the alloy will not pull back from them when mixed with the diamonds. Using this method, dressing the tools would be necessary. To avoid dressing, the brazing alloy and the diamond grains should be already applied where they are supposed to be. Therefore, methods (I) and (II) were identified as unfitting for brazing mounted points.

Sprinkling diamonds on top of the powdery brazing alloys blended with a water-based binding agent showed promising results after brazing. However, sample 7 looks like the diamonds are covered with brazing alloy after brazing, even though the grains were sprinkled on top of the filler metal. There might be two explanations for this phenomenon: Due to the high amount of brazing alloy and binding agent, the diamonds have sunk into the blend on the tool body. Much binding agent caused the blend to become liquid, so the diamond grains were already submerged right after application. The high titanium content (8%) in the brazing alloy leads to good filler metal wetting and flow. In comparison, the brazing alloy did not wet the diamonds thoroughly for samples 8 and 9, which were brazed with a brazing alloy with lower titanium content. Therefore, the high content of titanium might have a negative effect on the brazing result. The different grain sizes of 251 µm and 426 µm in samples 8 and 9, respectively, do not affect the brazing result. The only noticeable difference is that the larger diamond grains could not sufficiently cover the tool body's edges, which could already be observed during application.

The advantage of fluidized bed coating, which was used for method (V), is that even after vacuum brazing, the entire tool, including the tool's edge, is covered in brazing alloy and diamond. In addition, the distribution of diamond grains seems uniform after brazing.

Concerning the changes of colors, three cases are observable after vacuum brazing: Diamonds turning from yellow to green, white/grey, and black. Chen et al. explained the change of color for diamonds. In ambient air, the optical absorption of nitrogen colors the diamonds yellow. After brazing in high temperatures, single nitrogen atoms accumulate and let the diamonds appear green. [18] Thus, this phenomenon is an optical issue only and does not indicate damage to cutting material. This is supported by the change of color into green occurring for samples brazed with brazing alloy F1, which is an Ag-based alloy and, therefore, was brazed at temperatures considerably lower than 900 °C. Thus, thermal damage or graphitization should not have occurred in a vacuum. For samples 14 and 15, the diamonds' color has changed from yellow to dark green and partially black. Since the samples were brazed with brazing alloy F5, the temperatures were slightly higher than those with brazing alloy F1. This leads to the assumption that the diamonds have graphitized. However, there are still dark green diamonds, and brazing temperatures have not been too high either. The authors, therefore, assume that, at the most, the diamonds are coated with a graphite layer. Sample 13 is the only sample that seems to have a white/grey coating after brazing. This might be because it was brazed with an indium-containing brazing alloy. Since liquid indium is known for being silvery-white and leaving a film on, e.g., glass, it can be assumed that indium is shown as a grey/white coating on the diamonds.

Which application method shows the best results after vacuum brazing, and what are the influencing factors (filler metal composition, grain size, application method)?

The best results after brazing were associated with the sprinkling method using brazing alloy with a high ratio of binding agent and fluidized bed coating. However, the homogenous distribution of brazing alloy before applying diamonds is crucial. Additionally, a higher diamond-brazing alloy ratio leads to better results. Otherwise, even the sprinkling method leads to imperfect results. The best results were obtained after brazing with a high diamond-brazing alloy ratio. Nevertheless, a suitable method also depends on the brazing alloy. High titanium content or indium-containing brazing alloys lead to coated diamonds. Hence, dressing would be necessary. No difference in vacuum brazing results was noticeable regarding the grain size of the diamond. However, the adhesion of smaller grains on the tool body's edges was better than that of larger grains. Subsequently, using soldering paste with a 15% binding agent, 250 µm diamond grains and fluidized bed coating as the application method was considered the best. Therefore, that method and materials were used to produce tools for grinding experiments.

6.3 Grinding experiments

For grinding experiments, the results can be divided into tool wear and workpiece quality. No differences between the dissimilar manufacturing methods could be observed regarding tool wear. The electroplated and vacuum-brazed tools show no wear at all after grinding. The single diamond shown in Fig. 10 for the vacuum brazed tool, shows no wear and no cracks in the brazing alloy can be found either. Therefore, fluidized bed coating is generally suitable for producing diamond-mounted points for CFRP grinding. Fluidized bed coating seems even better suited when comparing the hard-brazed and the vacuum-brazed tools, given that the diamond grains are not covered with brazing alloy. The hard-brazed tool needs a running-in phase to dispose of the spare filler metal on top of the diamond grains. This can be seen slightly in Fig. 12: more diamonds appear out of the brazing alloy after grinding tests. Compared to Wang et al. [8], the authors, however, used utterly different cutting parameters. The parameters were taken from previous experiences in the grinding of CFRP. Nevertheless, for more detailed investigations of tool wear, tests should be repeated with new tools of the same grain size and diameter, higher cutting depths, lower feed, and, if necessary, longer cutting time.

The differences in workpiece quality can be attributed to the dissimilar grain size of the tools. The electroplated tool showed the best results, having the smallest diamond grains. Contrary to the hard-brazed tool, there are no disruptions in the workpiece surface cut with the vacuum-brazed tool. However, quite many fibers were ripped out of the matrix during manufacturing. Therefore, the grain size of the vacuum brazed tool should be adjusted and optimized.

What are the differences between vacuum-brazed and electroplated tools regarding the workpiece's tool life and surface quality?
There are no visible differences in tool life between commercially available tools and those manufactured using the FBC method and vacuum brazing. Generally, the vacuum-brazed tool might even be better suited for grinding CFRP than the hard-brazed tool. However, further experiments with more extreme parameters or more difficult to machine materials like ceramics would be necessary. The surface quality of the workpiece manufactured with the electroplated tool is slightly better than that of the vacuum-brazed tool. Nevertheless, it can be assumed that the cause lies within the grain size and is not attributed to the tool's manufacturing method.

7 Conclusion and further research

This paper presented an experimental investigation into preparing diamond-mounted points for grinding CFRP. The primary goal was to determine an efficient method for applying brazing alloy and cutting material conducive to automation in manufacturing. Various methods of applying the filler metal and diamond grain were explored, along with variations in the type and amount of filler metal, diamond grain size, cutting material, and the material of the tool body. The most effective method was then utilized to create samples for milling and grinding tests, with performance outcomes compared against commercially available tools.

In terms of application, all methods were suitable for applying filler metal and diamond grains. The method of fluidized bed coating was found to have excellent automation potential. The best results after vacuum brazing could be achieved by applying filler metal first and sprinkling diamond grains on top. Filler metal composition, distribution, and diamond-brazing alloy ratio were the main influencing factors. After investigating the different application methods, the FBC method shows high potential for the automated manufacturing of vacuum-brazed diamond-grinding tools. The method leads to a uniform distribution of diamond grains on cylindrical shaped mounted points, is easy to automate for various tools, and shows promising results for CFRP grinding compared to commercially available tools.

In contrast to the sprinkling methods that were also investigated, FBC does not waste any diamonds. Diamonds that do not stick to the tool will stay in the fluidized bed and can be used for the following tool. Therefore, the method is doing great regarding sustainability and material/production costs. Compared to current electroplating processes, it is also an environmentally friendly method because it does not use chemicals.

Further research is needed regarding an automated process for manufacturing tools and optimization of tools involving grain size and tool life experiments. For every manufactured tool, grinding tests should be performed until the end of its life with comparable tools (tool diameter, grain material, grain size, and grain distribution). The performance of the different manufacturing processes can be estimated by comparing the tool wear, process forces, and workpiece quality (surface roughness, damages) over the tool's life. With those results, the newly developed manufacturing process can be automated and transferred to other tools, like grinding wheels.

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Declarations

Competing interests The authors declare no competing interests.

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