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ORIGINAL ARTICLE

On-machine wire electrical discharge dressing (WEDD) of metal-bonded grinding wheels

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Abstract Metal-bonded diamond wheels, due to its strong grain retention and thermal conductivity properties, are generally used for grinding difficult-to-cut materials, such as high-performance ceramics. On the other hand, the poor dressability of this type of bond limits its application. This study aims to evaluate the use of a wire electrical discharge machining (EDM) principle for truing and dressing metal-bonded grinding wheels. Through the EDM process, the electrically conductive grinding bond is eroded, so that grain protrusion can be generated. For evaluating this dressing process, a wire electrical discharge dressing unit was designed, manufactured, and integrated into a universal cylindrical grinding machine. The dressing process is carried out using the grinding oil also as dielectric fluid. High material removal rates were achieved. Cylindrical plunge grinding tests on silicon nitride workpieces indicated that in comparison to conventionally dressed wheels, smaller cutting forces and wheel wear are achieved by using EDM-dressed grinding wheels.

Keywords Electrical discharge dressing · Grinding · Diamond wheels · Metal bond · Ceramics

1 Introduction

Ceramic materials have several exceptional properties such as high hardness, high stiffness, and good thermal and chemical stability, finding an increasing number of applications in the automotive, aerospace, medical, electronics, and machine-tool industries [1–3]. Grinding with diamond tool is a major machining process for advanced ceramics, since diamonds have key properties such as high wear resistance, high hardness, low friction, and thermal expansion coefficients [4, 5]. Additionally, the right choice of wheel bond material is essential too. Metal-bonded wheels are generally applied for grinding ceramics, due to their high grain retention forces and high thermal conductivity [6]. However, carrying out a proper dressing method is the main challenge of using metal-bonded diamond wheels [7]. The dressing method must grant the wheel sufficient grain protrusion and chip space, aiming to provide space for chip removal and increase the coolant flow rate through the grinding contact zone [8, 9]. Usually, a silicon carbide wheel is used for truing and dressing metal-bonded diamond wheels [10, 11]. The mechanism consists basically on the silicon carbide abrasive action on the metal bond. In other words, the main objective is not to crush the grains but to set back the metal bond. Using this conventional method, on one hand, dressing tool costs are relatively low; on the other hand, dressing times are high. For this reason, metal-bonded diamond wheels are conventionally dressed

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on special designed dressing machines outside the grinding machine [11]. Furthermore, due to high wear ratio on the silicon carbide dressing wheels, macro-geometrical accuracy is generally poor, as well as grain protrusion is small [12, 13]. Moreover, when the grinding wheels are mounted onto the spindle of a grinding machine, eccentricity or unbalance of the wheel is liable to occur [14].

Aiming to improve the dressability of metal-bonded wheels, several methods have been proposed, such as the electrolytic in-process dressing (ELID), the electrochemical discharge machining (ECDM), and the electrical discharge dressing (EDD). ELID leads to an anodic dissolution of the metal bond, producing high grain protrusion [12]. However, only small material removal rates are achieved, and water-based fluid must be used. In the ECDM method, the anodic dissolution is assisted by electrical discharges [13, 15, 16]. Higher material removal rates are achieved, but like ELID, a special fluid has to be used, restricting its application directly inside the grinding machine. In EDD, the bond removal occurs by the thermal effect of electrical discharges. High macro-geometrical accuracy and, due to high discharge frequencies (10^3–10^6Hz), high material removal rates are achieved [17]. Grain protrusion is generated since diamonds are not electrically conductive. Two different electrical discharge machining (EDM) processes, wire EDM and die-sinking EDM, can be used for truing and dressing metal-bonded grinding wheels [11, 14, 18, 19]. However, most applications of this dressing method are carried out in EDM machines [18–23], not being integrated on grinding machines. In these cases, standard EDM dielectric liquids like hydrocarbon oil and de-ionized water are used.

This paper discusses the application of the wire electrical discharge dressing (WEDD) process for dressing metal-bonded grinding wheels. The process is carried out inside the grinding machine, and standard grinding oil is used for both the grinding and the dressing process. A WEDD unit was first designed and afterwards integrated into the grinding machine. Accordingly, the dressing process was analyzed, characterizing the grinding wheel topography, measuring the dressing material removal rates, investigating the dressing process at high erosion energies, and evaluating the eroded grinding wheel performance.

2 Design of a WEDD unit for dressing metal-bonded grinding wheels

A dressing unit based on the wire electrical discharge machining (WEDM) method was designed, manufactured, and integrated into a computer numerical control (CNC) universal cylindrical grinding machine Studer Type S31. One advantage of the WEDM method is the reduction of unwanted effects caused by electrode wear on the dressing accuracy using constant feed of tool electrode from a spool. Better macro-geometry of wheel profiles can be manufactured, without adding a complex device to compensate the electrode wear like it would be the case if using die-sinking EDM. Moreover, wire-cut EDM is more flexible, since different wheel profiles can be dressed using the same tool electrode.

Figure 1 illustrates the wire drives unit and the two axes feed system of the designed WEDD unit, which was mounted on the support of the internal grinding spindle.

The WEDD feed unit is composed basically of two controlled linear axes, which allows for relative displacement from tool electrode to grinding wheel in the two directions, Y and Z. Servo feed control of both axes use the gap voltage as sensing parameter, enabling to achieve a stable electric discharge dressing condition. The position control is made by accessing actual positions of the axes supply by two absolute linear encoders model LC 483 (Heidenhain). Measuring steps of 0.1 μm can be acquired.

A wire drive system is integrated into the feed system of the WEDD unit. This drive system adjusts and controls a constant wire feed speed, provides constant wire tension, and is responsible for the supply and disposal of the tool electrode. It is basically composed of one DC drive motor and a hysteresis clutch, which is responsible for keeping a constant tension on the tool electrode, brake wheels, belt pulleys, and a wire guide for positioning the wire relative to the grinding wheel. The wire guide is used to reduce vibration and deflection and also for supplying dielectric fluid to the erosion process. Through a special internal

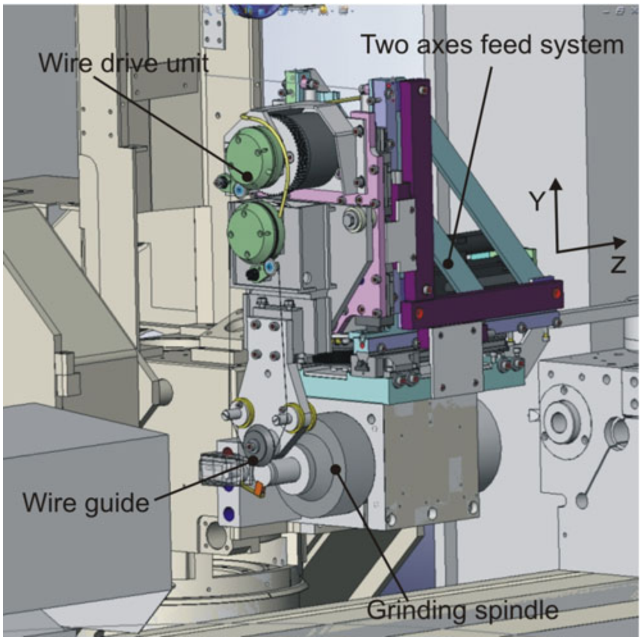

Fig. 1 Wire drive unit and feed system of wire electrical discharge dressing unit

channel machined on the wire guide, the dielectric fluid is guided pressurized directly into the erosion zone, ensuring a suitable erosion process.

Figure 2 shows the WEDD unit assembled and integrated into the grinding machine. The WEDD unit is covered with an enclosure, protecting it from grinding fluid as well as abrasive grains and grounded chips. This assembly allows an independent movement of the wire relative to the grinding axes, allowing an in-process dressing. The CNC system of an EDM wire-cutting machine, from GF AgieCharmilles was used to control the dressing unit.

3 WEDD—experimental work, results, and discussion

In order to evaluate the feasibility of wire EDM for truing and dressing metal-bonded diamond wheels, dressing and grinding tests were carried out. A grinding wheel, manufactured by Diametal AG, with the following specification, was used: 1A1-50-5-20-D46-C125-M263. It consists basically of a bronze alloy (M263) impregnated with diamond grains (D46), at a grain concentration of 30% in volume (C125). The diameter of the grinding wheel is 50 mm, and the width is 10 mm. A universal plunge grinding machine model Studer S31 was used for grinding silicon nitride workpieces. The workpieces were machined with both WEDD and conventional dressed grinding wheels. High-performance grinding oil, Blasogrind EDM 5, manufactured by Blaser Swisslube AG, was used for both grinding and dressing tests.

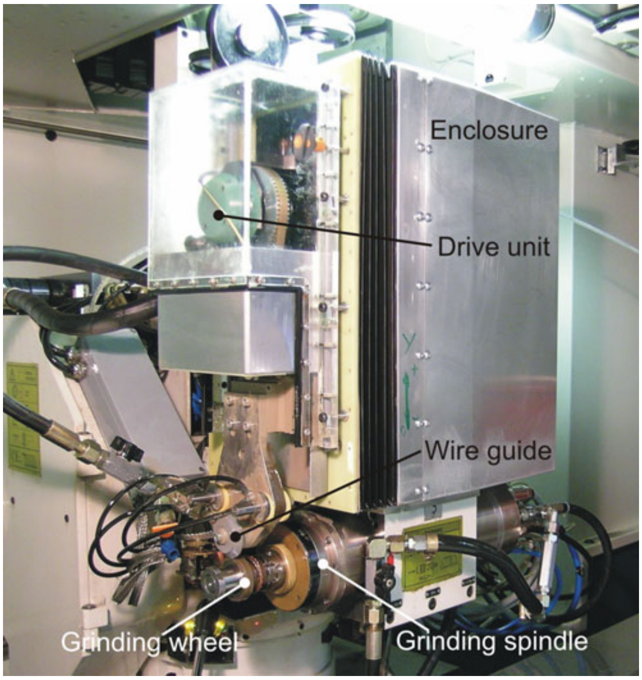

Fig. 2 Wire electrical discharge dressing unit integrated into the grinding machine

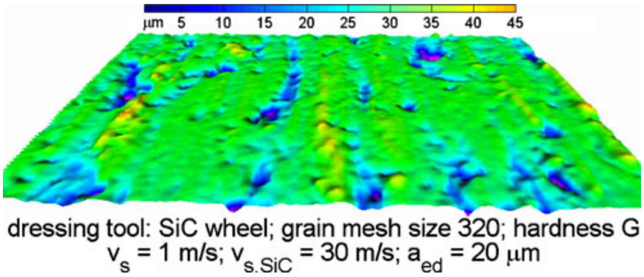

Fig. 3 Surface topography of a conventionally dressed metal-bonded grinding wheel

The used wire-cut electrode was a zinc-coated brass wire of 0.33 mm in diameter, type CobraCut V. For the conventional dressing process, a silicon carbide wheel was used.

4 Grinding wheel surface topography

In grinding wheels, grain protrusion is an important factor to achieve suitable grinding performance. The existence of sufficient porosity guarantees the collection of the chips as well as the transportation of cutting fluid into the grinding zone. The dressing method influences decisively the surface topography of the grinding wheel. Figure 3 shows the surface topography of a conventionally dressed grinding wheel, dressed with a SiC dressing wheel. The wheel surface was measured using an optical 3D measurement device Alicona InfiniteFocus. The wheel does not show an aggressive characteristic, since only small grain protrusion can be achieved by this dressing method. The traces in the surface clearly point out the dressing direction. According to Schöpf et al. [13], these traces on the wheel surface affect the workpiece surface quality negatively. They can be found on the ground workpiece surface.

On the other hand, Fig. 4 shows the same grinding wheel, now dressed by WEDM. Higher grain protrusion in comparison to the conventional dressed wheel is achieved,

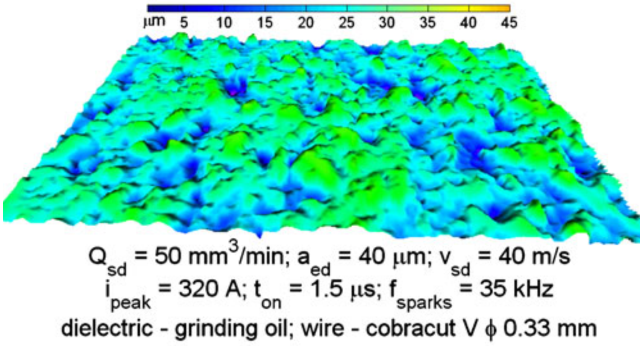

Fig. 4 Surface topography of a wire electrical discharge machining-dressed metal-bonded grinding wheel

and the grinding wheel shows a well-homogenized distribution of grains and chip spaces on the surface topography, which is independent on the dressing direction.

The WEDM process allows the generation of grain protrusion, since diamond grains are not electrical conductors, and therefore cannot be eroded. However, diamond grains are also removed during the erosion, as from a certain protrusion, the grains no longer have a sufficient retention force and are “pulled out” from the grinding wheel. The effect of this removal mechanism can be observed in Fig. 5, a micrograph of a WEDM-dressed grinding wheel surface taken using a scanning electron microscope. Marks left by the removed diamonds can be clearly identified on the surface of the metal bond (red arrows), indicating that diamond grains were removed during the dressing process.

Figures 6 and 7 illustrate the Abbott–Firestone curve and show some 3D surface parameters used to describe the topographies previously illustrated in Figs. 3 and 4, respectively. The 3D parameters are similar in definition to 2D parameters. They are calculated over an area rather than a profile. Thus, the values of S_a, S_k, S_{pk}, and S_{vk} are analogues to R_a, R_k, R_{pk}, and R_{vk}. The parameter S_a indicates the average height of the selected area, S_k the core roughness depth, S_{pk} the reduced peak height, and S_{vk} the reduced valley height.

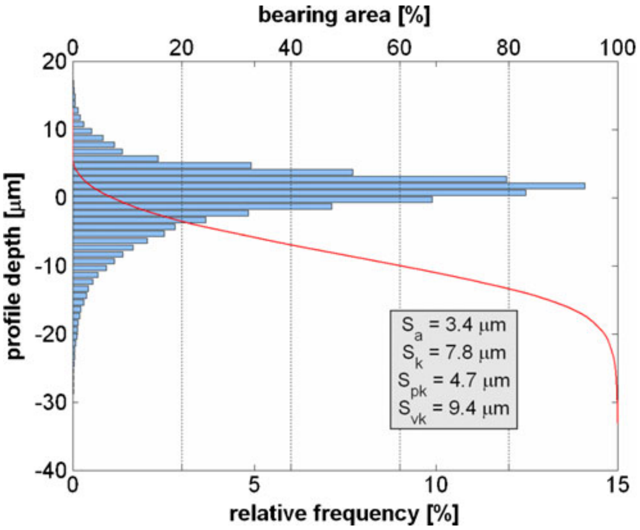

Fig. 6 Abbot–Firestone curve of a conventional dressed metal-bonded grinding wheel

The higher value of S_a for the WEDM-dressed wheel underlines the efficiency of WEDD on producing a very rough (aggressive) topography in comparison to the conventional method. Secondly, the WEDM-dressed wheel has higher S_{pk} values, indicating a surface with higher peaks. The profile depth distribution of the WEDM-dressed wheel extends over a wider range, resulting in a higher S_k value. Higher S_k values points out higher grain protrusion, indicating higher efficiency in removing material. This would be the case for WEDM-dressed grinding wheels, which have a more aggressive topography in comparison to the conventionally dressed ones.

Finally, Fig. 8 shows a micrograph of a WEDM-dressed grinding wheel surface. In the center, three geometrically well-defined diamond grains with high protrusion are visible, while on the top of the figure, new grains are starting to emerge from the metallic bond. A typically EDM melted surface is shown, where, for example, resolidified spherical particles were reattached to the wheel surface as well as to the diamonds. No damages were found on the diamonds surfaces after erosion. Schöpf [15] reported, however, that micro-holes were found in the diamond surface after erosion. According to Klocke et al. [20],

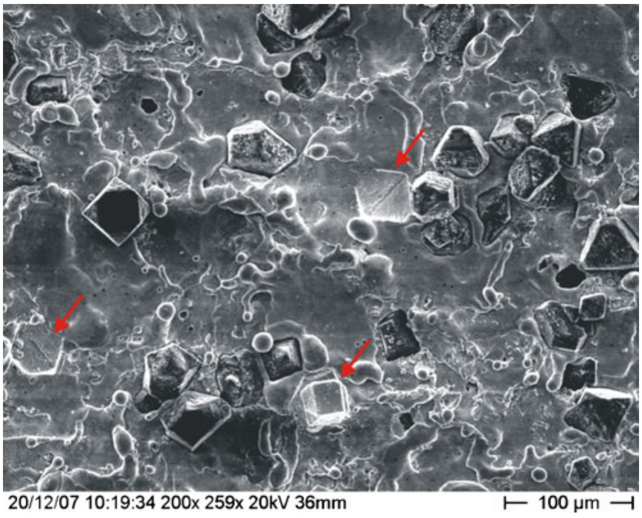

Fig. 5 Grain pull-out during erosion

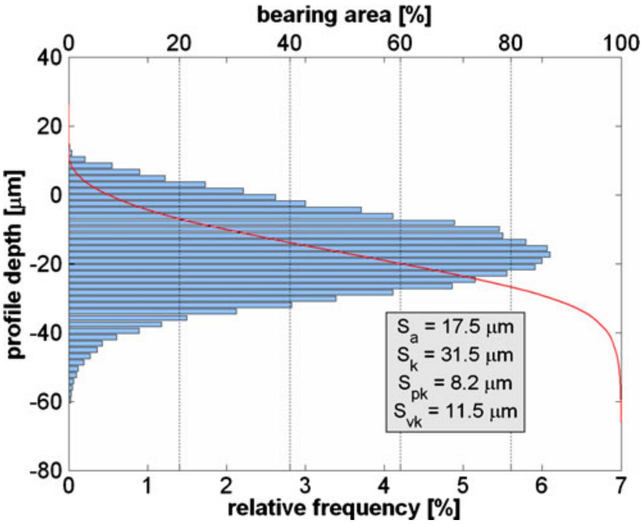

Fig. 7 Abbot–Firestone curve of a wire electrical discharge machining-dressed metal-bonded grinding wheel

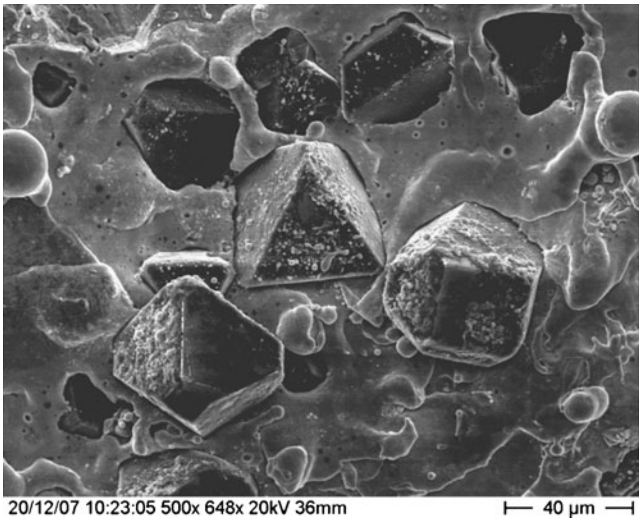

Fig. 8 Scanning electron micrograph of a wire electrical discharge machining-dressed metal-bonded grinding wheel

thermal damage of the diamond grains takes place after EDM dressing. However, the graphitization is limited to a very thin layer on the surface of the diamond, so that grinding can still be performed.

5 Influence of the dressing method on grinding

In order to evaluate the influence of the dressing method on the grinding wheel performance, plunge grinding tests were carried out on grinding silicon nitride workpieces. For each grinding test, a total specific material removal of 2,000 mm^3/mm was ground. A specific material removal rate of 10 mm^3/mms was used. Grinding oil type Blasogrind EDM 5 was applied for both WEDD and grinding. The cutting forces were acquired by using a rotating dynamometer type Z15168 SN473735 from Kistler. The wheel wear was directly measured with the optical 3D measuring device Alicona InfiniteFocus.

Figure 9 shows the results of tangential cutting forces for both dressing methods after grinding different grinding volumes. For these experiments, the grinding wheel speed was set to 60 m/s. Additionally, the wear parameter G-ratio, which is defined as a volume of ground material divided by the volume of wheel wear, is also shown. The higher the G-ratio, the better is the grinding performance concerning wheel wear. As shown in the figure, smaller cutting forces and higher G-ratios were achieved by using the WEDM-dressed grinding wheel. This better performance mainly results from the higher grain protrusion generated by erosion. As mentioned earlier, chip space helps cooling and lubricating the grinding zone and inhibits stuffing of chips. Both help reducing the generated heat during grinding, hence reducing cutting forces and wheel wear. The results also do not indicate any significant damages on the diamonds dressed by WEDD, even by dressing the wheel at high erosion energies (high current peak values with high discharge frequencies).

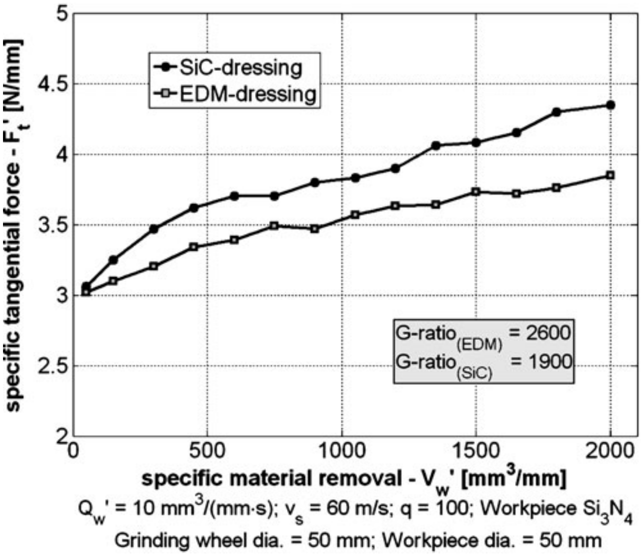

Fig. 9 Influence of the dressing method (SiC, wire electrical discharge dressing) on grinding forces and wheel wear

6 Material removal rate of WEDD process at dressing metal-bonded grinding wheels

Another key point concerning WEDD is the acceptable material removal rate during the dressing process. In order

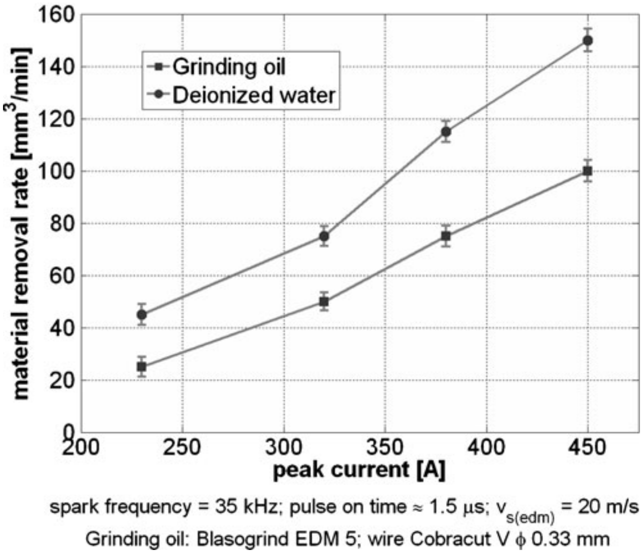

Fig. 10 Wire electrical discharge dressing material removal rate using grinding oil and de-ionized water

to minimize downtime and increase productivity, non-productive time related to dressing operations should be reduced. Small dressing times are prerequisite for on-machine dressing being acceptable. Dressing tests were carried out with two different dielectric fluids: de-ionized water and grinding oil. The first is a standard fluid used in most wire EDM machines. The tests with de-ionized water were carried out on a wire-cutting EDM machine model AC Progress VC4 from GF AgieCharmilles. The second fluid is a high-performance grinding oil, slightly modified (Blasogrind EDM 5), which was used directly on the grinding machine Studer S31.

Figure 10 shows the results of material removal rate obtained by dressing with each dielectric fluid. Different erosion energies were applied by increasing the peak current values and keeping a constant discharge frequency. First of all, material removal rates in WEDD were higher by using de-ionized water for all applied discharge energies (approximately 30% higher in comparison to grinding oil). Grinding oil has lower electric conductivity in comparison to de-ionized water, leading to smaller gaps between wire electrode and grinding wheel, which reduces the total material removal rate. However, the achieved material removal rates using grinding oil allow the dressing process to be carried out within acceptable times. For example, for a grinding wheel with a diameter of 400 mm and width of 10 mm, eroding a radial depth of dressing cut of 0.010 mm will take about 75 s. Especially for metal-bonded diamond wheels, this time indicates a very fast and efficient dressing process.

Another crucial result is the suitability of the grinding oil for a WEDM process. In WEDM processes, the workpiece is generally submerged in a dielectric fluid. In WEDD on the grinding machine, this would not be possible, and free jet nozzles must be used to deliver dielectric fluid to the erosion zone. The dielectric fluid used did not lead to any dangerous fluid ignition, even for high erosion energies. The application of grinding oil with a high flashpoint, like the one applied during the WEDD tests (Blasogrind EDM 5), is very important in this case. This fluid has a flashpoint of 165°C. According to the VDI guidelines 3400, substances with flashpoints lower than 21°C (danger class AI) are not allowed to be used in electric discharge machining. Most dielectrics used in EDM have flashpoints higher than 55°C, hence belonging to danger class AIII. Dielectrics with flashpoints greater than 100°C are classified as non-dangerous [24].

7 Conclusion

A WEDD unit was designed and integrated into a grinding machine, allowing metal-bonded grinding wheels to be dressed in a very flexible way. In-process dressing can be carried out since the unit was mounted on the structure of an internal grinding spindle. The WEDD method enables higher grain protrusion on metal-bonded diamond wheels in comparison to the conventional dressing method with SiC wheels. So, the wheels allow for a very aggressive grinding process. Lower cutting forces and better wheel wear ratio were achieved by using the WEDM-dressed wheels in comparison to conventionally dressed ones.

The use of grinding oil for both grinding and erosion processes proved to be suitable. Erosion material removal rates up to 100 mm^3/min were achieved, allowing the dressing process to be carried out within a reduced time. This is an important criterion for making WEDD to be carried out economically on the grinding machine. Although the EDM material removal rate is smaller by using grinding oil in comparison to de-ionized water, the advantages of carrying out the dressing process on the grinding machine outbalance the higher material removal rate by far. For example, non-productive times are reduced, and wheel-clamping errors are eliminated.

The applied WEDD technology, as a dressing method to be used directly on the grinding machine, proved to be suitable, flexible, effective, and reliable, ensuring a significant improvement on the dressability of metal-bonded diamond wheels.

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