CIRP Annals - Manufacturing Technology xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Conditioning and monitoring of grinding wheels

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ARTICLE INFO

Keywords:
Dressing
Grinding tool
Conditioning

ABSTRACT

The preparation of grinding tools is the most important enabling factor in the grinding process. It influences the material removal rate, the grinding forces, the surface quality as well as the material properties of the subsurface zone, and is the key issue for subsequent wear of grinding tools. The evolving and conventional conditioning technologies are reviewed based on technical and commercial aspects. Terms in the field of conditioning are defined. Strong emphasis today is put on the description and monitoring of the abrasive layer. For optimization of the dressing process, prediction of the grinding wheel topography and the ground surface are emerging scientific topics.

1. Introduction

"Grinding is dressing," is the slogan that is maintained in the grinding community. It indicates besides all other process parameters, the importance of conditioning technology on the manufacturing results. The conditioning process, consisting of dressing and cleaning, determines the material removal rate, the grinding forces, the surface quality and the material properties of the subsurface zone.

Preparation of grinding tools is classified in different tasks to be performed either simultaneously or sequentially like cleaning, sharpening and truing. More frequently, tools are also structured. The tool, thus develops into a complex and highly sophisticated system and requires careful treatment and monitoring, when reconditioning is necessary. Besides further development of indirect monitoring, direct observation of the tool's topography modification advances, in correlation with the possibilities of fast image processing, which raises the question of how well the topography performs and how it should look like. Therefore in some publications, models of grinding and dressing arise with the aim of predicting the grinding result from the knowledge of the topography and further from the dressing technology.

The paper aims at introducing different conditioning technologies, with special emphasis on new ones, what is the state of the art, where are typical for future application fields, and what can be expected from those technologies. The paper also aims at setting clear definitions of terms in conditioning.

Generally, the interaction between the workpiece and the surface of the grinding wheel defines the grinding process. Viewed from this aspect, the grinding wheels are composed of three elements, the abrasive grit for material contact and – removal, the intergranular space for the storage of removed material and the coolant flow, and the bond to retain the grit on the wheel.

Grinding wheels are distinguished by their abrasive material and classified as conventional (aluminum oxide and silicon carbide) and superabrasive (cubic boron nitride and diamond) grinding wheels (Fig. 1.1). They are further classified with respect to their bonding system. Ceramic bonded grinding wheels contain pores within the wheel body which create the intergranular space when dressed. For metal and resinoid bonded grinding wheels the intergranular space must be created within the dressing process. Metal bond grinding wheels are mostly used for superabrasive grains because of their improved bonding strength. From the appearance of the grinding wheel one can distinguish micro geometry and macro geometry. The macro geometry is described by a convex hull over all protruding grains in circumferential direction and average profile in meridian direction. The micro geometry is given by geometric features in the dimension of a grain or an intergranular space.

During the grinding process, mechanical, thermal and chemical loads are applied to the grinding wheel. One effect of these loads is wear, where macro wear describes the deterioration of the macro geometry which consists of radial wear and edge wear according to Fig. 1.2. This leads to a change in profile, size errors and runout. Fig. 1.3 illustrates micro wear, which describes the change of the micro topography [85].

Micro wear refers to wear on the grain level and is classified as four types displayed in Fig. 1.3.

If a complete grain is removed from the grinding wheel, this is called pullout. Due to high loads, the bond material bursts or the interface between bond and grain fails. In case the local load on one grain is unbearable, grain portions break off, creating new sharp but normally inactive cutting edges. This process is called grain breakage. During grinding, there is by definition a contact between cutting edges and material. This contact is responsible for grain abrasion, leading to grain wear which consists of attritious wear and therewith to flat and blunt cutting edges [32], micro fracture and macro fracture. Contact between the bond and chips lead to bond wear, which weakens grain retention. The sequence of

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0007-8506/$ – see front matter © 2011 CIRP.
doi:10.1016/j.cirp.2011.05.003

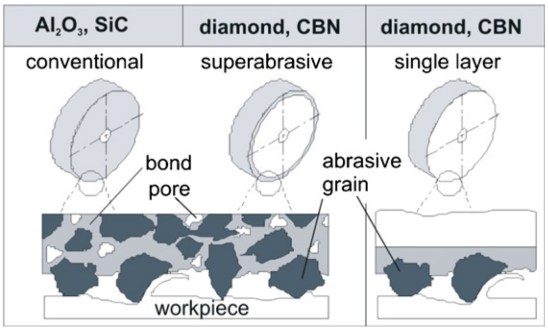

Fig. 1.1. Grinding wheel configuration.

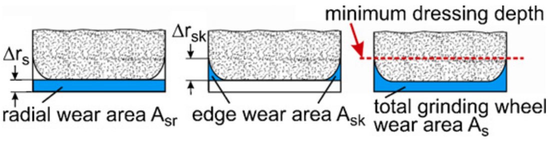

Fig. 1.2. Macro grinding wheel wear.

damage begins with attritious wear in the contact zones accompanied by an increase in the forces per grain or a weakening of the grain retention forces, giving rise to more prominent grit failure and furthermore leading to increased heat generation, which in turn increases wear and damages the workpiece surface integrity. All types of wear appear in parallel on the grinding wheel and can be minimized by the suitable set-up of the grinding process and wheel specification [32].

Information about the microscopic wear state, the surface topography as well as the profile and runout need to be acquired in order for suitable redressing only with the indispensible material loss to remove the wear state and provide a new micro and macro geometry. Different direct and indirect possibilities exist, and partly can be used as in-process monitoring. To reduce heat generation, grinding wheels are more often being structured before use which aims at enhancing the cutting condition for each grain by increasing chip thickness per grain and grinding efficiency.

The most important parameter to quantitatively describe grinding wheel wear is the grinding ratio G. It relates the volume of workpiece material removed V_w, to volume of abrasive wear V_s:

$$G = \frac{V_w}{V_s} \tag{1.1}$$

Due to increasing requirements from the workpiece in terms of material strength and quality, super abrasives and corresponding high performance bonds come into existence. These impose increasing requirements on the dressing process and lead to the development of alternative and unconventional dressing technologies such as chemical, electroerosive, laser and waterjet dressing technologies, where some of them have progressed rapidly to maturity, in some cases with the capability for in-process dressing, achieving constant grinding.

2. Terms and definitions

The term conditioning contains all different processes for preparation and regeneration of the grinding wheel macro and

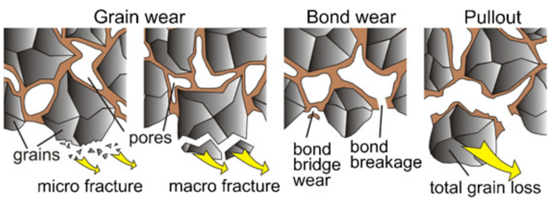

Fig. 1.3. Micro wear mechanism, according to König and Schulz [88].

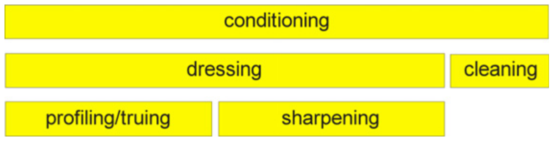

Fig. 2.1. Conditioning according to [183].

micro geometry influencing the grinding wheel topography. According to Spur, conditioning is classified into dressing and cleaning (Fig. 2.1). Dressing can further be classified into profiling respectively truing and sharpening, which also holds for new and alternative dressing methods [51,164,183].

Profiling contains the generation of the grinding wheel profile and macro geometry in axial and radial direction. This includes profile and runout accuracy [184,44].

Sharpening is necessary for generating the required micro geometry by resetting bond material. Thus, worn grains are removed and new cutting edges are generated [106,111].

The cleaning process removes remaining workpiece material and residues of grain and bond. Grain and bond itself stay unaffected. Cloggings, which reduce the chip space and impede that cooling lubricant reaches all points of the grinding wheel, are removed [85,120,160,163].

Vitrified bonded grinding wheels with aluminum oxide or silicon carbide grains can be simultaneously sharpened and profiled within one process called dressing [164]. For dressing of resin and metal bonded grinding wheels usually two separate processes and tools are required for profiling and sharpening.

For monolayer grinding wheels the only conditioning operation possible, is to bring the edges of abrasive grains to an equal and smooth radial alignment by using a very low depth of dressing cut. This conditioning process is then called touch dressing [40,164,163,171].Formulae characters for dressing are indicated by an index “d” like “dressing” at the otherwise well known symbols of grinding parameters. The input parameters of dressing depend on the dressing tool and dressing process (Fig. 2.2). The depth of dressing cut a_{ed} is required to determine the active width of dressing tool b_d, while r_{pd} is the radius of the dressing tool. The number of contacts of the grinding wheel surface and the dressing tool is given by the overlapping rate in dressing U_d (2.1), which contains the active width of cut a_{pd} and the axial dressing feed per grinding wheel revolution f_{ad}:

$$U_d = \frac{a_{pd}}{f_{ad}} = \frac{1}{2} + \frac{\sqrt{(2r_{pd}a_{ed})}}{f_{ad}} \tag{2.1}$$

By filling in the following equations for the width of cut a_{pd} and the active width b_d of the dressing roller and considering that that a_{ed} is much smaller than r_p then:

$$a_{pd} = \frac{1}{2} \cdot (b_d + f_{ad}) \tag{2.2}$$

$$b_d = \sqrt{(8r_{pd}a_{ed})} \tag{2.3}$$

Assuming that the width of cut equals the active width of the dressing tool, the overlapping rate is:

$$U_d = \frac{b_d}{f_{ad}} = \frac{\sqrt{(8r_{pd}a_{ed})}}{f_{ad}} \tag{2.4}$$

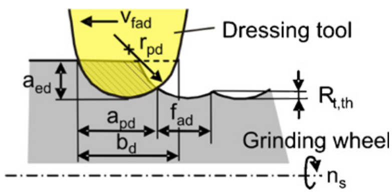

Fig. 2.2. Cutting conditions in dressing.

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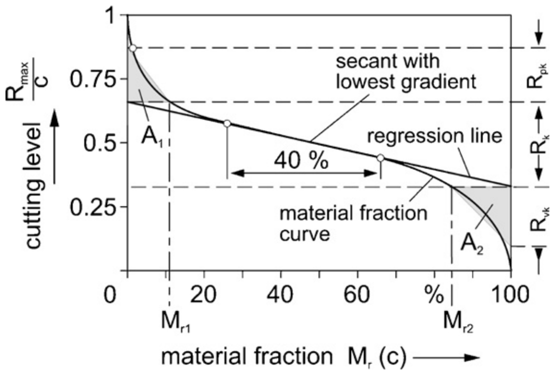

Fig. 2.3. Abott-curve and depending parameters [125].

Dressing processes with rotating dressing tools are highly effected by the ratio q_d of dressing speeds of grinding wheel circumferential speed v_{cd} and dressing tool circumferential speed v_{rd}:

$$q_d = \frac{v_{rd}}{v_{cd}} \tag{2.5}$$

Equivalent to the grinding ratio G according to (1.1) the dressing ratio G_d is the ratio between dressed grinding wheel volume V_{sd} and dresser wear volume V_d [119]:

$$G_d = \frac{V_{sd}}{V_d} \tag{2.6}$$

The most important parameter in sharpening is the material removal rate. The amount of required abrasive in sharpening determines the effectiveness of the process. In jet sharpening a large amount of abrasive is required to achieve the desired grain protrusion. In contrast, block sharpening is much more effective, although, the material loss of the sharpening block is much higher than of the grinding wheel [162,163].

Besides the common effective roughness parameter, the parameters of the Abbott-curve are used to describe micro geometry parameters (Fig. 2.3). It can be gauged with tactile and optical measurement systems. The secant covers over 40% of the Abbott-curve. The secant with the lowest gradient is found by adjusting the secant over the Abbott-curve and used to build the partial regression line. This line is required to find the reduced peak height R_{pk}, core roughness depth R_k and the reduced valley depth R_{vk} [125].

3. Classification of conditioning processes

While in the past only mechanical based dressing processes were known, today thermal, chemical and hybrid processes have emerged and the number of dressing processes is continuously growing. Fig. 3.1 shows a classification system of dressing processes currently known.

Usual classification criteria of conditioning processes are the process kinematics, the active medium and the active principle. After the active principle, cutting processes, erosive processes (electrochemical and spark-erosive) and forming processes can be distinguished [111]. This paper deals with these different aspects.

3.1. Classification by the type of profile generation

As shown in Fig. 3.2 mechanical dressing is classified in form dressing and profile dressing. The dressing process is termed form dressing, if the geometry is created by leading the tool in axial and radial direction, generally CNC controlled. Because there is no direct coherence between the dressing tool geometry and the desired grinding wheel geometry any desired profile can be created [120]. Path controlled dressing is possible with both rotating and fixed dressing tools. The major advantage is the dressing flexibility. Nevertheless the dressing time is increased

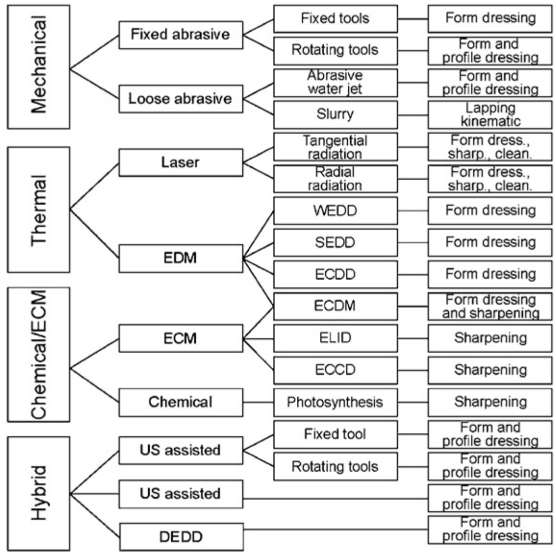

Fig. 3.1. Classification system for grinding wheel conditioning (green = usable for continuous dressing).

[127]. In general form dressing is conducted with a mixture of pull und push dressing. In pull dressing the dresser is moved from the lowest profile point outward of the grinding wheel to the highest point. Push dressing is just the reverse [29].

The process is called profile dressing if the desired profile of the grinding wheel is fully shaped as a negative in the conditioning tool and the grinding wheel profile emerges by radial plunge of the conditioning tool into the grinding wheel. Because of the small dressing flexibility, this technique is mostly used in serial and large batch production. Major advantage is the short dressing time per dressing cycle [120,127].

3.2. Process strategy/continuous dressing

Due to increasing wear during grinding, conditioning is necessary according to specific tool-life criteria. Embedding conditioning into the grinding process gives rise to procedural classification. Once the tool-life criterion is reached the grinding process is interrupted and the grinding wheel needs to be conditioned. To reduce machine and clamping influences and interrupt times of the grinding process, dressing today is normally done by a dressing device on the grinding machine in sequence to the grinding process. If the grinding wheel is dressed during grinding, the process is termed continuous dressing (CD) [216]. Continuous dressing is characterized by constant contact between grinding wheel and dressing tool and hence, a continuous volume reduction of the grinding wheel during grinding. High wheel loads during grinding of difficult-to-grind materials lead to a faster grinding wheel wear, especially at conventional grinding wheels. In case of continuous dressing the grinding wheel is getting regenerated simultaneously which allows steady sharp cutting edges and high cutting power. Thus, one of the most important applications is in creep feed grinding of super alloys, especially for turbine blades. Due to constant feed of the profiled dressing tool, the grinding wheel diameter is reduced correspondingly. The machine control has to compensate this reduction, as shown in Fig. 3.3 [85,120].

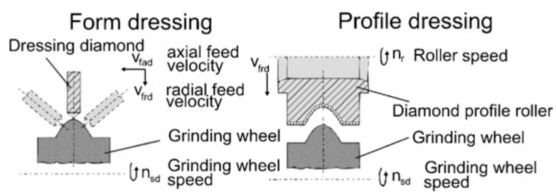

Fig. 3.2. Kinematics during form and profile dressing [120].

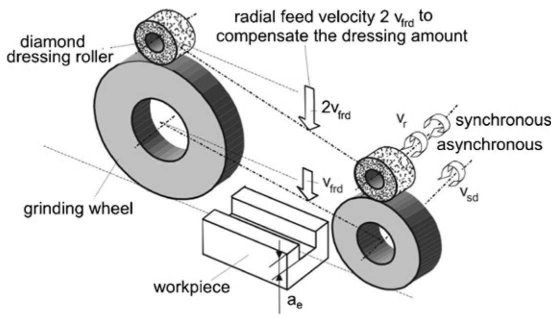

Fig. 3.3. Depth of dressing cut during continuous dressing [85].

4. Mechanical dressing with bonded abrasive tools

Mechanical dressing processes with bonded abrasives are the most common dressing processes. If the dressing tools are not performing any rotation around an axis they are called fixed dressing tools. Using rotating techniques, the dressing tools fulfill an additional rotation.

4.1. Fixed dressing tools

Mechanical dressing of grinding wheels with fixed tools includes dressing with bonded diamonds, block sharpening and free grinding.

4.1.1. Fixed truing tools

Truing of conventional grinding wheels with dressing diamonds is a standard process used with long process time and low tool costs [184]. Depending on the tool, there is a point or line contact. The tools can have one cutting edge or multiple edges, which can be stochastically spread or set after pattern (Fig. 4.1) [117,120].

Due to wear of dressing diamonds the overlapping ratio varies over time and the dresser feed needs to be adjusted to achieve a homogeneous grinding wheel topography [39,116,117,204,148]. Diamond dressing tools with a constant cross-section keep their effective width over the complete period of application [177].

A sufficient coolant flow is essential for mechanical dressing, as the coolant supports the removal of trued abrasive and bonding material. Furthermore, the coolant provides the required cooling of the truing diamond in order to prevent heat accumulation [204]. The thermal stability of diamonds ends at 720 °C, while corundum stays stable until 1160 °C. Thus, dressing temperatures of over 720 °C can cause abrasive wear of diamond through corundum [119].

The effective grinding wheel behavior is mainly determined by the surface topography, which is affected by the overlapping rate. Increasing the overlapping rate leads to a rising number of static and kinematic cutting edges. If the effective width of the dressing tool is higher than the axial feed velocity per revolution, each section of the grinding wheel surface is manifold overlapped during the dressing process [119]. Profile dressing requires an adjustment of overlapping ratio with changing dressing conditions. Otherwise, passive forces are generated in the grinding process [24].

Small dressing feed velocities can lead to insufficient grinding wheel topography, if the grinding wheel is not opened. The abrasive grains do not brake and thus, no sharp cutting edges are formed [204].

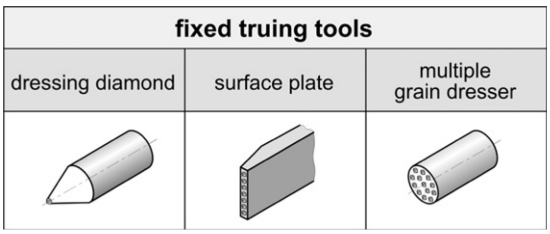

Fig. 4.1. Kinematics of fixed dressing tools [85].

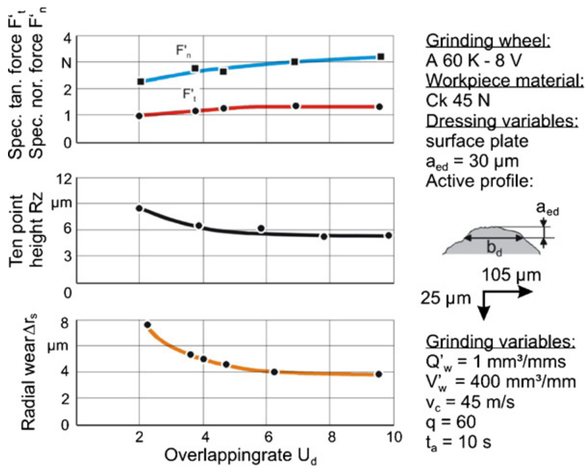

Fig. 4.2. Influence of the overlapping rate on process variables and the surface [85].

After dressing with high overlapping rates, the grinding wheel has a small effective roughness with a large amount of grain cutting edges and a small grain exposure (Fig. 4.2) [85]. Depending on the actual grinding wheel specification, there is a maximum reasonable overlapping rate. A further increase does not lead to an improvement of surface properties and is just increasing the dressing time [85].

4.1.2. Fixed sharpening tools

In sharpening with fixed sharpening tools two procedures are distinguished, block sharpening and free grinding.

4.1.2.1. Block sharpening. Especially in profiling resin or metal bonded CBN-grinding wheels the required grain protrusion cannot be generated. Thus, a subsequent sharpening process is required [171,70]. Block sharpening is operated under different kinematic conditions (Fig. 4.3). A rod shaped sharpening tool with height h_{dB}, width b_{dB} and length l_{dB} made of corundum or silicon carbide in vitrified or resin bond is used for block sharpening.

Since the abrasive grains of the grinding wheel are harder than those of the sharpening block, the sharpening block grain splits or is pulled out of the bond when hitting a grinding wheel grain. Predominantly, sharpening block grains are shred and fill the pores of the sharpening block where they are contemporarily fixed. Thus, manifold fine cutting edges are produced aiding cutting of the grinding wheel bond. With persisting sharpening process the chip space is enhanced until half the grain diameter is reached. Further sharpening causes grain pull out (Fig. 4.4) [70]. In the back of abrasive grains so called bonding spines are generated since the

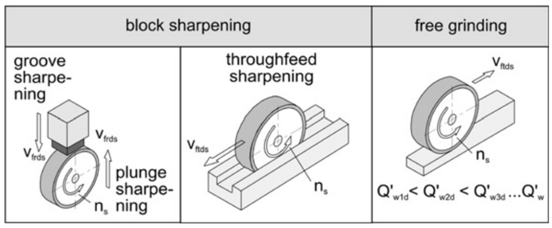

Fig. 4.3. Sharpening processes with bonded abrasives.

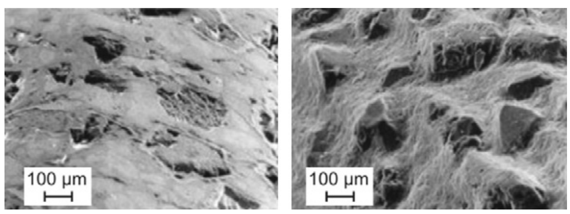

Fig. 4.4. (a) Left: wheel topography after profiling and (b) right: wheel topography after block sharpening [85].

sharpening material cannot cut the bond material at these places. The bonding spines support the abrasive grain in cutting direction [40,171].

The wetness of the sharpening block is very important since a papescent mixture of coolant and corundum grains of the sharpening block is generated, which is essential to remove the grinding wheel bond. Thus, the sharpening block needs to be soaked with coolant before or during the sharpening process [216,59].

Block sharpening processes are distinguished regarding process kinematics and controlling of the depth of cut of the sharpening block (Fig. 4.3) [181]. The feed is either controlled by constant force or constant velocity. The advantage of constant force is that force peak values at process start can be avoided. Nevertheless, force controlled sharpening is quite time consuming especially if the grinding wheel topography is very smooth after profiling. Furthermore, there is no interrelation between surface topography and feed velocity [171].

The advantage of feed controlled sharpening is the possibility to determine the grinding wheel topography due to defined kinematics. The well-known relation between material removal rate in sharpening and grinding wheel topography can be used. However, the process begins with unacceptable force peaks, especially if the grinding wheel is very smooth [171].

Through feed sharpening is also used for micro grinding wheels. Nevertheless, due to the effect on grinding wheel geometry, this process is limited to unprofiled grinding wheels with hard bond material [55].

4.1.2.2. Free grinding. The self sharpening ability of grinding wheels is used to achieve the required chip space in free grinding. The chip outflow cuts the grinding wheel bond and thus, leads to higher grain protrusion. The advantage of free grinding is the comparatively easy process set up because it can be conducted with and workpiece material. It is recommended to adjust the grinding wheel topography stepwise to allow a higher material removal rate due to a multistage free grinding process [187].

4.2. Rotating dressing tools

For rotating techniques, both the grinding wheel and the dressing tool are rotating, leading to an important variable of the dressing process, the speed ratio q_d. Rotating dressing tools normally have multiple cutting edges and can be used to generate any desired profiles with various complexities (Fig. 4.5). Opposite to fixed dressing tools, rotating dressing tools have a better wear resistance, because the dressing task is carried out by numerous grains [107,120,184].

The process is defined by the tool parameters number of cutting edges, grain size and minimum profile radius [184]. Small profile radii demand small diamond grain size, which reduces the dressing roller lifetime (Fig. 4.6) [87,120].

The accuracy of the grinding wheel is greatly determined by the precision of the dressing tools and thus, by the manufacturing method. Manufacturing with the positive method, the diamond grains are being applied directly upon a tool body. The uncertainty of the grain size thus determines the achievable precision of the dressing tool as shown in Fig. 4.7 [85,126]. For more precise tools the negative method is applied, where a high-precision negative profile, made of graphite or metal, is used. In this lost mould the diamonds are getting inserted hand-set or scattered. After inserting the body, the diamonds are being fixed on it by sintering or by galvanic bond.

The dressing system needs to have a high stiffness under static and dynamic loads to achieve reproducible high-precision dressing results [51,88]. The rotational speed of the grinding wheel in grinding and dressing should be equal, to avoid deviations due to centrifugal forces [111].

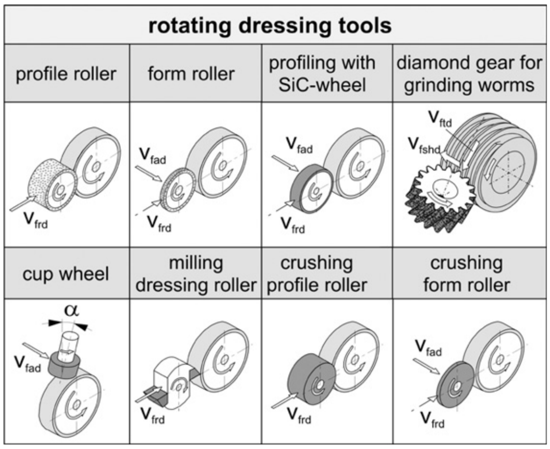

Fig. 4.5. Kinematics of rotating dressing tools.

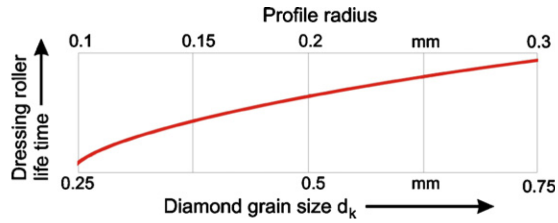

Fig. 4.6. Roller life time in dependence of diamond grain size and corresponding profile radii [84,120].

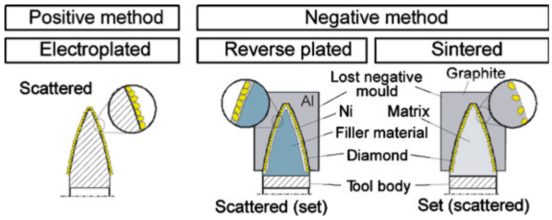

Fig. 4.7. Manufacturing methods of diamond rollers [126].

To gain the desired grinding results, it is absolutely necessary to know the influence of the input parameters and their combinations on the dressing result. Therefore, the most important influences are discussed in the sequel.

As illustrated in Fig. 4.8, with increasing radial dressing feed, the chip thickness and consequently effective roughness of the grinding wheel is proportionally increasing. Increasing effective roughness leads to smaller process forces and so reduces grinding power, which allows lower process temperatures. With low dressing feed more but smaller cutting edges emerge since grain pullout is reduced. The effective roughness is higher during down (synchronous or $q_d > 0$) dressing compared to up (asynchronous or $q_d < 0$) dressing with the same dependence on the radial dressing feed [120,216].

The speed ratio q_d highly influences the grinding wheel topography and thus grinding forces and workpiece roughness.

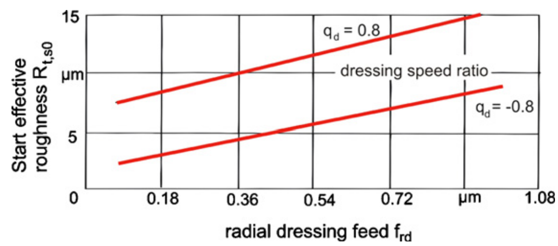

Fig. 4.8. Dependence of the effective roughness on the radial feed for different speed ratios [120,157].

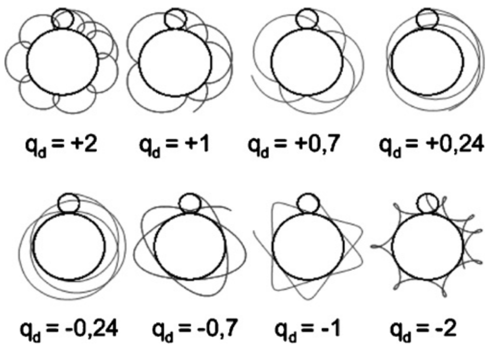

Fig. 4.9. Theoretical pathways of the dressing grains [51,173] upper row down dressing lower row up dressing.

The grinding wheel topography is described by the effective roughness $R_{t,s}$. It quantifies the peak-to-valley expansion of the cutting space and is decisive for the possible cutting power and the achievable surface quality of the workpiece [128].

The grains of the roller move on cycloid pathways relative to the grinding wheel. Assuming single point diamonds and ideal radial run-out of the dressing roller, the pathways can be calculated analytically [51,1,43,88,120,184,34,224]. In Fig. 4.9, the pathways for different speed ratios are illustrated.

The steeper the pathways leave the grinding wheel the higher is the effective roughness. During down dressing the pathways are significantly bent. Thus, a large radial force is applied to the grinding wheel, which leads to crushed and splintered grains. During up dressing the pathways run elongated flat and the particular impact partners have a large tangential velocity component, which leads to a shear off of grains in very short time. Thus, there is no crushing and splintering (Fig. 4.10) [1,11,184,51,173].

Flattening of diamond cutting edges is increased in up dressing through roll outs. This means that grinding wheel and dressing roller are rotating on each other without further radial motion, comparable to a spark-out phase during grinding. Thus, the number of active grains is increased and a better workpiece surface roughness can be achieved [43]. As shown in Fig. 4.11, with smaller depth of dressing cut better surface quality can be achieved [23].The suitable depth of cut also depends on the grinding wheel grain material. CBN grinding wheels are dressed with much smaller depths of cut because the dressing forces are much higher compared to those of dressing conventional grinding wheels due to stronger bond bridges and harder grains (Fig. 4.12) [23].

Wear occurs also at the dressing tool depending on process parameters, removed volume of the grinding wheel and the wear resistance of the truing tool, esp. the grains [86], which recommends diamonds as abrasive. The breakage behavior of the diamonds mainly occurs at the edge of the truing roller and

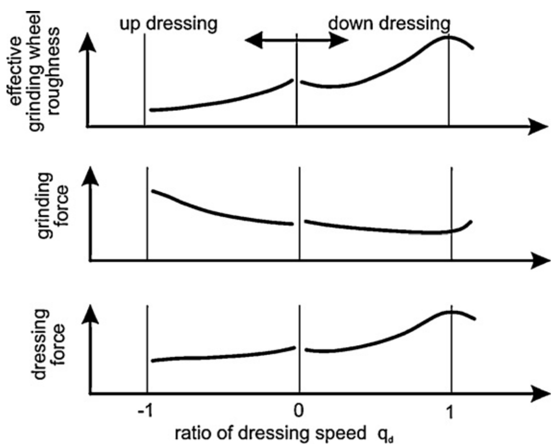

Fig. 4.10. Influence of dressing speed ratios on radial dressing force and effective grinding wheel roughness.

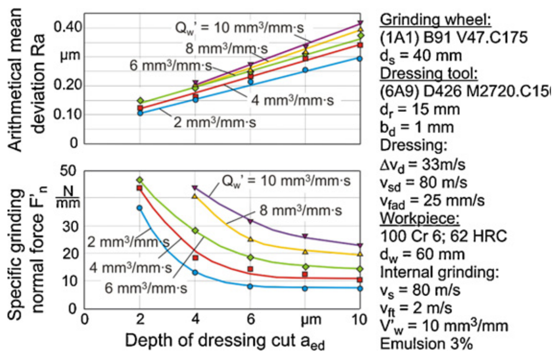

Fig. 4.11. Influence of the depth of dressing cut on the surface quality and specific grinding normal force [23].

rarely at the circumference [86,109,111]. Intense flattening of great grain areas is the dominating wear mechanism and is based on thermo chemical wear as well as splitter of the diamond in the area of microns or nanometers [86,109,110].

4.2.1. Form roller

For form dressing of grinding wheels, the width of cut, form roller edge radius and angle between dresser roller flanks should be smallest possible for flexibility and smaller than the intruded geometric features of the grinding wheel profile. Though, the influence on the life time of the form roller needs to be considered [88,113]. The most important variables for dressing processes with form rollers are depth of dressing cut a_{ed}, axial dressing feed f_{ad}, speed ratio q_d, up or down dressing and overlapping rate U_d.

In path controlled profiling pulling and pushing cuts are distinguished. The dressing chip thickness at equal dressing infeed is higher in pulling cut. Thus, the mechanical load and consequently the dresser roller wear are higher [111]. Denkena et al. [29] used form rollers to produce riblets on turbine blades by grinding. Multiple v-profiles were generated on a vitrified bond grinding wheel. He pointed out that the conventional truing process led to higher rounding of edges compared to the pure pulling or pushing process. Though, the best profile accuracy was achieved by pushing truing cut [29].

4.2.2. Profile roller

Using profile rollers the profile is directly devolved from the profile roller to the grinding wheel by plunge dressing. The dressing width is equal to the grinding wheel width [11,95]. Profile rollers need to have a high wear resistance and are expensive due to their high diamond volume. Thus, they are only suitable for large-volume production [51,88,176,184]. The most important parameters for dressing processes with profile rollers are radial feed in dressing f_{rd}, speed ratio q_d (up or down dressing) and roll out revolutions. Up to 100 roll outs at the end of the plunging process lead to stress relief in the system and reduced profile peaks of rough grinding wheel topographies [43,120,184].

The profiling process for grooved structures was divided into two steps, one for each flank [31]. Investigations on roll out

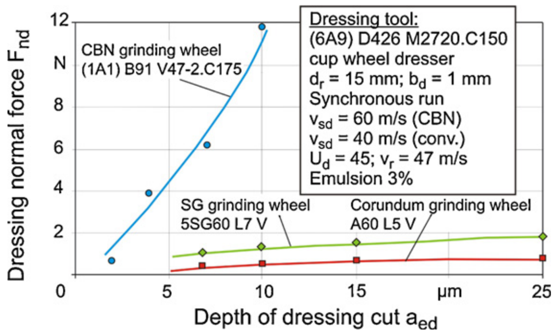

Fig. 4.12. Influence of the depth of dressing cut on the dressing normal force [23].

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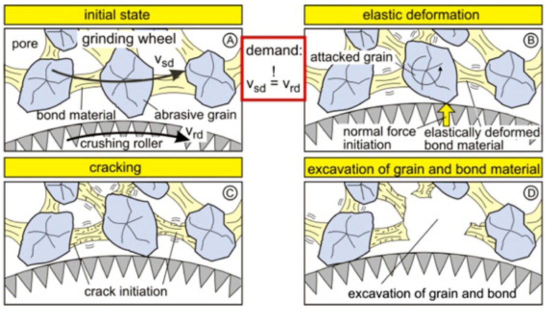

Fig. 4.13. Crushing mechanism after [54].

operations pointed out, that more homogenous grinding wheel topography could be achieved up to 80 roll outs [30].

Hoffmeister et al. investigated dressing with profile rollers. He pointed out, that the best dressing results were obtained using a CVD coated dressing roller with silicon base body. The low weight of the base body enabled the required high circumferential speeds. Though, the process is only suitable for vitrified and metal bonded micro grinding wheels [58,55].

Profile rollers can be used for continuous dressing, see Section 3.2 [96,120,172]. The grinding wheel position is constantly adjusted to compensate the radius wear of the grinding wheel due to dressing. Continuous dressing can only be performed with conventional grinding wheels and diamond profile rollers [56,95,120]. The advantages of continuous dressing can be used particularly in grinding difficult-to-machine materials such as Inconel. Burning is reduced and higher material removal rates become possible [95,120].Crushing

Profile crushing is related to profile dressing with profile rollers. Very large radial forces result from the relatively large contact area. This might introduce system vibrations and therewith profile-errors. For non-cylindrical profiles, the circumferential speeds can only be synchronized to $q_d = 1$ on one contact diameter. At all other points of contact, a relative velocity exists because of the radial dependence of the circumferential speed. This leads to high dressing roller wear [54] (see Fig. 4.13).

In form crushing due to point contact, relative speed can be totally avoided. The very small wear and with this the good profile accuracy of the roller allows the generation of very accurate grinding wheels [76,54].

As shown in Fig. 4.14 from [32,76] a torque based closed loop control to $q_d = 1$ can be used, where the dressing roller engine only provides the torque to overcome the friction, measured before the contact, detected by AE.

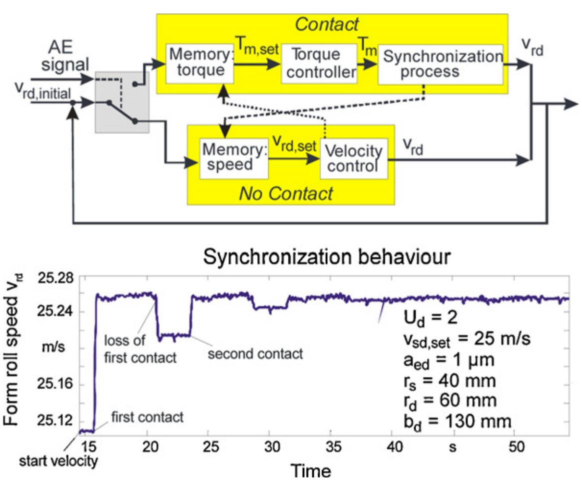

Fig. 4.14. Torque based synchronization [32,76].

4.2.4. Touch dressing

Touch dressing was developed for single layer metal bonded grinding wheels and is today used for other bonding systems also to reduce the runout and to improve the effective roughness of the grinding wheel. The depth of cut in touch dressing is such reduced, that only a small portion of the grain protrusion is cut [1]. Thus, one single dressing stroke is conducted with a radial depth of cut of only 2 μm prior to reaching the grinding wheel lifetime, which gives a higher overall lifetime [59].

4.2.5. Dressing with diamond gears

For finishing processes of gears a specially shaped dressing tool is used. If grinding worms for continuous generating grinding or internal geared honing rings are in operation, these tools might be dressed by using a diamond gear. Fig. 4.4 top right shows the application for grinding worms. The dressing gear is placed in the same rotary axis as the workpiece. One major advantage of dressing with a diamond dressing gear is the possibility of dressing with high speed (equal to the cutting speed), whereby other dressing systems just reach a dressing speed of approx. 2 m/s. The dressing wheel does not need to have the helix angle of the gear but can be employed straight-flanked. The manufacturing of diamond dressing gears is comparatively expensive and is thus only suitable for large series production [75,199].

4.2.6. Cup wheel dressing

With cup wheels, mainly cylindrical profiles can be generated. The cup dresser is positioned according to Fig. 4.5 with its axis tilted by 3° to 5° against the normal to the grinding wheel in the contact point and is guided in the axial direction of the grinding wheel by defined feed rate after a defined radial feed step without contact [51,120]. The most important variables for the dressing processes with cup wheel dressers are equal to form rollers, which is depth of dressing cut a_{ed}, axial dressing feed f_{ad}, speed ratio q_d (up or down dressing), overlapping rate U_d and tilting angle. The profile generation proceeds similar to dressing with form rollers.

The advantage of this process is the good evenness of the cup wheel, high lifetime, low dressing costs, self-sharpening effect of the dressing wheel, constant dressing quality as well as defined truing amount. Though, the disadvantage is the limited field of application and the risk of chatter marks in case of axial runout due to the low stiffness [146,73].

Azizi et al. [4,5] investigated on cup dressing of vitrified CBN wheels and showed the effect of the different dressing parameters such as overlapping rate and speed ratio on the grinding performance in terms of specific energy and wheel wear. The number of active grits per unit area and their sharpness are considered as the two grinding wheel topographical key parameters for studying grinding performance. A mathematical model was suggested to predict the dressing forces based on the fracture of abrasive grits, the fracture of the bond and the contact forces between dresser and grinding wheel. Nagase [129] recommends double cup dresser where the relative speed between grinding wheel and dressing cup wheels gives a cross with adjustable angle to the grinding speed direction, grooving the grinding wheel surface in those directions, giving beneficial surface topography. Not found in literature, but known from milling analysis: mathematically the best solution for this is using a torus shaped cup wheel and adjusting the tilt angle so that the osculating plane of the path of the dressing grains contacting the grinding wheel is the tangential plane of the grinding wheel surface in the contact points.

4.2.7. Milling dressing

Milling dressing is a special technique to dress grinding wheels with 1A1 profile once investigated, which did not find industrial acceptance. It is performed with a profile roller, which has one or more geometrically defined PCD made cutting edges at its circumference [47,51,180,211]. The width of the dressing roller has to be higher than the width of the grinding wheel [51,111].

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Milling dressing can be done in synchronous or asynchronous mode. The dressing roller is being fed radial to the grinding wheel, whereby the cutting edge point is moving on a circular pathway, which leads to an arched impact on the grinding wheel in peripheral direction. Significantly responsible for the pathway is the rotational speed ratio. The latter should be integer with only small deviation. A small speed ratio close to an integer basic speed ratio m ($m = 1–6$) is chosen to achieve a steady distribution of waves over the grinding wheel surface. The dressing time is exactly the time needed for one dressing stroke over the complete grinding wheel circumference. A second dressing stroke would lead to taking off the wave tips and thus, smoothing the grinding wheel surface [47,211].

4.2.8. Diamond roller with brushes

In [62] the application of a combination of a metal bond diamond from roller with two brushes at its sides for dressing of resin bond grinding wheels is proposed. The flexible bristles remove the bonding material and clogging. Furthermore, chip space around the abrasive grains is produced. Thus, better truing results were achieved compared to truing with only the form roller because the bond removal from the leading brush reduced the grain holding forces [62].

4.2.9. Sharpening using a SiC dressing wheel

Vitrified bonded silicon carbide (SiC) rollers are used for sharpening of CBN- and diamond grinding wheels [164,118,105]. Roller assembly with or without own drive exist. Though, the sharpening process is hardly controllable using a roller assembly without own drive [51].

Using external sharpening devices, the cutting mechanisms are characterized by steep effective passes and high forces on single sharpening grains. Thus, mainly splitter of the grains occurs. Greater chip cross-sectional areas cause higher forces resulting in breakage of the grinding wheel grain. The bigger chips remove the grinding wheel bond additionally. Thus, a sharper tool results [105]. Radial wear can be removed at grinding wheels with 1A1 profile.

4.2.10. Structuring using conditioning tools

Conditioning tools as form rollers or a stationary diamond tips can also be used for structuring of vitrified or resin bonded grinding wheels. Verkerk and Pekelharing [202] studied the effect of a simple dressed groove on the surface roughness of the workpiece. More complicated shapes can also be produced by variation of conditioning parameters as feed rate, depth of cut and dressing ratio. Using such structuring, the maximum chip thickness can be increased depending on the material specification, grit size, structuring condition and grinding parameters.

Tawakoli et al. [193,151] used both single point and roll dresser to structure the grinding wheel and showed reduction of the grinding forces and temperature together with higher surface roughness of the workpiece by dry grinding of metal. The residual stress on the ground workpiece was reduced but at the same time grinding wheel wear was higher using a structured wheel compared to a conventional one. Stepien [186] used a structured grinding wheel and modelled the grinding forces. Oliveira et al. [142] used a similar idea and developed a system to produce different patterns by actuating a dressing tool with high frequency related to the rotational speed of the grinding wheel. They investigated the effect of the pattern on the AE signals in external cylindrical grinding using a novel system of AE mapping (Fig. 4.15).

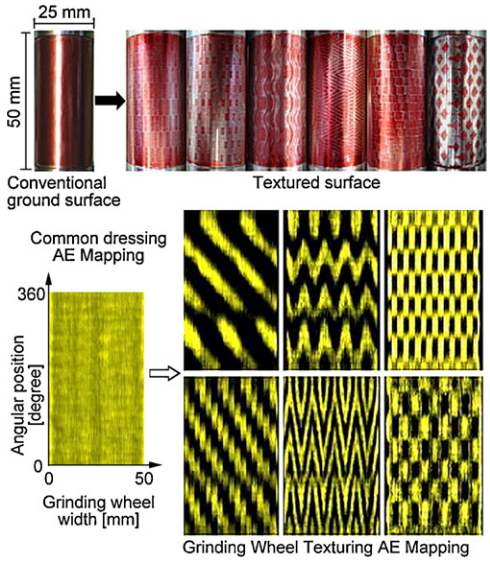

Fig. 4.15. Texture on grinding wheel surface and AE-mapping [142].

5. Beam-based conditioning

The advantage of beam based dressing is that it is free of contact and wear. Thus, displacements in the machine can be avoided [51,226]. Beam based dressing can be used for sharpening and dressing of grinding wheels, regardless bond material. Main classification parameter is the angle of the incoming beam in relation to the normal on the grinding wheel (Fig. 5.1), esp. radial and tangential direction is used.

5.1. Abrasive water jet conditioning

Abrasive water jet (AWJ) machining has been discovered for profiling, sharpening and cleaning, depending on the process parameters used. AWJ involves strong pollution of the grinding machine and is therefore normally conducted in a separate machine which reduces the accuracy and the abrasive needs to be removed [3]. The process heat can be neglected and the cutting forces are low.

For profiling a ratio of 20 between profile depth and jet diameter could be achieved by AWJ. Providing an optimal jet speed, the surface texture of the water jet dressed grinding wheel is closely related to the grit size and porosity of the wheel. Besides the achievable profile of the grinding wheel is limited due to the jet diameter of 1.1 mm, so the process is mainly applicable only for rough profiling. Fig. 5.2 shows some examples of the waterjet profiled grinding wheel.

AWJ was also investigated by Nanduri et al. [121] and Zeng et al. [227,228]. The results showed a good accuracy on the final geometry of the grinding wheels, which depends on radial feed.

Shen et al. [178] applied AWJ for dressing of a metal bond diamond wheel used for lap grinding of workpieces, from aluminum oxide ceramics and compared this method with, mechanical dressing with SiC, EDD and ECD. Fig. 5.3 shows the schematic of the process. The results show that the grinding force ratio during lap grinding of Al_2O_3 is the lowest compared to the

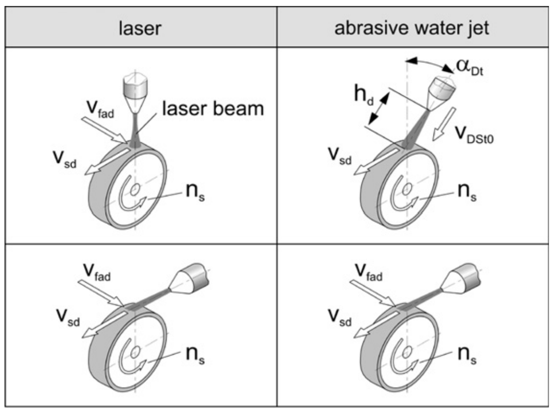

Fig. 5.1. Beam based dressing methods, beam directions for sharpening and profiling.

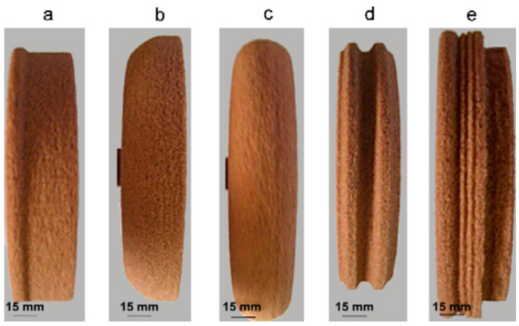

Fig. 5.2. Examples for AWJ conditioned grinding wheels [3].

others methods while the material removal rate is the highest. The important influence factors on the dressing process are pump pressure, distance between nozzle and wheel and the concentration of the mixture of abrasive and water. An influence of the grain size is also expected.

Sharpening is mainly necessary for resin or metal bonded grinding wheels [113,161]. In water jet sharpening (WJS), a high pressure jet added with an abrasive medium is used [50]. The advantages of WJS are the comparatively low costs, the relatively easy assembly and plain handling [50,182]. The sharpening process facilitates the profiling process and produces the necessary chip space for grinding [113]. Furthermore, wear of the truing tool is reduced, if sharpening and truing is conducted at the same time [159]. Nevertheless, the disadvantage is the poor correlation between sharpening conditions and grain protrusion [51,182]. Several nozzles in parallel can be used for grinding wheels with high width [50].

Regarding cost effectiveness a short, intensive WJS-process is recommended. Even though, the force may also be reduced by increasing sharpening time, it increases grinding wheel wear whereas wear is not affected by the WJS intensity [50].

A commonly used cleaning method is to deliver coolant under high pressure into the grinding zone [68]. Chips inside the grinding wheel bond clinging to abrasive grains cannot be removed by a tangent beam. Thus, the nozzle is adjusted perpendicular to the grinding wheel surface. Grinding wheel cleaning is twice effective, if the distance between nozzle and grinding wheel is reduced by 50%. Furthermore, increasing the flow rate is more suitable than increasing the pressure, since lower pressure reduces coolant fumigation [179].

5.2. Laser beam conditioning

Laser conditioning is based on heat input. Several types of lasers are used for conditioning though, in general a Nd:YAG laser is used in continuous wave or pulsed mode. Conditioning of the grinding wheel is accomplished with defined, laser generated grooves on the grinding wheel surface [80,57]. These are generated by scanning the surface with parallel laser paths [69,72,79].

If the laser is used for radial radiation (Fig. 5.1) radial deviations of the grinding wheel cannot be eliminated. Radial radiation is most suitable for sharpening and cleaning [57,196].

In tangential radiation, the laser beam is used like a truing tool and fed radial. Thus, bonding spines in the shadow of the grains can be generated to support the grains and radial deviations of the wheel can be removed. Nevertheless, higher laser beam power is necessary and it is hardly possible to achieve a profile generation [57,196]. The laser needs to be focused and positioned exactly to achieve micrometer accurate dressing [215].

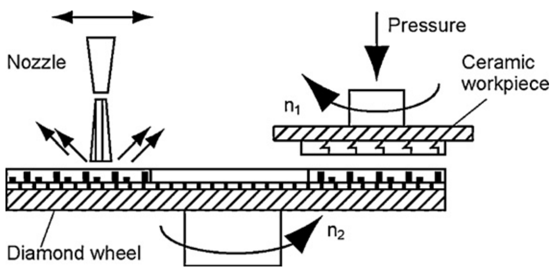

Fig. 5.3. Schematic of AWJ conditioning in lap grinding [178].

Axial radiation is not suitable for laser dressing. Neither straight profiles nor uniform energy distribution are possible over the grinding wheel width due to the Gaussian optics [57,196].

The term "laser dressing" is often used in a wrong manner, since usually the laser is arranged radial and the wheel is more sharpened rather than dressed. Only few papers [57,92,153,154,196] refer to using mechanical dressing before laser sharpening. Even though, no literature can be found today, picoseconds laser seem to be very suitable for conditioning of superabrasive wheels, especially diamond, since they allow cold ablation.

Wang et al. [205–207] stated that the processing parameters in laser dressing need to be chosen such that the power density suits the intended action. From that they predicted the influence of various parameters such as incident angle, focal offset and incident power on the power density in accordance with heat equation. After laser dressing of vitrified bond CBN grinding wheels, the grain protrusion was increased compared to conventional mechanical dressing.

Kang et al. [74] and Xie et al. [217] conducted a study of dressing of resin and metal-bonded diamond wheel by applying pulsed Nd:YAG laser tangentially to the grinding wheel surface. It was observed that the resin bond material is decomposed, whereas the bronze bond is molten or vaporized. The worn diamond grains are hardly influenced by the laser beam though they fall out of the dissipated bond material. For both bonding systems the surface topography and the roundness of the wheel were well after one pass dressing. However, a second time dressing is recommended for further improving the wheel topography and accuracy for the grinding process.

Laser sharpening of vitrified bonded grinding wheels leads to local melting and/or vaporization and resolidification of the grinding wheel bond surface [52,69,80]. A selective removal of bond material, abrasive grains and chips is made possible by adjusting the beam intensity [78]. The extremely high cooling rates in the order of more than 100 °C/s, depending on laser power, result in solidification of molten material without filling the grinding wheel pores [52,53,66,78]. Cracks are generated in the resolidified material due to the rapid heating and cooling. These micro cracks support the removal of resolidified material during the grinding process after several grinding strokes. Thus, new abrasive grains are exposed [67,69,153]. The melting depth is in the range of 500–900 μm [53].

Ramesh et al. investigated the effect of laser sharpening on conventional, vitrified bond grinding wheels. After sharpening and grinding of hardened carbon steel, an initial increase of the grinding forces was observed due to the rubbing action of smooth recast layer. During grinding, this layer was removed resulting in a reduction of grinding forces and an improvement of the grinding efficiency [153,154]. Further investigations figured that laser sharpening leads to noticeable grain refinement with well defined cutting edges and a characteristic morphology on the grinding wheel surface [52]. New micro cutting edges can be produced if laser sharpening leads to micro cracks on worn grains. Thus, multiple face grains can be seen after dressing [69,80].

Timmer investigated sharpening of metal bonded CBN grinding wheels. The required energy density was twice as high as needed for vitrified bond. He figured that radial radiation is more suitable due to the high profile deviation after tangential radiation. After sharpening a high amount of resolidified bond material remained on the surface. Nevertheless, it could be removed easily during the grinding process. The achieved grain protrusion was comparable to that achieved by electroerosion [196]. Hosokawa improved the process to enable sharpening of metal bonded diamond grinding wheels. By coordinating the laser parameters and wheel rotation speed, the appropriate grain protrusion height could be generated

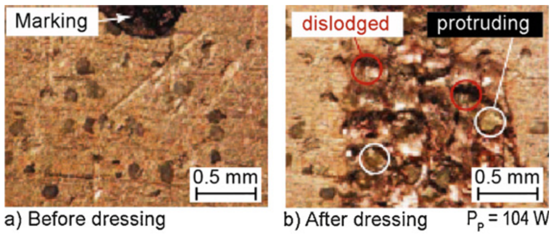

Fig. 5.4. Wheel topography before and after laser sharpening [60].

(Fig. 5.4). Due to the abrupt cooling with compressed air the recast layer could be removed using a brass brush. Almost all abrasive grains stayed in the bond after sharpening without being damaged [60].

Wang et al. [207] proposed to control the laser energy density so that it is well above the threshold of ablating the bond, but below the threshold for ablating the grain. Laser sharpening of resin bonded grinding wheels leads to plastifications resulting in weakening of the material [60]. The sharpening behavior of resin bond is based on vaporizing. The risk of grain damage increases if the energy is adjusted to achieve the necessary grain protrusion within one sharpening stroke [217]. Kunieda et al. [92] sharpened ultrafine resin bond diamond wheels resulting in a higher cutting edge density compared to one treated using conventional conditioning with cup truing method.

Acousto-optic Q-switched Nd:YAG lasers have higher pulse power and shorter pulse duration. Thus, each single pulse allows removing material in the range of nanometers individually. Proper grinding wheel topography is achieved through vaporization of the bond without damaging the abrasive grains, by adjusting the laser parameters. The normal and tangential forces in grinding were reduced by 10–15% compared to sharpening with corundum sharpening block. Furthermore, good topography of the wheel without destroying or damaging the CBN grains was reported [217,226].

Laser cleaning is based on melting and vaporization of metallic chips. The effects of CO_2-Laser on clogging and bond materials were investigated during cleaning of grinding wheels. The laser power was controlled by adjusting the focus. Short laser pulses with high power density are most suitable for grinding wheel cleaning due to the varying temperature behavior of chip, bond material and abrasive grains. So chips can be removed while the bond material and grain remained uneffected [19]. In [69] a pulse frequency of 98 Hz was most suitable for chip removal since higher frequencies led to damage of the grinding wheel bond.

Lasers are also used for structuring grinding wheels. Thus, different patterns can be produced on the wheel. Tawakoli and Rabiey [194] carried out their experiments on a CBN vitrified bond grinding wheel. A Nd:YAG laser system was used to make blind holes on the wheel surface so that the macro-topography of the wheel was changed as illustrated in Fig. 5.5. Hereby, a reduction of the grinding forces and the specific grinding energy as well as better surface integrity were reported. The surface roughness did not show great differences but the wheel wear was a little higher in case of the structured wheel.

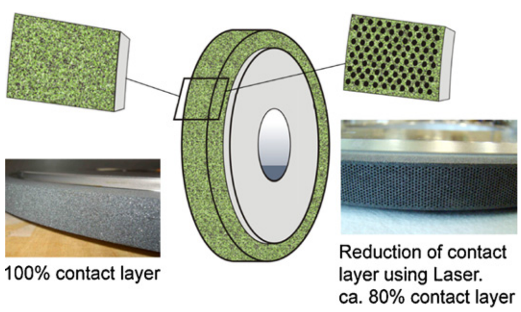

Fig. 5.5. Comparison of conventional and laser structured vitrified grinding wheel [193].

6. Electro chemical and electro physical conditioning

Metal bonds (generally cast iron, nickel, bronze or cobalt) are the most difficult to be conditioned because due to its ductility, mechanical dressing methods smear out the bond in between the abrasive grains eliminating the intergrain space. However, electro physical and electro chemical processes can be applied due to their electrical conductivity.

6.1. Electro chemical dressing

Although electro chemical processes can technically be used both for truing and sharpening of metal bond wheels, it is often used only for sharpening since accurate truing by electro chemical means is difficult and time consuming [175]. A principal arrangement is shown in Fig. 6.1.

Electro chemical dressing can be categorized into two main processes: electro chemical in-process control dressing (ECCD) [90,91] and electrolytic in-process dressing (ELID). The ELID process is characterized according to [91] as self-sustaining because the electrolyte generates with the bond metal an oxid-hydoxid isolating layer referred to as an oxide layer, whereas ECCD requires an electronic gap control. For both processes, the grinding wheel is the positive electrode and the negative electrode is mounted within a gap to the grinding wheel.

6.1.1. Electrolytic in-process dressing (ELID)

Dressing of grinding wheels based on the oxidation of the metal bond was initially developed by Ohmori and Nakagawa [132,133,134]. It rapidly found its application in high precision grinding during the last two decades as ELID is capable of generating extremely fine surfaces with R_a of a few nanometers and high accuracy.

The potential has yet to be fully exploited, which is indicated by the large number of issued publications regarding ELID. Fig. 6.2 shows the sequence of wheel preparation for ELID.

The electrode, generally made of copper, is positioned with a gap of 0.1–0.3 mm to the cast iron bond grinding wheel. The electrolyte is generally water based and serves as a coolant but is hazardous, which gives rise to further research. The coolant properties are adjusted to the ELID process (conductivity of about 0.1–0.3 S/m and pH value of about 10) with the help of additives. An appropriate nozzle delivers coolant to the gap between the electrode and the grinding tool. Electrolysis reacts with the bond to an oxide layer of increased volume and thickness dependent electric resistivity. This slows down the electrolytic dissolution of the cast iron bond. Because of their softness the oxides can easily be abraded in contact to the workpiece. So grain wear also limits the thickness of the isolating layer. Cut chips are absorbed by the oxide layer, acting thus as chip space [132,133]. Truing of the grinding wheel is generally required before the ELID process starts, as ELID, despite the introduced terminology, is more a sharpening process. Truing is carried out by electro discharge or by

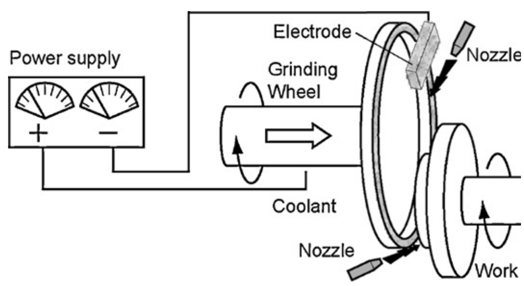

Fig. 6.1. Schematic of ECM (ELID and ECCD) process [132,133].

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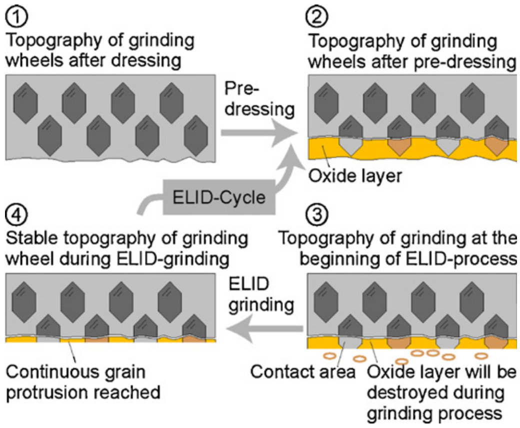

Fig. 6.2. Schematic of ELID process [132,133].

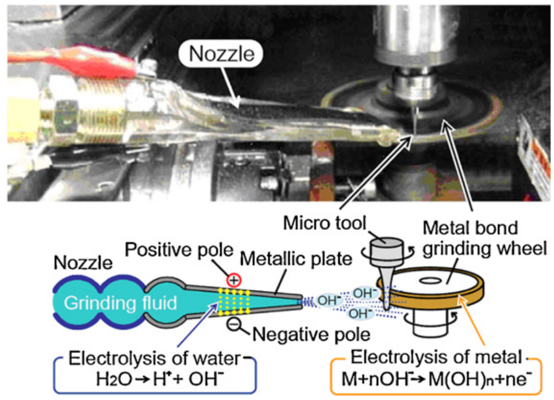

Fig. 6.4. A schematic of the nozzle ELID process [138].

conventional processes [135]. To obtain a stable oxide layer, a predressing step by electrolysis is necessary before starting.

Ohmori et al. [7,63,108,132,134,138] investigated ELID grinding for different grain sizes, different work piece materials such as ceramics and glasses, and with different electrolytes. Significantly lower grinding forces and very good surface quality was achieved. Lim et al. [108] explained that the oxide layer acts as a damper. A threshold value for feed rate was mentioned above which wear is greater than the oxide layer formation, therefore leading to grinding burn.

Zhang et al. and Qian et al. [230,149,150] developed two new variations, ELID II (or ELID interval dressing) and ELID III (or ELID without electrode) shown in Fig. 6.3. ELID II has a cast iron bond (CIB) CBN wheel, which is dressed at intervals when it is retracted from the workpiece.

In ELID III, a metallic workpiece is maintained as the negative electrode and the tool is a metal–resin bond (MRB) CBN wheel. To isolate the workpiece from the machine tool, a ceramic chuck is used. To reduce the spark effect, minimal values for voltage and electric power should be chosen. For both ELID II and III, a mirror reflective internal cylindrical surface with a roughness R_a of less than 40 nm was achieved.

Ohmori et al. [136,139] also proposed a variant using a second generator to increase oxidization of the grinding wheel making it suitable for grinding biomaterial and for applications requiring corrosion resistance. Ohmori et al. [138] later developed a variant, known as nozzle ELID or ELID IV, which is shown in Fig. 6.4.

This method utilizes a nozzle in which two electrodes are positioned and dissociate the water molecules in the coolant stream. The ions impact the grinding wheel surface and oxidation of the surface takes place. The oxidation is not as strong as in the conventional ELID but ELID IV is useful for micro grinding where only small material removal rates are required.

Itoh et al. [65] introduced a tape type electrode enabling a better exchange of electrolyte in the gap between the electrode and the grinding wheel. This prevents waste and regulates the flow rate of the electrolyte during the process [65,233].

The problem faced with fundamental investigations and modelling of ELID is that direct measurement of the oxide layer thickness is

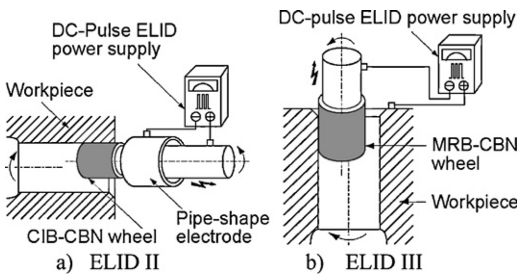

Fig. 6.3. Schematic of ELID II and ELID III [150].

not yet possible, leading to measuring of voltage and electric current instead. For process analysis also grinding forces, acoustic emission and wear of the wheel are measured. Lee [97,98] proposed a numerically controlled dressing system for ultra precision grinding.

ELID is possible not only with cast iron bond wheels but also with metal–resin bond wheels [64,149,150,225] and bronze bond wheels [10]. Different kinds of grinding processes such as internal, external, surface and centreless grinding can be equipped with ELID. Profile grinding with ELID needs special attention for accuracy because of wear induced deterioration of the wheel geometry. Saleh et al. [158] and Rahman et al. [152] investigated the requirements of profile ELID grinding and automatic wear compensation. Itoh et al. [64] addressed the application of ELID for a lapping process of silicon and tungsten carbide. A honing process using ELID was reported by Ohmori et al. [137].

6.1.2. Electro chemical in-process control dressing (ECCD)

By ECCD, a constant or pulse current is applied to the wheel for a continuous dressing process. Based on the physical principle of electrolysis and using a direct current (DC), the grinding wheel is the anode and an electrode (usually copper or graphite) is the cathode. Electrolytic coolant flows from a nozzle in between the grinding wheel and electrode.

ECCD leads to anodic dissolution of the metal bond to achieve higher grain protrusion similar to Fig. 6.2 but without oxide layer. Kramer [90,91] controlled the voltage and current of the electrolytic process using an adaptive control generator based on the measured grinding force ratio (the ratio of the tangential to the normal grinding force) which was used as indicator for the grain protrusion of the grinding wheel.

Golabczak and Koziarskj [45] developed electro chemical dressing using alternating current (AC) instead of DC using a specially diluted electrolytic coolant. The authors mentioned that the changing polarity enables the removal of metal when the wheel has positive polarisation and enables the removal of passive hydroxide layers when the wheel has negative polarisation.

Suzuki et al. [188] proposed a double electrode with an isolating layer between them for pre-process and in-process dressing of the metal bond wheel using AC supplier (Fig. 6.5). In this development, the current flows by AC supplier from the first electrode to the second such that the metal bond of the grinding wheel between these two electrodes is removed.

6.2. Electro discharge dressing

In the electro discharge dressing process, the grinding wheel can be connected either to the positive or negative pole, or a DC generator. The other electrode will be either a metal wire in the case of wire electro discharge dressing (WEDD), or a rotary or stationary electrode tool (graphite, copper or brass) in the case of sink electro discharge dressing (SEDD). There is a gap between the tool and grinding wheel which is filled with a dielectric (oil [214], emulsion [188] or air [201]). Within a short period of time, the

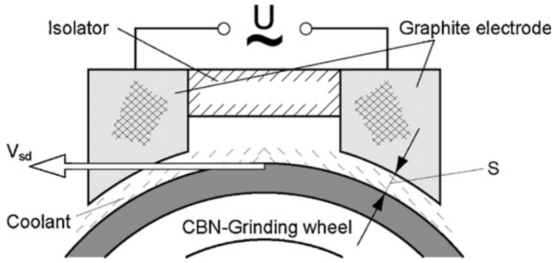

Fig. 6.5. Schematic of double electrode with isolation system.

plasma condition allows a discharge, which erodes the bond of the wheel leaving a crater on the grinding wheel surface. The accumulation of such discharges and induced erosions result in a dressed grinding wheel. The superabrasive grains (either diamond or CBN) are not electrically conductive (or very low conductive) and are theoretically unaffected by erosion. But the heat generated due to the spark which is locally applied on the wheel can possibly cause grain damage [83]. Due to the selective material removal of EDD grain protrusion increases, the grinding forces are reduced (up to 50%), loading is prohibited and the surface integrity tends to becomes better (compare for example [99,100,155,156,167]). In any EDD process, material removal occurs not only on the wheel but also on the tool electrode. The difference between WEDD and SEDD is that in the case of SEDD, through the wear of the sinking tool, wear compensation must be taken into consideration and after a while, the used sinking tool must be reshaped or replaced. In the case of WEDD, the renewal of the electrode is carried out via a continuously moving wire and there is no wear to be compensated. Very good flexibility of wheel profiling can be achieved using CNC control and wires with small diameters down to 0.2 mm. However, the vibration of the wire is a source of deviation from the correct profile and decreases the efficiency of the process [214].

The application of an electro discharge process for conditioning of grinding wheels by integrating an EDD system to a grinding machine was initially reported by Suzuki et al. [188]. Fig. 6.6 shows a schematic of both EDD systems.

Ohmori et al. [135] combined ELID as the dressing process with SEDD as the truing process in which both processes were energized with one DC generator.

The effect of different kinds of dielectric as well as mist air, dry, compressed air and cold air on the EDD process was investigated by Uematsu et al. [201]. Even without using grinding fluids, it is possible to profile a complicated form on the wheel and eliminate run out. Moreover, using cold air as dielectric the wheel wear during grinding is lower in the case of SEDD compared to conventional mechanical one.

Suzuki et al. [189,190] developed a grinding wheel with electrically conductive diamonds for precision grinding of ceramics, carbides and glasses. An SEDD process was employed where the bond and the diamond both were conditioned. For example, a significant decrease in the grinding forces (about 21%) when grinding tungsten carbides compared to non-conductive diamond

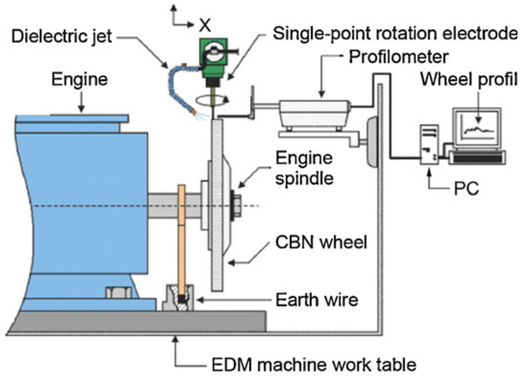

Fig. 6.7. Schematic of a single point SEDD grinding machine [168].

wheels was determined. The reason is mainly due to sharp cutting edges employed by SEDD on the conductive diamonds.

Rhoney et al. [155,156] investigated on the WEDD of a diamond grinding wheel with average grain size of 54 μm. After WEDD some protrusion of 32 μm was found. SEM observations showed that such grains with high protrusion were fractured with light grinding conditions and 20–40% lower grinding force is achieved. The wheel dressed with WEDD had a longer life time.

One of the problems faced with the EDD process is the limitation and constraint when the grain size is so large, that it comes into contact with the electrode before falling out of the bond [167].

Ortega et al. [143] and Sanches et al. [167] could successfully carry out the SEDD of large grain sizes (B126) of metal bond CBN grinding wheels and achieved to eliminate run out or any macro geometrical defects of the wheel.

Sanches et al. [168] developed a single point electrode with CNC compensation for tool wear of the SEDD process. Fig. 6.7 shows a schematic of a single point SEDD integrated to an EDM machine. A mathematical model was derived to compute electrode path and velocity so that the electrode wear is compensated and the final profile can be accurately achieved.

Klink [82,83] investigated the WEDD process of metal bond diamond wheels. An edge and corner rounding effect of diamond grains was observed after WEDD. Also a graphitization layer less than 0.5 μm thickness of diamonds due to heat generated from the WEDD process was detected (Fig. 6.8).

Weingärtner et al. [213,214] also integrated the WEDD unit into a cylindrical grinding machine. With a new wire guide system with reduced free wire length, they could reduce vibrations and reach material removal rates of up to 100 mm^3/min when dressing bronze bond diamond wheels with grain size of D46. In addition, a decrease in run out and a reduction in waviness were achieved compared to free stretched wire systems (Fig. 6.9). Grain protrusions of up to 90% were achieved with grain sizes of 46 μm. Grain sizes of up to 125 μm were successfully tested [214]. The system is especially designed for in-process dressing with relative velocities between the electrode and grinding wheel of 80 m/s and running with grinding oil as dielectric.

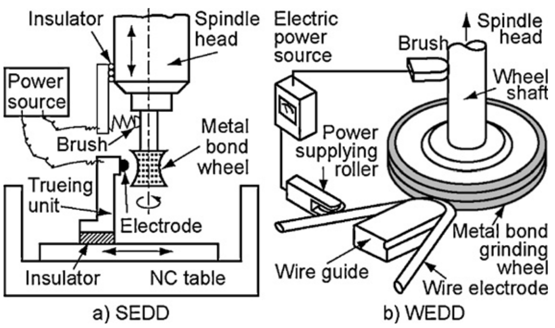

Fig. 6.6. Schematic of (a) SEDD and (b) WEDD [188].

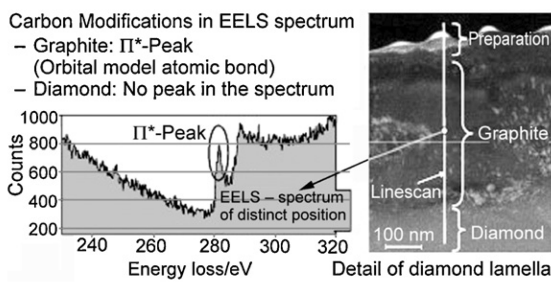

Fig. 6.8. Graphitization of diamond after WEDD [83].

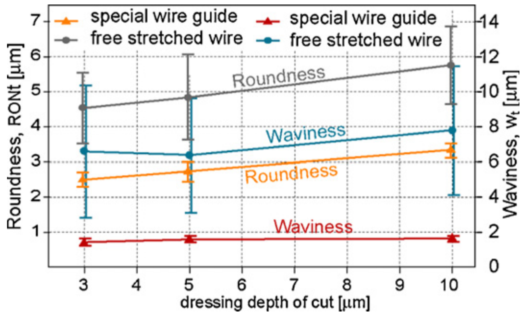

Fig. 6.9. Decreasing the roundness and waviness using special guided compared to free stretched wire.

6.3. Electro chemical discharge dressing (ECDM)

The combination of electro chemical and electro discharge dressing is a hybrid technology which was successfully applied by Schöpf et al. [174,175]. The thermal erosive effect of the electro discharge allows truing of the grinding wheel, while the electro chemical process performs sharpening, so that truing and sharpening of the wheel is done just in one step. Fig. 6.10 shows a schematic of the ECDM and Fig. 6.11 shows the pulse generation in the process. The pulse begins with the classical ECD phase followed by an erosion phase. The pulse time can be varied depending on the application. The coolant plays the role of the electrolyte as well as dielectric. The electrical conductivity of the coolant was according to the investigation of Schöpf about 0.2 S/m and the pH value of pH = 9.20.

The ECDM process was applied for centerless grinding of cermet and was demonstrated to be suitable for truing and dressing of metal bond wheels. The results showed a better surface roughness and roundness compared to mechanical truing [175].

6.4. Electro contact discharge dressing (ECDD)

The method of electro contact discharge dressing was firstly introduced by Tamaki and Kitagawa [191,192]. The mechanism of this dressing method is based on the erosion and at the same time chip removal. The abrasives form a micro chip on the surface of the electrode, fed towards the grinding wheel surface. A DC voltage is applied between the electrode and the grinding wheel, which builds up an electric field in the gap according to Fig. 6.12.

As the chip reduces the distance between the electrodes a discharge pulse occurs whereby the micro chip is molten and partially evaporated. The metallic bond is locally eroded and grain protrusion increased, which in turn reduces the erosive material removal of the bond at that point. Therefore the process is self controlled, wear intensifies the bond erosion. An important advantage is that there is no need for a dielectric and pulse generator, as the rotation of the wheel continuously generates new contact zones [197,35,27,41,218,219]. ECDD is capable of in-process dressing. Compared to conventional dressing the grinding forces as well as the dressing time are reduced, but the surface roughness increased.

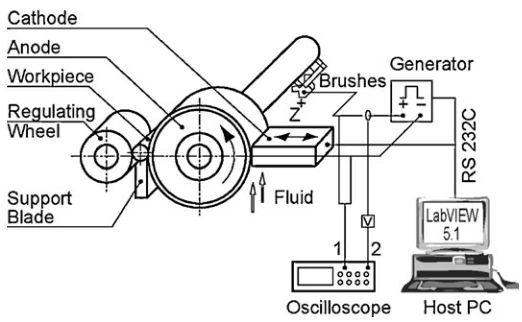

Fig. 6.10. Principle of ECDM dressing [174].

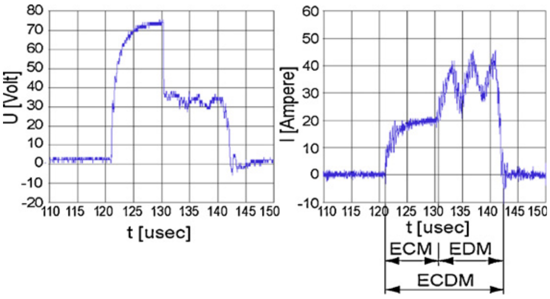

Fig. 6.11. ECDM-pulse generation process [174].

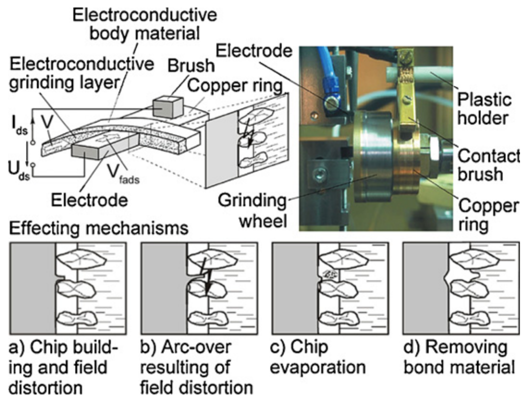

Fig. 6.12. Schematic of the ECDD [27].

Based on the same principle, Xie et al. [220,221,222] used a cup dressing kinematic, where it was pointed out, that the dressing area with a conical cup dresser electrode can be adjusted such, that the kinematic surface roughness of the grinding wheel is reduced. Also the contact forces can be drastically reduced, which gives a more accurate cylindrical profile as indicated in Fig. 6.13 in comparison to truing with sticks or rollers.

7. Hybrid and special technologies for conditioning

7.1. Ultrasonic assisted conditioning

Ultrasonic assisted conditioning (UAC) is only sparsely researched and not yet industrialized in the grinding process. In ultrasonic-assisted dressing, high-frequency and low-amplitude vibrations are superimposed on the movement of the dressing or grinding tool. Fig. 7.1 shows the different kinematics of applying ultrasonic waves to the dresser. Almost all the publications regarding UAC show the reduction of grinding forces and wheel wear when using UAC compared to conventional methods.

Ikuse et al. [61] used a stationary diamond dresser to dress a vitrified bond CBN wheel with an ultrasonic vibration frequency of about 33 kHz and maximum amplitude of 2.5 µm. Also an improvement of the ground surface quality as well as an increase of the dressing ratio were reported. Liebe [105] used a rotary diamond dressing cup to profile vitrified and resin bond diamond grinding wheels by applying the ultrasound for the grinding of

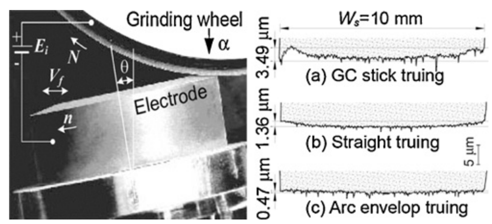

Fig. 6.13. Arc enveloped truing with conical cup dresser and the result on the cylindrical profile of a grinding wheel [220].

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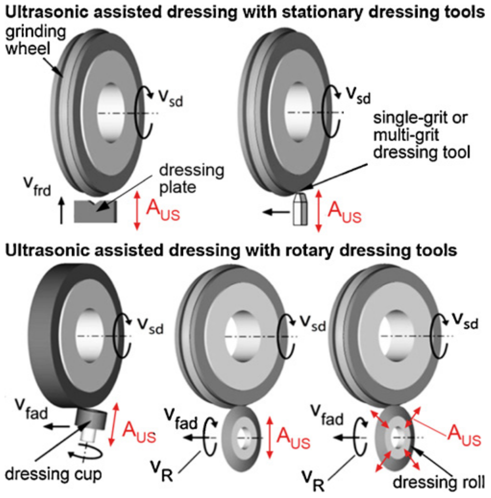

Fig. 7.1. Ultrasonic assisted conditioning types [195].

ceramics. Using axial vibration of dressing cup, an increase of dressing removal rate is achieved but is accompanied by micro-cracks in the vitrified bond, which causes a reduction of the grinding ratio for grinding of ceramics. In case of UAC of resin bond wheels an increased dressing ratio with almost unchanged grinding forces was reported. Besides more micro breakages of the diamond grains were observed under the SEM in case of UAC compared to conventional conditioning [105]. Sroka [184] made tests with the same type of tool for dressing resin bond diamond grinding wheels using ultrasonic vibrations and detected a significant increase of the dressing ratio.

Nomura et al. [129,130,131] studied UAC of small vitrified bond CBN grinding wheels used for internal grinding of small holes. The grinding wheel was ultrasonically vibrated in its axial direction during truing with a rotary cup dresser as well as during grinding process. It was found that applying ultrasonic vibration to the grinding wheel caused a reduction of more than 20% by the normal grinding and more than 24% by the tangential grinding force. Also the grinding wheel run out was decreased and a better surface roughness (18% lower in R_a) on the work piece was achieved.

Jiao et al. [71] investigated the effect of the ultrasonic vibration in dressing of a SiC grinding wheel by single point diamond dresser in the radial direction. Different surface roughness can be achieved depending on whether the dressing depth is larger or smaller than the vibration amplitude. A totally different distribution of micro cutting edges was found when using UAC compared to conventional conditioning.

Tawakoli et al. [195] applied ultrasonic vibration to a stationary as well as rotary dresser for the conditioning of vitrified CBN wheels. They found a reduction of grinding forces (up to 30%) and lower heat generation in the grinding process of 100Cr6. An Increase of the dressing ratio was also reported.

7.2. Heat assisted conditioning

7.2.1. Conditioning with laser

A laser assisted conditioning method was proposed by Zhang et al. [231,232] to reduce the wear of diamond dressers and to achieve good dressing quality and efficiency. The irradiation of a CO_2 laser with a power of 1.5 kW is applied to a vitrified CBN grinding wheel and simultaneously a diamond dresser does the conventional conditioning. The diamond dresser moves with the laser along the wheel surface, while the focused laser beam heats the rotating CBN wheel a little ahead of the cutting point. With the proper heating time and energy density selected, the vitrified bond (ceramic phase) of the wheel is softened or even molten, thus facilitating the removal of the bonding material. Fig. 7.2 shows a conceptual laser-assisted conditioning process, where the distance between dresser and heat source is trade off between high temperatures and low dressing forces for minimum wear of the dresser.

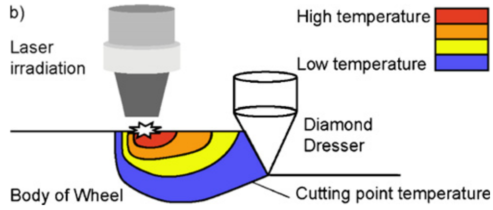

Fig. 7.2. Schematic of laser assisted conditioning [231].

The material removal rate achieved by laser assistance in dressing can be 5 times higher with the same force exerted on the dressing tool [231]. The wear rate of the diamond dresser and the dressing force are also much smaller for the same material removal rate [26]. The dressing ratio – right after conventional dressing is slightly higher but after several dressing cycles and more material removal, the dressing ratio by laser assisted dressing becomes higher.

Yamada et al. [223] used a Nd:YAG laser to remove the hard but worn grains thermally, transform or damage them (by graphitization of diamond) and then remove the irradiated and thus grain-free layer mechanically by a conventional abrasive wheel and generate the correct geometry. The thickness of this layer is estimated beforehand. The results show an improvement of truing efficiency in terms of reduction of the dressing tool wear rate.

7.2.2. Conditioning with EDM

Wang et al. [208,209] combined the conventional dressing with a dry sinking electro discharge process for conditioning of diamond wheels called dry electro discharge assisted dressing (DEDD) Fig. 7.3 shows the schematic of the process. The electro discharge assistance reduces the dressing forces and a decreases the dressing tool wear due to the softening of the metal bond. The surface roughness value achieved after grinding of a hard alloy (YG8) was R_a = 0.8 μm in case of the DEDD and in comparison R_a = 1.4 μm for conventional dressing with the same grinding parameters.

7.3. Special conditioning methods

Tests with alternative processes and energy sources are also conducted with the aim of overcoming some of the restrictions of grinding and/or dressing alone. Some examples are microwaves [169], plasma torches for thermal treatment. Enhancement of chemical processes by photocatalyst activation in ELID is reported in [229] and advantages of dressing with slurry between profile rolls and the grinding wheel in [21].

8. Condition monitoring

8.1. Monitoring of macro wear

Detecting macro wear requires measurement of the diameter, the profile and the geometric runout. Runout yields signals varying with the rotation angle and thus can be detected by measuring the

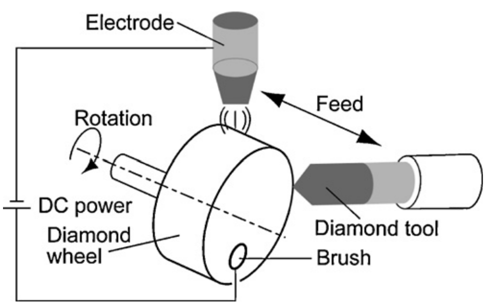

Fig. 7.3. Schematic of DEDD process and the real machine [208].

force or power signal such that it also portrays a unique footprint within the AE signals. The diameter is directly derived from the positional data of the dressing device on the grinding machine, because the valid profile is the envelope of all meridian lines of the grinding wheel. Direct probing becomes impossible because of probe wear when scanning the profile. Profile data is thus gathered by transmission of the grinding wheel in some workpiece, which then can be scanned by mechanical means. This can also be carried out by plunge grinding into some soft material like graphite as mentioned in [32]. Another possibility is the measurement of the outer envelope of the profile by optical means as described in [102].

8.2. Monitoring of micro wear

The primary goal is essentially to decide whether an abrasive layer is sufficiently good for grinding or not. This is already a demanding challenge, since this decision needs to survey the totality of the abrasive surface. Only one bad area of the surface is able to degrade the grinding wheel to uselessness. Due to this fact, monitoring begins by sampling the process parameters to allow for decisions from the view of the process, which are indirect parameters of the abrasive layer. Other classes of monitoring strategies are to directly observe the abrasive layer and evaluate the geometry in different directions. The following technologies exist:

1. force monitoring [93,19,25,103,210]
2. temperature/heat monitoring [19,25]
3. power monitoring [48,25]
4. acoustic emission[185,28,81,46,212,101,104,103,140,141]
5. optical observation [2,94,36–38,19,14]
6. optical observation of profile [102]
7. scanning electron microscopy [42]
8. monitoring of fluid flow characteristics [114,115]
9. tactile probing of the surface [170]
10. magnetic properties of the surface [101]

Indirect monitoring does not indicate the reason of a bad grinding process. But the threshold to decide on a good or bad wheel can be defined, which is dependent on the workpiece material and all other process parameters such as feed, cutting speed, coolant flow and wheel characteristics. But also, closed loop controls, warning and shut down levels can be specified. Somewhat unique is the use of acoustic emission (AE), since this does not give direct information from the grinding process, but delivers indirect signals, from which the process properties may be derived. Also, acoustic emission is much more related to the direct monitoring from the evaluation point of view, as it yields continuous signals from which the relevant data needs to be extracted and then correlated to the process. AE can be evaluated in the direction of spectral composition in frequencies by FFT or for the detection of transients by wavelet transform [103]. Furthermore, amplitude, RMS value and also time patterns are extracted. With changing penetration depth and also with the number of grit interactions, the AE signal will change as shown in [28]. AE is used to monitor the state of the grinding wheel during grinding as well as during dressing. The AE sensor typically is placed nearest to the process, mostly on the work piece holder, or the dresser, sometimes in the grinding wheel [27,28,212] with telemetric or slide ring data transfer and also on tailstock or spindle head.

Fig. 8.1 shows the sampling procedure for AE measurements and the significant change in AE with wear. Nevertheless, it is reported that the reliability of AE is limited due to changes in the machine's behavior.

Oliveira et al. [141,140] presented an AE analysis, where the AE signal is correlated to the position on the grinding wheel with a sampling rate, that allows for detection of each collision between a truing diamond and the grinding wheel as seen in Fig. 8.2.

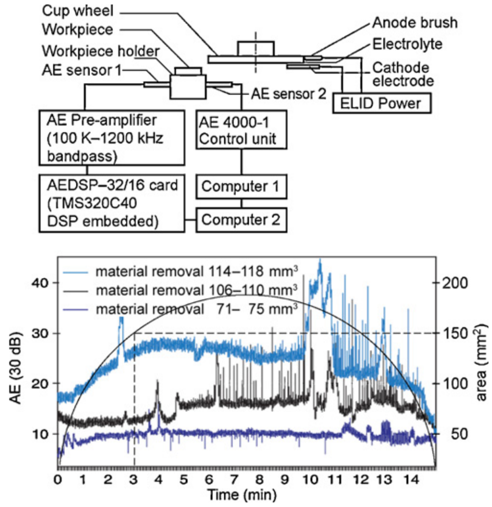

Fig. 8.1. AE-RMS-signals for cast iron grinding wheel after different material removal [185].

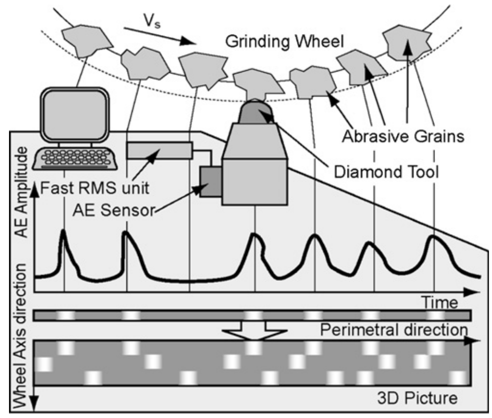

Fig. 8.2. Image construction procedure for fast AE RMS analysis from [141,140].

Thus a complete image of the interaction between wheel and truer can be developed, showing the density of active grains at low cutting depth. Furthermore, application of the system during grinding shows wear behavior by characteristic changes of the noise.

Optical observation of the layer gathers enormous amount of data and thus must be condensed to a few parameters which can be correlated to the behavior of the grinding wheel and are significant. Optical detection of the abrasive layer yields:

1. reflectivity [37,38,36]
2. grey levels [2,94]
3. topographical data [20,42]

Scanning electron microscopy today is impossible for in-process measurement, but yields fine topographical information (see [42]).

Reflectivity measurements are used to detect loaded areas, as they become shiny. The image processing is shown in Fig. 8.3. The derived parameters are the total loaded area fraction or parameters

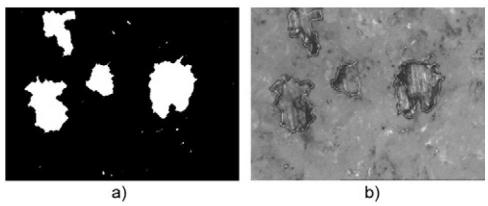

Fig. 8.3. Image processing to extract shiny areas [37,38,36]. Area: 2.1 mm × 1.6 mm.

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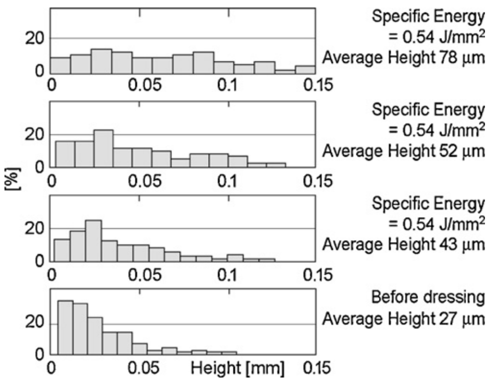

Fig. 8.4. Change of the distribution asperity heights due to wear [20].

of some fractal analysis of the contour of the shiny areas [36–38]. Grey levels furnish the database for texture analysis, where especially [2] shows some investigation on the suitability of 1st and 2nd order parameters indicating wear states of the grinding wheel.

It was shown, that change in the grey level co-occurrence matrix indicates wear and the arithmetic average of the grey level can be correlated to wear, but no causality could be derived. From full 3D-topograhical data in [20], the distribution of asperity heights is deduced and it can be shown, that the distribution when dressing significantly changes to a more even distribution as shown in Fig. 8.4.

In [14] *F*-tests on optically detected volume filling distributions are used to differentiate between surface layers generated by different dressing conditions.

Monitoring with the help of fluid flows has been applied by [115] through a flapper nozzle, issuing air and measuring the flow resistance/pressure. For free chipping space, the flow resistance is smaller than for loaded or worn grinding wheels. Monitoring the flow field of the coolant is yet to be found in literature. Surface monitoring through magnetic field changes and detection has yet to be developed, but can be applied for loading detection. All these monitoring strategies can be and partially are utilized during grinding to detect the degradation of the wheel, and during dressing to detect the degree of regeneration. An example is given in [28] where with AE, the number of necessary dressing paths is detected.

Application in grinding shops involves the use of force and power monitoring as well as to a certain degree, AE monitoring.

9. Modelling of dressing methods

Modelling of conditioning follows principally two tasks:

- predict the surface topography of the grinding wheel (for instance as input for grinding models)
- reveal parameters of the conditioning process such as forces, wear of the dressing tool, optimal process parameters

Despite the large influence of conditioning on the grinding process and the quality of the ground workpiece, a reliable physical model of the dressing processes, and the dressing – wheel topography – workpiece surface topography and/or quality sequence has yet to be investigated. The reason is perhaps the nature of the conditioning and grinding process. This implies undefined cutting edges with great variation in the grain morphology and their distribution, the complexity of the wear and its corresponding mechanisms, as well as dynamical and tribological aspects of the process. Even the wear of grinding wheels has not been satisfactorily modelled either.

A number of models exist to derive the topographies and the resulting workpiece properties of a given wheel, but the topography is generated either from measurements or artificially [13,165,166,123,124]. One approach is to measure the wheel topography produced by conditioning, and then relate the conditioning parameters empirically to this topography and performance of the wheel, resulting in a close interrelation between monitoring and modelling. Minke [120] used this approach in a model to find the relation between specific dressing force and dressing parameters for a stationary diamond dresser. An example for the description of the grinding wheel topography is given in [122], where the protrusion height is described by a 2-dimensional non Gaussian random field, which is transformed to save computational effort of a Gaussian field, for instance by Johnson transformation. It can be shown, that especially for the important, most protruding grains, the deviations from normality are significant in the measured topographies as well as in the generated ones. But no connection to any dressing procedure is given. Doman et al. [33] survey different wheel topography models where the influence of the dressing procedure is coded within the generating parameters of the random protrusion fields as phenomenological variables. A generalized physical modelling framework is also presented, that takes into consideration grain shape, size and density, dressing mechanisms accounting for grain fracture, grain deformation and bond cutting, which transform the topography of the undressed wheel.

The papers reviewed by Verkerk and Pekelharing [203] and the publications on dressing models until today mostly attempt to predict the topography left on the grinding wheel by the dressing process, using kinematic models either by a single point diamond, or by a diamond roll with geometrically well defined cutting edges. The topography of the wheel can then be related to the dressing depth and dressing lead. Modelling the interaction between the dresser and the grains simple geometric interaction is assumed which holds true for touch dressing [147], or a mixture of bond fracture (pullout) and grain fracture. In [198], the statistics of bond fracture follows a Weibull distribution and all grains that are not pulled out are fractured.

Chen and Rowe [15] model and simulate the dressing process by a stationary single diamond tool when the grains are randomly distributed on the wheel surface such that the dressing tool generates a random sine wave as a fracture line. In [89], the grains, modelled as spheres remain intact and fall out after the protrusion surpasses a critical value, which may be an approximation for erosive dressing. Chen et al. [16,17] calculate the electric field distribution for diamond grinding wheels with different geometrically determined grains and the resulting current in ELID, which then can be converted to material removal rate with Faradays law. Other publications assume uniformal field distributions and take into account the varying thickness of the oxide-hydroxide layer due to electrolytic growth and wear removal [10].

A simple model for the prediction of material removal by laser dressing of vitrified silica bonded alumina was given in [144] using averaged material parameters. For resin bonded CBN wheel, a numerical simulation for the effective laser pulse power density on the surface was developed by Xie et al. [217], which together with an experimental curve of crater depth over pulse power density gives information of the topography of the grinding wheel after laser dressing. An ablation model was proposed by Chen et al. [18], where the profile of laser generated grooves can be calculated.

A very crude but efficient approach for touch dressing has been undertaken by Pinto [147], who simply attributed the cutting of most protruded grains in an engineered grinding tool to an ideal cylinder and derived how the roughness of a workpiece is influenced by this dressing operation as shown in Fig. 9.1.

In the general model of a grinding process proposed in the keynote paper by Tönshoff et al. [197], the grinding force and workpiece roughness is related to the active cutting edges. Badger and Torrance [6] predicted this number per unit area of the grinding wheel based on the dressing condition and wheel properties, and then compared it with measured topography. They mentioned that the other important aspect of topography is the average slope of asperities. This was used as a basis for the modelling of form roll dressing by Baseri et al. [8,9].

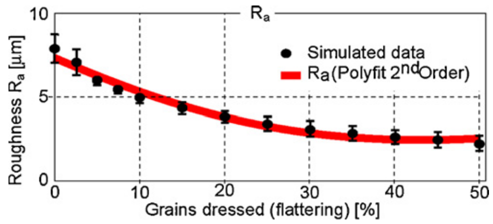

Fig. 9.1. Surface roughness as a function of dressing parameter percentage of grains touched by dressing.

The collision number between the grinding wheel and the dresser is mathematically modelled by Cinar and Brinksmeier [22,12]. This number combines the influence of the dressing overlap ratio and the dressing speed ratio to predict the grinding forces and workpiece surface roughness.

Linke [111], Linke et al. [200] generated a general modelling framework for grinding and wheel wear, which is based on dressing process simulations. The basis for this model has been laid by Brinksmeier, Cinar, Minke and Schultz [12,22,119,112,176]. It predicts the dressing forces, AE RMS signals during dressing as well as the topography based on the number and intensity of collisions between the dresser and the abrasive layer.

10. Conclusion

Since the condition of the grinding wheel severely influences the grinding result, conditioning is the veil in front of the grinding process. The number of publications concerning the art of conditioning is fairly small. The evolution of conditioning follows the large evolution lines of grinding. Increasing application of super abrasives for the grinding of ultra-hard materials, or for the reduction of wheel wear is the reason for further expansion of binding systems capable of retaining these highly loaded grains. A prominent trend towards metallic and startup of hybrid bonds can be observed. Hence, the development of conditioning follows the processing methods of such challenging wheels, which is the clear driving force towards non-mechanical conditioning. Another main stream of development in grinding is ultra-precise grinding with lowest surface roughness and highest brilliance. Extremely fine grains down to a few nanometres in size and roughness values of less than $R_a = 1$ nm can be achieved. In this region of quality, the preferred conditioning technology is ELID or other electric technologies. To achieve constant quality, in-process dressing has set the trend in the last years and other conditioning technologies besides ELID have developed in line for in-process capabilities.

Numerous emerging technologies for conditioning are developed, driven by the development of their respective base technologies. Laser based technologies profit from the development of high brilliance, ultrashort puls regions and of new processes such as remelting of vitrified bonded corundum wheels.

Method		Application in industry	Research activity	Application potential
Mechanical	Fixed dressing tool	++	+	++
	Rotating dressing tool	++	+	++
	Abrasive water jet	-	+	-
	Slurry	-	-	+
Thermal	Tangential laser radiation	-	++	++
	Radial laser radiation	-	++	++
	WEDD	+	++	++
	SEDD	+	++	+
	ECDD	+	++	+
	ECDM	+	+	+
Chemical & ECM	ELID	++	++	++
	ECCD	+	+	+
	Photocatalyst	-	-	-
Hybrid	US assisted dressing	-	+	+
	Laser assisted dressing	-	++	+
	DEDD	-	+	+

Fig. 10.1. Industrial penetration and research potential of different conditioning technologies.

Little research in mechanical dressing with fixed and rotating dressing tools is now taking place indicating their maturity. Fig. 10.1 shows the industrial penetration and research potentials of the different technologies.

Research impact on mechanical processes comes from the modelling of dressing to predict the grinding results from dressing parameters. An intermediate step in that process chain is the topography of the grinding wheel as the direct dressing result, where modelling and monitoring of grinding wheels touch each other. Research impact stems from the evaluation of surface data of grinding wheels to derive condensed key figures for the condition state.

Also emerging are structuring technologies subsumed under profiling in the definitions. The driving force is the reduction of heat affected zones on the workpiece surface and the reduction of coolant utilization for ecological reasons.

Acknowledgements

The authors wish to acknowledge the valuable contribution, comments, and encouragement from the following individuals in the preparation of this paper: D. Axinte, B. Denkena, E. Brinksmeier, C. Brown, M. Cinar, C. Guo, C. Heinzel, I. Inasaki, F. Klocke, Mr. Köchig, Mrs. B. Linke, S. Malkin, H.-R. Meyer, E. Minke, and J.F.G. de Oliveira.

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Please cite this article in press as: Wegener K, et al. Conditioning and monitoring of grinding wheels. CIRP Annals - Manufacturing Technology (2011), doi:10.1016/j.cirp.2011.05.003