Title
A review on properties of abrasive grits and grit selection

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Abstract:

Although abrasive machining is among the oldest manufacturing principles, it is still essential for today's industry. Abrasive tool quality is significantly affected by the quality of the contained abrasive grits. This paper gives an overview on the most important grit properties for grinding tools with regard to tool performance and manufacture. These properties include grit size, shape, and toughness. Relevant techniques for grit sorting and analysis (sieving, sedimentation, shape sorting, friability testing, etc.) are presented and compared with regard to the controlled grit properties. Grit quality remains an important criterion for tool performance. More transparency in grit sorting techniques and quality indicators for abrasive grits can help many stakeholders: grit producers, tool manufacturers, and tool users. Moreover, recycling of used grinding tools might become a future market.

Keywords:
Grinding tools, abrasive tools, abrasive grits, grinding grits, grit selection, grinding tool design, grit properties, tool performance, grit sorting

Text:

INTRODUCTION

Abrasive machining processes utilise abrasive grits and can achieve high surface quality, dimensional tolerance, and process stability. Grinding, as the most important abrasive manufacturing process, is either used as a finishing method or a shaping method for difficult-to-machine material. The abrasives market is strong and has recently benefitted from demand in the growing construction, renovation, aerospace, automotive, medical and electronics industries (Dickerson and Caldwell, 2012). The total value of abrasive products produced in the USA in 2008 was $4.8 billion as estimated by The Abrasives Hub Market Report (Abrasives Hub, 2009). Around $2.1 billion comprised coated tools (e.g. grinding belts or pads), $1.3 billion comprised bonded products (e.g. grinding wheels or pins), and the rest comprised grits, metallic abrasives for shot blasting, and others (Abrasives Hub, 2009). In 2013, the global market for abrasive tools was worth about 10 billion Euros (Saint-Gobain, 2012).

In grinding, the grinding tool is one of the most important process elements besides the cooling lubricant and grinding machine. Its structure, chemical composition, surface topography and wear behaviour define the machining process with regard to workpiece quality, surface integrity, process stability, productivity, and more. The tool might be a monolithic wheel, a wheel with an abrasive layer on a tool body, or a coated tool such as grinding belt, pad or disc. The abrasive grits perform the chip formation and are held in a bonding matrix, which defines the tool hardness and impacts wear behaviour.

Multi-layer grinding wheels are made of vitrified, resin, rubber, or metallic bonds (Klocke, 2009). All multi-layer grinding tools undergo similar manufacturing steps in general, such as mixing, forming, pressing, heat treatment, and post-processing (Tyrolit, 2003). Additional auxiliary steps include raw material quality control, weighing, intermediate control steps, sieving, stocking, etc. In the forming and pressing process, packing density of the grit/bond mixture becomes important. Homogeneity of the abrasive layer is necessary to assure a predictable grinding process behaviour.

Single-layer grinding wheels are made with electroplated or brazed grits on a wheel body (Klocke, 2009). Coated abrasive tools, such as grinding belts, pads or discs, are commonly also single-layer tools with grits held on backing material (Klocke, 2009). In these tools, the bond material can be applied in one or more layers (Borkowski and Szymanski, 1992). Grits are either scattered by gravity or by means of electrostatic force; the latter giving an even distribution and higher reproducibility (Klocke, 2009).

In abrasive operations, grits are used in large numbers with a distribution of size, shape and other properties. Engineered grinding tools with a defined grit distribution try to overcome some of the modeling problems of the statistically distributed grits (Herzenstiel and Aurich, 2010). Another approach is to produce a defined pore space on the grinding wheel surface to enhance transport of chips and cooling lubricants (Nadolnya, 2013). Still, tools with randomly distributed grits comprise the majority of grinding tools today.

The grit characteristics largely define the tool properties. For a uniform and predictable grinding process the abrasive grits must be free from impurities, of a controlled size and uniformly distributed inside the abrasive layer (Lewis and Schleicher, 1976). Therefore, grinding tool producers and grit suppliers need to characterise abrasive grits to control the quality of the in- and out-going material, monitor the distribution of characteristics in one batch, and predict abrasive tool performance. Producers in all fields are challenged by increasing responsibility for the life cycles of their products (Johnson and McCarthy, 2014, McClarence, 2010). This so called extended producer responsibility is forced by several policies, such as the EU directive on Waste Electronics and Electrical Equipment (Johnson and McCarthy, 2014). At the end of the product life, companies can either remanufacture their products (make it as new) or recycle as much material as possible (Johnson and McCarthy, 2014). For grinding tools, recycling would include recycling of the abrasive grit material. Grit recycling or re-use is also important under the growing awareness of resource efficiency. However, today the recovery rate of abrasive material in the abrasive industry is low even for precious material such as diamond (McClarence, 2010). Recovered grit material needs to be of consistent quality and size to be considered for re-use. Therefore, reliable grit selection and quality control is necessary.

The ongoing globalisation opens new markets, but also puts new legislative restrictions in place (such as Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), the European regulation on chemical substances). Production of abrasive grits is done increasingly by developing countries such as China and India, which provides a challenge to established market leaders (Asami and Santorelli, 2010). Because of the large range of available grits, a thorough grit characterisation is crucial for tool manufacturers to guarantee highest product quality and accuracy of desired properties.

Manufacturing practices are increasingly evaluated by their sustainability (Haapala et al., 2013). However, there is nearly no information on the economic or environmental performance of sorting and analysis methods available (Linke, 2014).

This paper defines the most important grit properties first and discusses their impact on tool performance and manufacture. Then relevant grit sorting and analysis techniques are presented, followed by a comparison. The review finishes with a summary and outlook.

GRIT PROPERTIES

The main task of abrasive grits is to conduct material removal through chip formation in ductile materials, or surface shattering and pressure softening in brittle materials. The grit therefore has to be harder than the workpiece material to facilitate chip formation. Self-sharpening through grit fracture is appreciated when grinding forces get too high. The bond can also release grits when they are blunt and contribute to self-sharpening. Four main grit properties decide on the efficiency of the cutting process: hardness, heat resistance, toughness, friability (Salonitis et al., 2014). In addition to these performance based parameters, grit size and shape / morphology define the number of active cutting edges in the grinding process. Furthermore, chemical, thermal, electric and magnetic properties are particularly important for tool manufacturing.

All of these grit properties occur as a distribution in the grit batch. Packing density and uniformity are additional characteristics. All properties have to be balanced between their impact on tool use and tool manufacturing. Table 1 summarises the most important grit properties and their main impacts. More details of properties and effects are later in the discussion.

Table 1: Grit properties and affected tool life stages

Grit size

In grinding tools, grit size and concentration define the number of cutting edges. The undeformed chip thickness is a function of the cutting edge number (Werner, 1971). A small grit size commonly achieves smaller surface roughness, but also causes higher machining forces and shorter tool life.

Oversize particles can have negative effects on part surface quality, so a defined grit size distribution is important. The grit size distribution in single-layer CBN grinding wheels is one reason for touch-dressing; this process equalises the highest cutting edges and maintain a predictable part surface quality (Ghosh and Chattopadhyay, 2007).

Grit size and size distribution affects grinding tool production (Benea, 2010), in particular, packing density. Mold packing density and homogeneity can be increased by mixing different grit and bond material sizes (Webster and Tricard, 2004).

In addition to the grit size, the number of particles per carat (PPC) is often used as measure for coarse diamond grits, e.g. for electroplated tools, dressing tools or stone sawing tools. The number of particles per carat offers a measure for the consistency of the diamond batch (List, et al., 2008).

Grit shape / morphology

The grit shape and morphology stems from the growth conditions during grit synthesis and from the post-processing strategy. Diamond or CBN can be synthesised in different shapes (octahedron, cube, tetrahedral) depending on the pressure/temperature conditions. Alumina appears as polycrystalline material and is broken down to the desired grit sizes. The different synthesis methods lead to different purities and single crystal sizes (e.g. monocrystalline alumina, molten, white alumina, or sintered alumina with very small crystals). Post-processing such as crushing or chemical processes changes the shapes. Grit shapes are hardly ever ideal and need to be described by several geometrical indicators, such as edge roundness and ellipticity.

The grit shape affects the number and shape of cutting edges and the grit breakage behaviour. Each grit can have one or more cutting edges and grit splintering changes the number and shapes of the cutting edges. Many grinding models for superabrasive grits work with simplified grit geometries like balls, ellipsoids, or octahedrons (Doman et al., 2006, Heinzel, 2009, Koshy et al., 2003, Basari et al., 2008).

The grit surface defines how well the grits mechanically adhere in the bonding, so a rough surface is preferred (Dyer, 1979). Grit coatings are often applied to support retention by increasing the surface area or offering chemical bonding (Metzger, 1986, Kompella et al., 2005). The packing density is also affected by grit shape. Blocky grits have a higher packing density than less symmetrically shaped grits (Malkin and Guo, 2008).

Grit hardness

Grit hardness is defined as the static indentation hardness determined by a Knoop or Vickers hardness test (Malkin and Guo, 2008). Hardness is necessary to transfer the forces require for chip formation. The cutting edge stability and sharpness are also affected by grit hardness. Abrasive wear can only occur if the abrasive particle is harder than the wearing material in the process of friction (Khruschov, 1974). Still, abrasive wear can also be found on hard diamond grits from alumina grits, because diamond has a lower temperature stability than alumina (Minke, 1988). So temperature hardness is important since grinding has commonly high peak temperatures (Jackson and Davim, 2011).

Grit toughness and friability

Toughness is the resistance of a material against breakage and crack propagation and is often measured under dynamic conditions. Jackson and Davim introduce the term friability as inverse term of fracture toughness (Jackson and Davim, 2011). Toughness index, temperature toughness index and friability index are used by the industry and are measured in friability tests (Vollstaedt-Diamant, 2012, Jackson and Davim, 2011).

Grit toughness implies how likely the grit will fracture when engaging with the workpiece. The breaking behaviour can vary from breakout of large to small particles leaving a smooth or rough surface with one or more cutting edges. Hard and friable abrasives are generally applied in precision grinding, whereas tough, large grits are more suitable for heavy-duty grinding (Malkin and Guo, 2008). Tough grits imply low tool wear, but they might become dull and increase friction leading to the danger of thermal damage and process vibrations. Friable grits expose new, sharp cutting edges easily, but may result in short tool life and form errors. Grit fracture is also important in tool conditioning because it defines the tool sharpness (Baseri et al., 2008).

Grit toughness and hardness are not related, but commonly harder grits are more friable (Malkin and Guo, 2008). Grit size and toughness are connected, because smaller single-crystal grits have fewer defects (Field and Freeman, 1981).

Grit thermal properties and chemical reactivity

Heat resistance is affected by the temperature hardness, but also by the chemical reactivity of the grit material at higher temperatures and pressures. The reactivity needs to be considered for the atmosphere, cooling lubricants used, and workpiece material.

The most important thermal properties during tool use are the thermal conductivity, the point of softening under load, and the melting point (Klocke, 2009). Whereas the latter two properties define the tool end of life, the thermal conductivity changes the impact on the part surface integrity. The grits are loaded with frictional heat at the cutting edges, but high thermal conductivity leads to a quick distribution of heat throughout the whole grit volume. This can have positive effects on surface integrity, e.g. in the case of superabrasives acting as heat sinks. Alumina grits have comparatively low thermal conductivity at room temperature which also decreases at higher temperatures (Klocke, 2009, Coes, 1971). This leads to high thermal stresses inside the grit. In addition, the different thermal expansion coefficients of grit and bonding can create further stress (Klocke, 2009).

For vitrified tools, sintering temperatures over 1,300 °C can occur. Diamond especially features low thermal wear resistance in air, leading to the necessity of inert atmospheres or low-temperature sintered bonds.

Grit electric and magnetic properties

Electric and magnetic properties are mainly important for tool manufacturing not tool use. First, they affect the deposition of the galvanic bond on grit and tool body in electro-plated bonds. Here, the metallic inclusions in synthetic diamonds can cause problems (Yin et al., 2000). Second, electrostatic distribution for coated grinding tools can be affected by the electric grit properties (Klocke, 2009).

Packing density

Packing density or bulk density depends on grit size and shape. For example, equidimensional shapes pack to a higher bulk density than flat shapes (Menard and Thibault, 2000). The packing density is a rather simple but effective measure for the dominant grit shape of a batch, if grit size and size distribution are known (Malkin and Guo, 2008, Schuetz, 1981).

Grit density and grit size are related to the number of cutting edges in a bonded abrasive tool (Yegenoglu, 1986). Packing density affects the mold packing density in manufacturing of multi-layer grinding tools.

Uniformity

Abrasive layers need to be homogeneous to exhibit a stable grinding behaviour and produce no rotational imbalance. A narrow distribution of grit characteristics allows a good predictability for tool performance (Dyer, 1979).

Novikov et al. describe a calculation method for “uniformity”, which allows assessing powder uniformity from diverse characteristics (Novikov et al., 2008). Uniformity can be improved during the abrasive grit production, at the stage of grit selection, and by grit sizing (Novikov et al., 2010).

GRIT SELECTION AND ANALYSIS METHODS

Grit selection and analysis methods can be described with different factors: accuracy, precision, resolution, and reproducibility (Benea, 2010).

Sieving

Sieving is a simple method to separate particles with sieves of defined mesh sizes (Salmang et al., 2007). Sieving can be performed either by hand or machines and can be used for dry or wet materials. Larger abrasive grits are sorted by size by sieving, finer grits are sorted by sedimentation

(Klocke, 2009, Marinescu et al., 2007). Multiple national and international standards exist to define the size ranges, such as ANSI B74.12, FEPA 42-1:2006, FEPA 61/97.

Defining a size through sieving does not imply a single value, but rather a size band. The size band is classified by a set of sieves retaining and letting pass a defined amount of grits. The sieving quality depends also on the grit shape. For round grits, the mesh defines the maximum diameter, but for irregular grits (e.g. needle shape) the maximum dimension can be larger than the mesh size, because irregular grits might pass with their smallest cross-section. Therefore, the size distribution is wider for irregular grits.

Sedimentation

Sedimentation or Stokesian methods work with a stationary medium and free falling particles (Salmang et al., 2007). These methods are commonly used for grading finer grits. Stokes' law relates the settling velocity of small sphere particles to the sphere radius and density and medium density and viscosity (ANSI, 1977). Since Stokesian methods work best for spheres, and flat particles experience a greater drag per unit mass, sedimentation processes can result in oversized particles. This can become a problem in lapping or polishing operations and ruin part surface quality (Davies, 1974). Sedimentation can also be a very time consuming method (more than 24 hours for very fine particles) (Unified Abrasives Manufacturers` Association, 2009).

Laser granulometry

Laser granulometry is a counting method where a mixture of loose particles in a fluid medium flows through a ring. Laser light is directed through the ring and results in shadowing effects depending on the particle size. Other sizing methods are laser light diffraction, dynamic light scattering, photon correlation spectroscopy, Brownian motion turbidity, etc. (Benea, 2010).

Picture analysis

Picture analysis works on a two dimensional projection of the abrasive grits, for example via back light microscopy, film scanner, scanning electron microscopy (SEM) picture. It has to be considered that the grit placement and orientation interferes with the measured results. For example, some grit shapes are more likely to fall on certain grit planes. Common metrics from picture analysis are maximum and minimum grit diameter, grit circumference, and grit cross-sectional area in the projection plane (Pirard, 2003). Particle analysers can be coupled with a sorting device.

Shape sorting

Shape sorting machinery are based on the principle that different grit shape move differently on an inclined, vibrating table (Vollstaedt-Diamant, 2010). Boxes at one side of the table collect different shapes. Rounder shapes like cubo-octahedrons tend to roll down, whereas irregular shapes, such as needle-like crystals or platelets, might move upwards. Shape sorting works only if the grit batch has the same grit size range.

Procedure for packing density

Packing density can be determined by the weight of grits required to fill a cylinder of known volume when the grits are allowed to flow through a funnel and fall from a fixed height (ANSI, 1992). The packing density is given in [kg/l], [g/l] or [g/cm^3] (Schuetz, 1981, ANSI, 1992).

Impact strength test

Impact strength tests, so called friability tests evaluate the grit fracture behaviour (O'Donovan, 1976, Marinescu et al., 2004). A grit sample of defined weight and a steel ball are encased in a capsule, which is shaken with a defined cycle number (Vollstaedt-Diamant GmbH, 2012). The percentage of the non-destroyed grits is defined as Toughness Index (TI), the number of cycles needed to break 50% of the grits is defined as the Friability Index (FI) (Vollstaedt-Diamant GmbH, 2012). In addition, a thermal toughness after heating (TTI) can be measured as well (Marinescu et al., 2007).

Single grit breakage tests

The single grit breakage test measures the maximum force to break a particle along one axis (Vollstaedt et al., 2003, Vollstaedt and List, 2003). A single particle is positioned between two anvils which are closed with an increasing force (List et al. 2006). The maximum breakage force is measured and divided by the grit area to define the breakage strength. Modern systems allow to record pictures of the grits to analyse shape and size individually.

Magnetic sorting

Magnetic sorting is done by moving the particle close to a drum or belt with a magnetic force higher than the grit gravity force (Vollstaedt-Diamant GmbH, 2011). Magnetic sorting is used to separate magnetic and non-magnetic grits or grits from blasting processes and metallic chips (Vollstaedt-Diamant GmbH, 2011, Drenter et al., 1997).

Magnetic susceptibility analysis

Magnetic susceptibility analysis is performed with a standardised magnetic analyser on a defined sample size (Menard and Thibault, 2000, American National Standards Institute, 1990). The unbalance between the electrically excited reference coil and the sample coil translates into the relative magnetic content of the sample (American National Standards Institute, 1990).

Electrostatic separator

Particles with conductive surfaces can be selected by means of an electrostatic separator. An electrostatic field can be built between two flat electrodes (Johnson and Marchant, 1944).

Comparison of methods

The above described methods are commonly used in industry. They assess different grit properties of conventional or superabrasive grits. Some methods will give quantitative measurements, some are used for (relative) sorting of grits and some are non-destructive tests. Table 2 gives a comparison of common methods according to these criteria.

Since abrasive grit sorting and selection is often a core competency of companies and defines the quality of the abrasive tools, there is only few information on time, cost and efficiency of the methods published. Furthermore, the costs of each method scale with apparatus size and type and were therefore not evaluated.

Table 2: Comparison of common grit analysis methods

CONCLUSIONS AND OUTLOOK

Grit quality remains one of the most important criteria for grinding tool performance. Grit producers, abrasive tool manufacturers and users of abrasive tools are challenged by increased global competition and increased ranges of ingredients. A comprehensive quality control of the abrasive grits helps tool manufacturers to enable a predictable tool use. As grit sorting techniques and quality indicators are often company specific knowledge, they are commonly not openly discussed. As the above review shows, no single method is able to give all information about grit quality and performance. In addition, the tests on grit strength and breakage behaviour are destructive. The users of grits therefore need a set of quality test methods.

Detailed knowledge about grit shape, size and size distribution is not only important to specify the grinding tool for a certain application, but it is furthermore advantageous to wheel topography simulation and tool wear modelling (Doman et al., 2006). Predictable grinding processes increase overall sustainability through reduced wastes. In particular engineered wheels, i.e. wheels with a defined grit pattern, need a tight quality control for the grits (Aurich and Kirsch, 2012). Tool recycling receives growing attention as well, but can only be successful if re-used or recycled grits can be properly analysed and sorted (Behrends et al., 2011).

The growing interest in manufacturing sustainability leads to growing interest in the embodied energy of all materials and tools used (Kirsch et al., 2014). Grinding tools can have substantial embodied energy (Aurich et al., 2013, Linke, 2014). Grit sorting and analysis is commonly neglected in energy studies, and should therefore be focused in the future. Furthermore, leveraging effects might happen: a better quality control might cost more time, money and other resources, but improve the grinding wheel performance significantly and save more resources on the user end.

In conclusion, more transparency of grit sorting techniques and quality indicators for abrasive grits helps many different stakeholders: grit producers, tool manufacturers, and tool users. There is an increasing interest in grinding tools with higher sustainability and the recycling of used grinding tools might become a future market. All developments in the abrasive market are tied to proper grit quality control.

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Table 1: Grit properties and affected tool life stages

	Influence on chip formation	**Influence on tool wear**	**Influence on multi-layer tool manufacture**	**Influence on single-layer tool manufacture**
Size	X		X	X
Shape/morphology	X	X	X	
Hardness	X	X		
Toughness, friability		X		
Thermal properties, chemical reactivity	X	X	X	X
Electric and magnetic properties				X
Packing density	X		X	
Uniformity	X	X	X	X

Table 2: Comparison of common grit analysis methods

Method	**Size**	**Shape**	**Toughness**	**Magnetic susceptibility**	**Electric conductivity**	**For conventional grits**	**For superabrasive grits**	**For quantitative measurements**	**For sorting**	**Non destructive**
Sieving	X					X	X	X	X	X
Sedimentation	X					X	X		X	X
Laser granulometry	X						X	X		X
Picture Analysis	X	X				X	X	X	(X)	X
Shape sorter		X	(X)				X		X	X
Procedure for packing density		X				X	X			X
Impact strength test			X			X	X	X		
Single grit breakage tests			X			X	X	X		
Magnetic sorting				X			X		X	X
Magnetic susceptibility analysis				X			X	X		X
Electrostatic separator					X		X		X	X