Journal of Manufacturing Science and Engineering

Review on grinding tool wear with regard to sustainability

Barbara S. Linke
University of California Davis
Department of Mechanical and Aerospace Engineering
1 Shields Avenue
Davis, CA 95616, USA
e-mail: bslinke@ucdavis.edu
ASME Member since 12/2011

ABSTRACT

Manufacturing processes have to become more sustainable. For grinding processes, this means that tool wear and performance need to be critically evaluated in their economic, environmental and social impact. Tool wear affects several stakeholders. Different wear mechanisms on the grit and bond level lead to a change in tool profile and sharpness. For the user, wear changes tool costs, process stability and maybe worker safety. Tool manufacturers need tool wear to sell replacements, whereas tool users might not like the higher waste and costs from tool wear but need tool self-sharpening.

INTRODUCTION

Manufacturers are under increasing pressure to succeed economically in a global market while incorporating environmental and social aspects [1]. Therefore, manufacturing processes have to become more sustainable. Commonly, sustainability holds the three dimensions: economic, environmental, and social.

Grinding is an abrasive machining technology which produces parts with high quality, productivity, and process stability [2, 3]. Sustainability aspects in abrasive machining is gaining more interest by industry and academia [4, 5]. In grinding processes, sustainability can be analyzed by different sustainability indicators, such as energy intensity, residuals intensity, water intensity, productivity, or labor intensity [6]. Screening and in-depth approaches have been developed to quantify energy, resource consumption, and emissions in unit manufacturing processes [7]. The temporal and spatial boundaries of the sustainability analysis can change the analysis results considerably, e.g. is the manufacturing of just one product or of a batch analyzed, or are factory facilities (such as supply systems for cooling lubricants) included or not [8]. To evaluate overall sustainability, Linke et al. propose a customized method based on the utility analysis with chosen sustainability indicators [6]. Other frameworks and indicators are discussed in [9-13].

In 1968, Malkin stated that “the main difficulty encountered by the grinding engineer is the choice of the grinding wheel best-suited for a given work” [14]. This statement is still true today. The design of grinding tools bears the challenge of providing either a cheap, mass-produced product versus an expensive, customized product. The grinding tool behavior is decisive for the grinding process performance.

The global market for abrasive tools was worth about 10 billion Euros in 2013 (with North America = 25%, EU = 34%, Asia Pacific = 32% and the rest of the world = 9%). In the U.S. alone, those sales break down as follows, coated abrasives = 42%, bonded abrasives = 22%, thin wheels = 18%, superabrasives = 10%, and construction products = 7%. [15]

Abrasive tools need to meet certain requirements. The abrasive grits engage with the workpiece to form chips and therefore need to be hard, tough, and chemically resistant [3]. The tool bonding has to hold the grits until they become blunt and release them to let new, sharp grits engage. Pores in the abrasive layer are important to supply cooling lubricant and remove chips from the contact zone. Tool self-sharpening through grit splintering and break-out is favorable. In the industrial practice, multi-layered tools undergo frequent tool conditioning, so called dressing, to restore sharpness and profile.

Products have four life stages: raw material extraction, manufacturing, use, and end of life. Case studies have shown that the first two life stages of grinding tools might result in a considerable amount of embodied energy, e.g. 454 MJ for an alumina grinding wheel of 400x20x200 mm or 1257 MJ for a cubic boron nitride wheel of the same dimensions with an abrasive layer thickness of 5 mm [5]. Tool wear then decides on how much of this embodied energy has to be added to the embodied energy of the product.

Tool wear can be split into macro effects (tool profile loss) and micro effects (sharpness loss). Marinescu et al. add roundness deviation as an additional performance characteristic to profile and sharpness loss [2]. The following review summarizes common findings and cannot be comprehensive for all applications, because tool wear depends strongly on the process parameters, machine, workpiece material, and cooling conditions. Grinding tool wear is intrinsic to all grinding processes and therefore encloses a wide range of appearances. This paper gives examples on wear mechanisms, discusses wear on a microscopic level (sharpness loss) and macroscopic level (tool profile loss), debates about limits of the grinding ratio, and evaluates grinding tool wear under the viewpoint of sustainability. Recent developments are highlighted.

WEAR MECHANISMS

Chip formation in grinding involves rubbing, plowing and cutting in ductile materials. In brittle materials, crack formation and propagation lead to material removal in the form of particles. If the penetration depth of grits is not high enough, only rubbing and plowing will occur. Researchers have tried to model the grinding process for many decades, but the models still inherit many uncertainties or empirical measurements [16, 17].

In the cutting zone, high temperatures and high pressures act on the grinding tool. These conditions lead to tool wear because of mechanical effects (vibrations and grinding forces), chemical effects (reactions with cooling lubricant and workpiece material), and thermal effects (grinding pressure and friction) [3, 18]. A better understanding of heat flows in the grinding contact zone will also improve the understanding of wheel wear [19]. The abrasive layer of grits, bonds, and pores wears through several mechanisms, which can be sorted into four main types: grit surface layer wear, grit splintering, grit-bond-interface wear, and bond wear (Fig. 1, Table 1). The wear types are related to the material removal mode, for example resulting from the workpiece material [20], and the material removal rate [3, 21] among other factors.

In addition, clogging of the pores occurs. Grit-bond-interface wear and bond wear are more important for the tool profile wear (macro effects), whereas grit surface layer wear and grit splintering are mostly responsible for a change in wheel sharpness (micro effects).

Grit Surface Wear

Malkin defines attritious wear as referring to the development and growth of wear flats on the tips of active grits. Attritious wear is measured by the percentage of the wheel surface covered with wear flats [14]. Jackson explains that attritious wear occurs “atom by atom” by physical and chemical interaction between grit and workpiece [22]. Several wear mechanisms are responsible for grit surface wear, in particular abrasion, adhesion, and tribochemical reactions. For example, a highly viscous oxide layer forms on sol-gel alumina grits in single grit scratching tests [23]. This oxide layer presumably reduces the strain energy between the workpiece and the abrasive grit, so that friction coefficient and grit wear are decreased [23]. Second-phase inclusions in the sol-gel alumina were found to enhance the tribological properties [24]. Nadolny confirmed oxide layers on sol-gel alumina grits as well as plastic flow and abrasion in the surface layer resulting from high grinding temperatures [25].

The grit type affects how the grits get dull. Common grit materials are silicon carbide (SiC), alumina (Al_2O_3), cubic boron nitride (CBN) and diamond. They occur in different grit types depending on synthesis and post-processing. For example, green silicon carbide and white alumina are friable and offer new cutting edges easily [26]. Regular alumina acts comparatively tough and gets blunt [26]. Pure white alumina is one of the hardest, but most friable alumina grit types [2]. Under small process loads such as for small chip thicknesses, SiC wears by tribochemical mechanisms, likely oxidation and silicization [27]. At room temperature, diamond is nearly inactive regarding chemical reactions. At temperatures above 800 °C, diamond burns to carbon dioxide with oxygen in air [28]. During grinding of ferrous materials with low carbon content diamond wears because of diffusion and graphitization [29]. The diamond turns to graphite in the surface layers, which is accelerated by oxygen as catalyst [29]. Then the carbon diffuses from graphite into the ferrous material. In the presence of oxygen, the diamond surface graphitizes already at temperatures of 900 K [30].

Grit Splintering

Grit splintering depends on the crystal structure of the abrasive grit and the cleavage planes. For example, sintered and sol-gel alumina consist of small crystals whereas molten alumina has larger crystals [27]. Above a certain load, sol-gel and sintered alumina wear by micro-crystalline fracture; below this minimum load, they wear mainly by surface flattening [31, 32]. It can be hard to find the “sweet spot” of a wheel with sintered alumina where the wheel wears in a controlled, self-sharpening manner rather than getting dull or showing excessive grit and bond fracture [33].

Silicon carbide is known for wearing mainly by splintering in the medium grinding size ranges. Instead of steady and slow wear by adhesions, abrasion or chemical mechanisms, SiC wears by breaking into bigger grit particles [27].

Natural and synthetic diamond grits show different breakage behavior. Natural diamond collapses in several breakage events; synthetic grits, however, fail with one breakage event [34]. Grit structure, types and occurrence of crystal growth defects define the breakage behavior [35]. The density of atom bonds in the different diamond planes defines hardness and cleavage behavior [30, 36]. Diamond has four cleavage planes, whereas cubic boron nitride (CBN) has six offering more splintering options.

Grit-Bond-Interface Wear and Bond Wear

The grits might fall out with or without bonding attached (bond wear vs. grit-bond-interface wear). Mechanical loads cause fatigue in the bonding bridges and cause bond breakage [37].

The wheel hardness is an important impact factor on the wear phenomena [38, 39]. Hardness is defined as resistance to grit break out from the tool and results from the strength of bond bridges and adhesiveness of the bond at the grit [3]. Softer wheels show higher wear rate, but can also stay in a sharp cutting state longer [38]. The wheel costs per part might be higher but the danger of thermal damage to the workpiece is reduced.

In addition, the process parameters also affect the wear phenomena. For example, higher specific material removal rates result in higher single grit loads, which change the wear mechanism from abrasion to particle break-out and total grit break-out [3, 21]. The different wear mechanisms then result in different amounts of wheel profile loss [38].

Clogging

Clogging or loading of the abrasive layer describes the adhesion of chips to the abrasive grits or interlocking of chips in the pore space. Lauer-Schmaltz and Koenig defined three loading types: Chip nests, welded chips, and grit adhesions, which differ in particle size and position [40]. With more wheel clogging, the danger of thermally induced damage to the workpiece, higher workpiece roughness, and grinding wheel wear rise [40]. Among other things, wheel loading depends on the machined material [27, 41, 42]. Adibi et al. propose an analytical model based on adhesion of workpiece material to the abrasive grits [43]. Monitoring of wheel clogging is attempted through Acoustic Emission or optical techniques, but is still challenging [44, 45].

EFFECTS OF WEAR

In multilayer grinding tools, three wear phases can be observed [37, 46]. High initial tool wear happens after dressing or for a new tool (phase I), followed by steady-state tool wear (phase II) (Fig. 2) [22, 47]. Wheel collapse (phase III) occurs as a failure mode presumably because of wheel dulling and high grinding forces and should be avoided [37, 48]. The dressing process affects the initial wear dominantly, whereas the steady-state wear is dominated by the grinding process conditions.

Malkin and Shi relate grinding forces and thermal workpiece damage mostly to the wear flats (grit surface layer wear), whereas grit splintering and bond wear form the profile wear [49].

Micro Effect - Sharpness Loss

Loss of wheel sharpness, or wheel dulling, leads to a change in part surface roughness and higher process energy bearing the risk of thermal workpiece damage. A growing wear flat area through attritious wear leads to higher grinding forces [50] and potentially chatter [51]. The wheel surface topography changes with grinding time and the average chip cross sectional area [52, 53]. Smaller chip load leads mainly to a decrease in wheel surface roughness, while a larger chip load tends to increase wheel surface roughness [52, 53]. Excessive wear with large volume grit breakout reduces grinding forces and increases surface roughness, but dimensions are hard to keep and the shorter wheel life increases tool costs. A balance between self-sharpening and wheel costs is favored. For example, high performance processes need a grinding tool with high grit retention over a longer period [54]. Precision parts need high surface quality and high process stability, which is commonly accomplished through shorter dressing intervals. Dressing restores tool sharpness and profile. Superabrasive tools enable longer intervals between dressing operations than conventional tools. Initial wheel costs for superabrasive tools are commonly higher, but are offset by higher process stability and productivity [55]. In a case study on sharpening of high speed steel (1.3343) the tool costs for the alumina wheel were negligible whereas the standard CBN wheels costs had to be considered with 1.72 DM/cm^3 [56]. However, the 6 times higher material removal rate and lower tool wear for the CBN tool (G-ratio of 38 for CBN vs. 2 for alumina) resulted in much lower time-dependent costs (2.22 DM/cm^3 vs.

13.33 DM/cm^3) [56]. Therefore, the overall workpiece costs are also lower for the CBN wheel (3.94 DM/cm^3 vs. 13.33 DM/cm^3), even though the tool costs make up 30%.

Single-layered tools show an initial wear phase followed by quasi-stationary behavior until the tool`s end of life defined by thermal damage to the workpiece [3, 57]. Single-layered tools are not profiled or sharpened in the common sense, although sometimes so called touch-dressing is applied to level protruding edges. The performance of electroplated CBN tools can vary significantly over the tool life so that process control and effective utilization are challenged [58]. Shi and Malkin found for electroplated CBN wheels, that grit pullout was dominant in the initial transient wear state followed by grit fracture; in the steady-state wear regime grit fracture dominates [57]. Attritious grit wear does not contribute much to the tool profile loss, but the decreased wheel sharpness leads to higher grinding forces and power [57]. Fractal analysis of three dimensional grit pictures provides a new method to study grit wear of brazed CBN grinding tools [59].

Macro Effect - Tool Profile Loss

Dimensional wear at the grinding tool leads to a loss in workpiece dimension and profile. In the case of cylindrical grinding wheels, wear at the radius and at the edges can be measured and both wear volumes define the dressing allowance to retrieve the original tool profile. Corner wear [46] is also known as edge wear [3]; radius wear [60] is called radial wear [3] or uniform wear [46].

Werner explains that all wear effects depend on the average single grit cutting force, friction speed, contact time, and contact frequency [60]. At tool corners, grit support within the abrasive layer is weaker, so the wear rate is faster [60]. In external cylindrical plunge grinding, the edge wear appears with an elliptical contour [21, 61]. Circular edge profiles occur only for small material removal rates or short process times [21]. Load direction, e.g. defined by feed direction, affects the wear profile. Tool profile loss can become specifically critical for the workpiece accuracy in five-axis grinding operations [62].

Tool wear measurement is complicated due to the high number of randomly distributed, geometrically undefined cutting edges. In research settings, wheel wear can be determined by reproducing the rotating grinding wheel into a steel plate. Single grits or clusters of grits are examined to attempt to generalize the wear studies to real-scale grinding tools [63]. In most industrial applications, wheel wear is assumed from workpiece profile deviations rather than directly measured. However, there are many sensors for measuring the macroscopic profile of grinding tools available, for example through grinding fluid monitoring, acoustic emission, embedded force sensors, etc. [44, 64-67]. Tool condition monitoring in real life processes can reveal tool wear and defects, such as unbalance, cavities, or waviness, [68] and continues to be a pressing need [65].

Impact on costs, worker and environment

Tool wear affects wheel life time and tool costs. The manufacturer balances tool price by considering raw material costs, production costs, and the price a tool user is willing to pay. To the tool user, the direct costs of different grinding wheels need to be compared with the total costs in a facility for process stability, auxiliary times, scrap parts, etc.

Tool conditioning is non-productive and considered as auxiliary time, adding costs. The dressed wheel volume is lost for processing. Nevertheless, tool wear and conditioning define product quality, grinding forces, maximum material removal rate, and auxiliary times. Tool manufacturers are able to generate desired tool capabilities within a certain range, but the grinding setup and parameters chosen by the tool user also decide strongly on the tool performance, so both stakeholders have a large responsibility for the sustainability of grinding tools. It is also not surprising that tool wear enables tool manufacturers to sell tools.

The biggest concern of social sustainability is the safety of the tool user. Above a circumferential speed of 20 m/s, bursting grinding tools are already potentially harmful to the machinist and the machine tool [2, 67]. Hand-held tools in particular can be very harmful. For home use, angle grinders ranked third in a list of most dangerous tools by The British Royal Society for the Prevention of Accidents with an average of 5,400 injuries recorded yearly in the UK between 2000 - 2002 [69-71]. A Brazilian study in 2012 revealed that operators of grinding machines earn more money than operators of hard turning machines (10.11 R$/h vs. 8.42 R$/h) and need more training (152 h vs.

120 h) [72]. However, the risk factor for accidents and the noise level for the operator are higher for grinding personnel.

OSHA (Occupational Safety and Health Administration), the German Berufsgenossenschaft, and other organizations define safety measures for grinding wheel use. For example, the bursting speed of grinding tools needs to be larger than the maximum wheel speed by certain safety factors [73]. Malkin and Guo show how the bursting speed increases with wheel hardness and decreases with grit size [46], but few bursting speed models exist [74, 75]. Therefore, burst tests are conducted and safety guards are necessary.

In addition, the grinding tool user might be affected by grinding dust through inhalation, eye or skin contact [76]. Knight addressed respiratory problems from grinding process emissions already in 1822 [77]. He recognized the so-called Grinder`s asthma from inhaled particles which led to the development of exhaust air systems [77]. Sparks and hot chips can also be dangerous, in particular when using manual grinding tools [78]. An additional danger occurs for portable power tools around explosive or flammable materials.

Environmental impacts come from the whole tool life cycle [79], but it is unclear which emissions come from the grinding wheel use. Grinding tool manufacturers proved in unpublished tests that no harmful gaseous emissions derive from the grinding wheels during grinding. Still, in grinding or dressing, high peak temperatures can occur such that grit and bond materials melt [80, 81]. There are opposite and unproven opinions regarding the existence of leaching effects from metal bonds into the cooling lubricant.

The literature indicates that reactions of cooling lubricants with heavy metals or non-ferrous metals exist, but without further detailing. Inhibitors in the coolant are therefore important. Metals from the ground material can dissolve into the cooling lubricant [82]. For example, in tool grinding of cemented carbides, cobalt leaching into the cooling lubricant can occur [83]. This might pose problems for the worker and complicate waste disposal. Inhibitors and the correct choice of cooling lubricant suppress leaching [83].

G-Ratio and Wheel Wear Modeling

Tool life between conditioning is measured in elapsed time, number of workpieces machined, or workpiece volume removed [26]. The grinding ratio, G-ratio, or G is a common parameter for describing the tool lifespan. It is the ratio of machined workpiece volume, V_w, and worn grinding tool volume, V_s, as defined in equation 1 [46].

$$G = \frac{V_w}{V_s} \tag{1}$$

The G-ratio depends on the machined material, tool design, grinding operation and parameters, cooling lubricant, machine tool, etc. Therefore, no certain value can be given for a generic application, but literature and tool supplier databases provide ranges of G-ratios, e.g. in [22, 26, 84]. Although a high grinding ratio is desirable, a highly wear-resistant tool may generate higher forces and grinding energies, thus increasing the potential of thermal workpiece damage.

Calculation of grinding costs may vary for different companies, but generally grinding costs depend on time-dependent and constant costs [6]. Time-dependent costs might include machine and labor costs; constant costs often consist of coolant costs per part, grinding tool costs per part and non-conformity costs. Grinding tool costs per part can be calculated as ratio of total tool costs and number of parts between conditioning operations [55]. The number of parts are related directly to the machined workpiece volume, V_w. The number of parts between conditioning has a high impact on superabrasive tool costs per part because the initial tool costs are considerably higher, but this may be off-set by the longer tool life, higher process stability and higher productivity which all reduce the time-dependent costs [55]. Case studies can be found in [55].

A few issues with the grinding ratio need to be mentioned. First, the wear rate might not be constant and differs along the three phases of grinding tool wear (Fig. 2). The G-ratio for the entire wheel wear is different than calculated only within one wear phase [46]. Therefore, Malkin and Guo suggest calculating the G-ratio in the steady-state wear phase II after equation (2) [46].

$$G = \frac{\Delta V_w}{\Delta V_s} \tag{2}$$

Second, literature mostly disregards that tools can have the same G-ratio but different machined workpiece volume as shown in equation (3). Fig. 3 shows an idealized example in the steady-state wear (phase (II)) for three different wheels. The end of life differs despite the same G-ratio. A small wheel might wear earlier and not grind as many workpieces as a large wheel before the profile loss gets unacceptable.

$$G = \frac{V_w}{V_s} = \frac{10\text{mm}^3}{0.1\text{mm}^3} = \frac{500\text{mm}^3}{5\text{mm}^3} = \frac{4{,}000\text{mm}^3}{40\text{mm}^3} = 100 \tag{3}$$

Third, even if the same G-ratio is achieved for the same workpiece volume, V_w, the tool performance might vary greatly. Figure 4 shows an example where wheels A and B wear differently, although the G-ratio is similar. Wheel A has a shorter initial wear phase and a longer steady state wear phase than wheel B. This results in a presumably more stable and predictable grinding behavior for wheel A as well as in a narrower bandwidth of forces and workpiece roughness.

In 1914, Alden proved that a larger depth of cut causes greater tool wear [14, 85]. Still it is not possible to model grinding tool wear purely analytically and empirical constants are needed. For example, Decneut et al. related the G-ratio to the equivalent chip thickness with charts [86]. Simplified models, such as relating the radial wheel wear to a grinding wheel wear stiffness coefficient and the normal grinding force, allow for basic mathematic process modeling [87].

Physics-based models are still under research. Werner built a wear model by multiplicative superposition including four wear criteria: contact pressure, friction velocity, engagement time, and engagement frequency [60]. In single-layered diamond tools, the total sliding length seems to provide a good indicator for wheel wear if attritious wear is dominant [88]. Recent studies of the wheel topology in single-layer CBN wheels may lead to tool life expectancy models [89]. Wheel wear prediction becomes important for automated form control [90].

G-Ratio and maximum material removal rate are often contradictory, so Helletsberger proposes an additional characteristic [84]. The performance factor, L, is the factor of the grinding ratio, G, and the specific material removal rate, $Q`_w$ (equation (4)). It allows looking at time-dependent costs in addition to wheel costs aiming for the maximum performance factor, L [84].

$$L = G \cdot Q`_w \tag{4}$$

Equation (5) results from combining equations (2) and (4) and assuming that the effective wheel width is constant throughout the process. C is a constant value. Equation (5) shows that productivity expressed through $Q`_w$ has a higher importance than the wheel wear costs in practice [84]. One example is given by comparing tools with different hardness. The harder tool has lower tool wear, ΔV_s, but the specific material removal rate might also drop which might lead to a decrease in the performance factor, L [84].

$$L = C \cdot \frac{{Q`_w}^2}{\Delta V_s} \tag{5}$$

A case study of outer diameter grinding of cemented carbide drums with resin bonded diamond wheels revealed that reducing the material removal rate by 20% (from 2 cm^3/min to 1.6 cm^3/min) resulted in increasing the G-ratio by 100% (from 75 mm^3/mm^3 to 160 mm^3/mm^3) [56]. The higher time-dependent costs were compensated by the lower tool costs per part, so that total costs were reduced by 28% [56].

Grinding Tool End of Life

Tool life can mean two different things: The life between conditioning operations and the end of life. These must be distinguished. Whereas the tool life between conditioning operations depends on the grinding parameters and quality requirements, the absolute end of tool life has predetermined boundaries, as discussed in the following. The most important causes for the absolute end of grinding tool life are tool wear to the minimum abrasive layer dimensions and tool degradation at the end of shelf life. For example, coated abrasive tools may contain organic material and may degrade with time [91]. Tools with magnesite bonding age faster in humid environments [78]. In contrast, vitrified grinding wheels are not subject to degradation and have an almost infinite shelf life, but these are susceptible to damage during storage which might lead to tool failure during use [91].

Once products reach end of life, they may be placed in a landfill, combusted, recycled, re-engineered, or re-used [92]. The majority of grinding tools will end in landfill or combustion facilities. Conventional grinding wheels can be crushed and backfilled in roadworks. There are also some attempts to regain abrasives from conventional grinding wheels for refractories, but this is a down-cycling of abrasives. Because of high safety and liability requirements for rotating abrasive tools, grinding wheel manufacturers have refrained from using recycled tool raw materials; however, a new manufacturing procedure for vitrified bonded tools from partly recycled tool material may overcome these problems [93]. In this invention, the tools consist of an abrasive layer made from new materials as well as a body material made with recycled materials in the form of particles with a minimum diameter of two times the grit diameter [93].

Superabrasive grinding tools consist of a tool body and an abrasive layer. The grinding wheel bodies are manufactured with high dimensional quality and can easily be re-plated or re-layered if the old abrasive layer can be removed. To strip the abrasive layer often chemical and electrochemical methods are used [94] with a trend towards higher environmentally friendliness of the chemical baths [95]. For example, steel bodies can be re-used multiple times in industrial settings [2], which is favorable to reduce the embodied energy of superabrasive tools [5]. The end of life option to re-layer tool bodies is of economic interest to both the tool maker and user, because the costs for the re-layered tool are considerably lower than for a new tool and the order process is shorter.

Tool disposal has to follow waste regulations and can lead to high disposal costs. Special care has to be taken for tools with hazardous bond ingredients such as metal bonds. Tool manufacturers can offer collecting and recycling of abrasive tools as take-back services. Re-layering of tool bodies for superabrasives reduces not only the costs for the tool body making, but also decreases the material impact. Steel bodies can have a significantly higher amount of embodied energy than the abrasive layer itself as can be seen in the case study in [5]. Recovery of superabrasive grit material from grinding wheels or dressing tools is often economically not feasible, because recovery costs might offset the value of the reclaimed material [96].

Tool wear is waste that should be reduced to enhance material efficiency. In life cycle assessments of the grinding process, the tool debris needs to be added to the consumed filter material, metalworking fluid, produced chips, and scrap parts [8]. However, as tool performance determines product quality and scrap rate, there might be a trade-off between tool wear and scrap parts. Furthermore, trade-offs between grinding process and product performance in its use phase, defined by the surface integrity, are possible [97].

SUMMARY AND OUTLOOK

Grinding wheel wear is a complex phenomenon and visible on both a microscopic level (as sharpness loss) and a macroscopic level (as tool profile loss). Both effects happen simultaneously and are based on several wear mechanisms. These wear mechanisms can be sorted into four main categories: grit surface layer wear, grit splintering, grit-bond-interface wear, and bond wear. Researchers and tool manufacturers need to understand wheel wear better to achieve **predictive models**, following groundwork in [16, 17, 60, 88].

Tool wear occurs in three phases: initial wear, steady-state wear, and wheel collapse. Research in [80] indicates that the **initial wear** depends on dressing forces and structural damage to the abrasive layer from dressing. This needs to be investigated further to reach the predictable steady-state wear earlier and with less wheel material loss in the initial wear phase. Changing the process physics seems to be a promising path as can be seen in research on vibration-assisted grinding, where tool wear was significantly reduced [98].

The grinding ratio or G-ratio is a widely used characteristic for tool life, but might neglect the wear behavior, the total productivity or process stability. Suggestions for defining the G-ratio only in the steady-state of the wheel wear or assessing a new performance factor were given in [46, 84]. **Low cost, real-time and in-process monitoring of tool wear** will help tool users to improve wheel performance. Acoustic emission [99] or spindle power [100] monitoring are promising methods.

The complexity of tool wear and tool use lead to a wide range of economic, environmental, and social sustainability issues (Table 2). The different aspects are sometimes contrary, e.g. economic sustainability for tool manufacturers needs tool wear, but this reduces the environmental sustainability because of more waste. A specific answer is only possible for a specific application and value system. Li et al. have started including grinding tool wear into modeling of process sustainability [101]. More research on **life cycle models** between tool manufacturers, tool users, academia, and regulating organizations is necessary to tackle tool sustainability holistically. For example, tools are commonly disposed without any recycling, but researchers and tool manufacturers could invent better designs for end of life or service options that reduce material and energy use. The above mentioned stakeholders should work on better life cycle models for grinding tools and model visualization, so that consumers become aware how tool wear affects several economic and environmental aspects of their business. **Leveraging effects** can happen, if tool users invest in more expensive tools or tools with higher embodied energy, but reduce the costs or environmental impacts of the grinding process. Examples for initial life cycle models and leveraging case studies can be found in [5, 79, 97, 101].

In summary, future research on grinding tool wear should focus on

- Predictive models,
- Shortening the initial wear phase,
- Low cost, real-time monitoring of wear,
- Life cycle models,
- Leveraging effects.

ACKNOWLEDGMENT

The author thanks Dr. Dieter Busch wholeheartedly for the many discussions on grinding tool manufacturing, wear, and difficulties in analyzing industrial setups. The author is furthermore very grateful to Prof. Fritz Klocke for fueling her interest in grinding tool design and manufacture and discussing these issues. Thank you to Maria Celeste Castillo, Helen Papadopoulos and Kyle Odum, students at UC Davis, for their valuable comments.

FUNDING

This work was sponsored by the Deutsche Forschungsgemeinschaft (DFG) through the project LI1939/3-1.

NOMENCLATURE

G	G-ratio, grinding ratio
V_w	workpiece volume
V_s	worn grinding tool volume
ΔV_w	change in workpiece volume in wear phase II
ΔV_s	change in worn grinding tool volume in wear phase II
L	performance factor
$Q`_w{}^2$	specific material removal rate
C	constant

REFERENCES

[1] Haapala, K. R., Zhao, F., Camelio, J., Sutherland, J. W., Skerlos, S. J., Dornfeld, D. A., Jawahir, I. S., Clarens, A. F., and Rickli, J. L., 2013, "A Review of Engineering Research in Sustainable Manufacturing," Journal of Manufacturing Science and Engineering, 135(4), pp. 041013-041013.

[2] Marinescu, I. D., Hitchiner, M., Uhlmann, E., Rowe, W.B., Inasaki, I., 2007, Handbook of Machining with Grinding Wheels, CRC Press.

[3] Klocke, F., 2009, Manufacturing Processes 2 – Grinding, honing, lapping, Springer.

[4] Oliveira, J. F. G., Silva, E. J., Guo, C., and Hashimoto, F., 2009, "Industrial challenges in grinding," CIRP Annals - Manufacturing Technology, 58(2), pp. 663-680.

[5] Aurich, J. C., Linke, B., Hauschild, M., Carrella, M., and Kirsch, B., 2013, "Sustainability of abrasive processes," CIRP Annals - Manufacturing Technology, 62(2), pp. 653-672.

[6] Linke, B. S., Corman, G. J., Dornfeld, D. A., and Tönissen, S., 2013, "Sustainability indicators for discrete manufacturing processes applied to grinding technology," Journal of Manufacturing Systems, 32(4), pp. 556-563.

[7] Kellens, K., Dewulf, W., Overcash, M., Hauschild, M., and Duflou, J., 2012, "Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)—CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description," Int J Life Cycle Assess, 17(1), pp. 69-78.

[8] Linke, B., 2013, "Sustainability Indicators for Grinding Applied to Dressing Strategies," Journal of Manufacturing Science and Engineering, 135(5), pp. 054502-054502.

[9] Jayal, A. D., Badurdeen, F., Dillon Jr, O. W., and Jawahir, I. S., 2010, "Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels," CIRP Journal of Manufacturing Science and Technology, 2(3), pp. 144-152.

[10] Singh, R. K., Murty, H. R., Gupta, S. K., and Dikshit, A. K., 2012, "An overview of sustainability assessment methodologies," Ecological Indicators, 15(1), pp. 281-299.

[11] Joung, C. B., Carrell, J., Sarkar, P., and Feng, S. C., 2013, "Categorization of indicators for sustainable manufacturing," Ecological Indicators, 24(0), pp. 148-157.

[12] Krajnc, D., and Glavič, P., 2003, "Indicators of sustainable production," Clean Techn Environ Policy, 5(3-4), pp. 279-288.

[13] Zhang, H., and Haapala, K. R., "Integrating sustainable manufacturing assessment into decision making for a production work cell," Journal of Cleaner Production(0).

[14] Malkin, S., 1968, "The attritious and fracture wear of grinding wheels," PhD, MIT, Cambridge, USA.

[15] Saint-Gobain, Proc. Saint-Gobain grinding symposium.

[16] Brinksmeier, E., Aurich, J. C., Govekar, E., Heinzel, C., Hoffmeister, H. W., Klocke, F., Peters, J., Rentsch, R., Stephenson, D. J., Uhlmann, E., Weinert, K., and Wittmann, M., 2006, "Advances in Modeling and Simulation of Grinding Processes," CIRP Annals - Manufacturing Technology, 55(2), pp. 667-696.

[17] Tönshoff, H. K., Peters, J., Inasaki, I., and Paul, T., 1992, "Modelling and Simulation of Grinding Processes," CIRP Annals - Manufacturing Technology, 41(2), pp. 677-688.
[18] Bold, L., 2002, "Galvanische Werkzeuge – Ein Leitfaden," S.-G. Abrasives, ed.
[19] Mihić, S. D., Cioc, S., Marinescu, I. D., and Weismiller, M. C., 2013, "Detailed Study of Fluid Flow and Heat Transfer in the Abrasive Grinding Contact Using Computational Fluid Dynamics Methods," Journal of Manufacturing Science and Engineering, 135(4), pp. 041002-041002.
[20] Yao, P., Gong, Y., Matsuda, T., Zhou, T., Yan, J., and Kuriyagawa, T., 2012, "Investigation of wheel wear mechanisms during grinding optical glasses through statistical analysis of wheel topography," International Journal of Abrasive Technology, 5(1), pp. 33-47.
[21] Bierlich, R., 1976, "Technologische Voraussetzungen zum Aufbau eines Adaptiven Regelungssystems," PhD, RWTH Aachen University.
[22] Jackson, M. J., and Davim, J. P., 2011, Machining with abrasives, Springer.
[23] Klocke, F., Engelhorn, R., Mayer, J., and Weirich, T., 2002, "Micro-Analysis of the Contact Zone of Tribologically Loaded Second-Phase Reinforced Sol-Gel-Abrasives," CIRP Annals - Manufacturing Technology, 51(1), pp. 245-250.
[24] Mayer, J., Engelhorn, R., Bot, R., Weirich, T., Herwartz, C., and Klocke, F., 2006, "Wear characteristics of second-phase-reinforced sol–gel corundum abrasives," Acta Materialia, 54(13), pp. 3605-3615.
[25] Nadolny, K., 2014, "Wear phenomena of grinding wheels with sol–gel alumina abrasive grains and glass–ceramic vitrified bond during internal cylindrical traverse grinding of 100Cr6 steel," Int J Adv Manuf Technol, pp. 1-16.
[26] Paucksch, E., Holsten, S., Linß, M., and Tikal, F., 2008, Zerspantechnik, Prozesse, Werkzeuge, Technologien.
[27] Ludewig, T., 1994, "Auswahlkriterien für SiC- und Korundschleifkorntypen beim Schleifen von Stählen," PhD, RWTH Aachen University.
[28] Hollemann, A. F., and Wiberg, E., 1995, Lehrbuch der Anorganischen Chemie Walter der Gruyter, Berlin.

[29] Komanduri, R., and Shaw, M. C., 1976, "On the diffusion wear of diamond in grinding pure iron," Philosophical Magazine, 34(2), pp. 195-204.
[30] Field, J. E., 1979, The properties of diamond, Academic Press, London.
[31] Müller, N., 2001, "Ermittlung des Einsatzverhaltens von Sol-Gel-Korund-Schleifscheiben," PhD, RWTH Aachen University.
[32] Uhlmann, E. G., and Stark, C., 1997, "Potentiale von Schleifwerkzeugen mit mikrokristalliner Aluminiumoxidkörnung," Jahrbuch "Schleifen, Honen, Läppen und Polieren", pp. 281–309.
[33] Badger, J., "Microfracturing ceramic abrasives in grinding," Proc. 2012 International Manufacturing Science and Engineering Conference MSEC 2012.
[34] Himmel, T., Bettles, C. J., and Swain, M. V., 1990, "Crushing strength of diamond grits," Journal of Hard Materials, 1(2), pp. 103-121.
[35] Benea, I. C., and Griffin, S., 2003, "Mechanical strength and fracture characteristics of micron diamond," Industrial Diamond Review, 3/2003, pp. 53-60.
[36] Brunton, J. H., "Fracture propagation in diamond," Proc. The first international congress on diamonds in industry, pp. 329–341.

[37] Borkowski, J. A., and Szymanski, A. M., 1992, Uses of abrasives and abrasive tools, Ellis Horwood Limited and PWN Polish Scientific Publishers.
[38] Stetiu, G., and Lal, G. K., 1974, "Wear of grinding wheels," Wear, 30(2), pp. 229-236.
[39] Yoshikawa, H., and Sata, T., 1963, "Study of wear of grinding wheels – 1 Bond facture in grinding wheels," Journal of Engineering for Industry, Feb., pp. 39-42.
[40] Lauer-Schmaltz, H., and König, W., 1980, "Phenomenon of Wheel Loading Mechanisms in Grinding," CIRP Annals - Manufacturing Technology, 29(1), pp. 201-206.
[41] Pai, D. M., Ratterman, E., and Shaw, M. C., 1989, "Grinding swarf," Wear, 131(2), pp. 329-339.
[42] Nagaraj, A. P., and Chattopadhyay, A. K., 1989, "On some aspects of wheel loading," Wear, 135(1), pp. 41-52.
[43] Adibi, H., Rezaei, S. M., and Sarhan, A. D., 2013, "Analytical modeling of grinding wheel loading phenomena," Int J Adv Manuf Technol, 68(1-4), pp. 473-485.
[44] Dornfeld, D., and Cai, H. G., 1984, "An investigation of grinding and wheel loading using Acoustic Emission," Trans. of the ASME, 106(Feb.), pp. 28-33.
[45] Adibi, H., Rezaei, S. M., and Sarhan, A. A. D., 2013, "Grinding Wheel Loading Evaluation Using Digital Image Processing," Journal of Manufacturing Science and Engineering, 136(1), pp. 011012-011012.
[46] Malkin, S., Guo, C., 2008, Grinding technology : theory and application of machining with abrasives, Industrial Press.
[47] Buttery, T. C., Statham, A., and Percival, J. B., 1979, "Some effects of dressing on grinding performance," Wear, 55, pp. 195–219.
[48] Badger, J., 2009, "Factors affecting wheel collapse in grinding," CIRP Annals - Manufacturing Technology, 58(1), pp. 307-310.
[49] Malkin, S., and Cook, N. H., 1971, "The wear of grinding wheels, Part 2 – Fracture wear," Trans. of the ASME(Nov.), pp. 1129-1133.
[50] Malkin, S., and Cook, N. H., 1971, "The wear of grinding wheels, Part 1 – Attritious wear," Trans. of the ASME(Nov.), pp. 11209-11128.
[51] Li, H., and Shin, Y. C., 2005, "Wheel Regenerative Chatter of Surface Grinding," Journal of Manufacturing Science and Engineering, 128(2), pp. 393-403.
[52] Dornfeld, D., and Lee, D.-E., 2008, Precision Manufacturing, Springer.
[53] Inasaki, I., 1998, "Challenges to advanced machining technology”."
[54] Bailey, M. W., Juchem, H. O., Cook, M. W., Collins, J. L., Butler-Smith, P., 2002, "The importance of PCD/diamond/CVD diamond and PCBN/CBN tooling in the automotive industry," Industrial Diamond Review, 1/2002, pp. 53-60.
[55] Rowe, W. B., 2009, Principles of modern grinding technology, William Andrew.
[56] Holz, R., and Sauren, J., 1988, Schleifen mit Diamant und CBN, ERNST WINTER & SOHN (GmbH & Co), Hamburg.
[57] Shi, Z., and Malkin, S., 2005, "Wear of Electroplated CBN Grinding Wheels," Journal of Manufacturing Science and Engineering, 128(1), pp. 110-118.
[58] Guo, C., Shi, Z., Attia, H., and McIntosh, D., 2007, "Power and Wheel Wear for Grinding Nickel Alloy with Plated CBN Wheels," CIRP Annals - Manufacturing Technology, 56(1), pp. 343-346.

[59] Miao, Q., Ding, W. F., Xu, J. H., Yang, C. Y., and Fu, Y. C., 2013, "Fractal analysis of wear topography of brazed polycrystalline cBN abrasive grains during grinding nickel super alloy," Int J Adv Manuf Technol, 68(9-12), pp. 2229-2236.
[60] Werner, G., 1973, "Konzept und Technologische Grundlagen zur adaptiven Prozessoptimierung des Aussenrundschleifens," Habilitation, RWTH Aachen University.
[61] Weinert, K., 1976, "Die zeitliche Änderung des Schleifscheibenzustandes beim Außenrund-Einstechschleifen," PhD, TU Braunschweig.
[62] Denkena, B., Turger, A., Behrens, L., and Krawczyk, T., 2012, "Five-Axis-Grinding With Toric Tools: A Status Review," Journal of Manufacturing Science and Engineering, 134(5), pp. 054001-054001.
[63] Kumar, K. V., Cozminca, M., Tanaka, Y., Shaw, M.C., 1980, "A new method of studying the performance of grinding wheels," Trans. of the ASME, 102(Feb.), pp. 80-84.
[64] Karpuschewski, B., 2001, "Sensoren zur Prozessüberwachung beim Spanen," Habilitation, University Delft.
[65] Roth, J. T., Djurdjanovic, D., Yang, X., Mears, L., and Kurfess, T., 2010, "Quality and Inspection of Machining Operations: Tool Condition Monitoring," Journal of Manufacturing Science and Engineering, 132(4), pp. 041015-041015.
[66] Karpuschewski, B., and Inasaki, I., 2006, "Monitoring Systems for Grinding Processes," Condition Monitoring and Control for Intelligent Manufacturing, L. Wang, and R. Gao, eds., Springer London, pp. 83-107.
[67] Tönshoff, H. K., Friemuth, T., and Becker, J. C., 2002, "Process Monitoring in Grinding," CIRP Annals - Manufacturing Technology, 51(2), pp. 551-571.
[68] Denkena, B., Ortmaier, T., Ahrens, M., and Fischer, R., 2014, "Monitoring of grinding wheel defects using recursive estimation," Int J Adv Manuf Technol, 75(5-8), pp. 1005-1015.
[69] Triggs, D., 2012, "White Paper: Grinding: Severe Risks, New Solutions ", Equipois.
[70] Carter, L., Wales, C., Varley, I., and Telfer, M., 2008, "Penetrating facial injury from angle grinder use: management and prevention," Head & Face Medicine, 4(1), p. 1.
[71] "HSMO Department of Trade and Industry. 24th (Final) report of the Home and Leisure Accident Surveillance System. 2000, 2001 and 2002 data. 2003," DTI/Pub 7060/3k/12/03/NP URN 03/32.
[72] de Araujo, J., and de Oliveira, J., 2012, "Evaluation of Two Competing Machining Processes Based on Sustainability Indicators," Leveraging Technology for a Sustainable World, D. A. Dornfeld, and B. S. Linke, eds., Springer Berlin Heidelberg, pp. 317-322.
[73] DIN, 2011, "Sicherheitsanforderungen für Schleifwerkzeuge mit Diamant oder Bornitrid," Beuth Verlag.
[74] Münnich, H., 1956, "Beitrag zur Sicherheit von umlaufenden Schleifkörpern," PhD, University of Hanover.
[75] Behrens, B.-A., and Kammler, M., 2007, "Calculation of the bursting speed of one side recessed grinding wheels," Prod. Eng. Res. Devel., 1(2), pp. 213-218.
[76] Inc., U. A., 2009, "Material Safety Data Sheet Diamond Wheels," IH&SC Inc., Shelton, CT 06484.
[77] Knight, A., 1822, "Observations on the Grinder`s Asthma," U. o. London, ed., Goldsmiths' Library.

[78] Metall-Berufsgenossenschaften, V. d., Metall-Berufsgenossenschaft, M.-u., Berufsgenossenschaft, H.-u. W.-., and Süd, B. M. N., 2010, BG-Information Schleifer BGI 543.
[79] Linke, B. S., 2014, "Sustainability concerns in the life cycle of bonded grinding tools," CIRP Journal of Manufacturing Science and Technology, 7(3), pp. 258-263.
[80] Linke, B., 2007, "Wirkmechanismen beim Abrichten keramisch gebundener Schleifscheiben," PhD, RWTH Aachen University.
[81] Zeppenfeld, C., 2005, "Schnellhubschleifen von γ-Titanaluminiden," PhD, RWTH Aachen University.
[82] Liedtke, S., 1999, "Schleifschlammentölung und Qualitätskontrolle der zurückgewonnenen Kühlschmierstoffe," PhD, University Carolo-Wilhelmina.
[83] Rehbein, W., 2012, "Cobaltaufnahme in nichtwassermischbaren Kühlschmierstoffen," http://www.oelheld.de/fileadmin/content/pages/Innovation/pdf-Wissenschaftliche_Berichte/Cobaltaufnahme.pdf
[84] Helletsberger, H., 2005, Grindology Papers G3 Schleifverhaeltnis/G-Faktor, Grindology College of Tyrolit Schleifmittelwerke Swarovski K.G.
[85] Alden, G. I., 1914, "Operation of Grinding Wheels in Machine Grinding," Trans. of the ASME, pp. 451-460.
[86] Decneut, A., Peters, J., Snoeys, R., 1974, "The significance of chip thickness in grinding," Annals of the CIRP, 23(2).
[87] Pawłowski, W., 2013, "Dynamic Model of Oscillation-Assisted Cylindrical Plunge Grinding With Chatter," Journal of Manufacturing Science and Engineering, 135(5), pp. 051010-051010.
[88] Hwang, T. W., Evans, C.J., Whitenton, E.P., Malkin, S., 2000, "High Speed Grinding of Silicon Nitride With Electroplated Diamond Wheels, Part 1: Wear and Wheel Life," Trans. of the ASME, 122(Feb.), pp. 32-41.
[89] Yu, T. B., Ashraf F. ; Chandra, Abhijit 2014, "Experimental Characterization of Electroplated CBN Grinding Wheel Wear: Topology Evolution and Interfacial Toughness," ASME 2014 International Manufacturing Science and Engineering Conference ASME, Detroit, Michigan, USA.
[90] Giridharan, T., Dix, R.C., Nair, S., 1986, "Wheel-wear compensation for numerical form grinding," Trans. of the ASME, 108(Feb.), pp. 16-21.
[91] Association, U. A. M., 2012, "Introduction to Abrasives, Abrasives Information," http://www.uama.org/
[92] Ashby, M. F., 2009, Materials and the Environment: Eco-informed material choice, Butterworth-Heinemann.
[93] Behrens, B.-A., Kammler, M., Lange, F., 2011, "Schleifkörper mit Zusatzpartikeln aus recycelten Schleifkörpern und Verfahren zur Herstellung hiervon," U. Hanover, ed.
[94] Buljan, S.-T., Eagar, W.T., Miller, J.B., Shiue, R.-K., 1999, "Removable bond for abrasive tool," N. Company, ed.
[95] Gebhardt, H., and Macht, W., 1999, "Innovatives Nickel-Ablöseverfahren für Diamantwerkzeuge," Industrie Diamanten Rundschau, 33(1), p. 78.
[96] Abrasives, S.-G., 2011, "Recycle used diamond dressing rolls," S.-G. Abrasives, ed.
[97] Helu, M., Vijayaraghavan, A., and Dornfeld, D., 2011, "Evaluating the relationship between use phase environmental impacts and manufacturing process precision," CIRP Annals - Manufacturing Technology, 60(1), pp. 49-52.

[98] Li, K.-M., Hu, Y.-M., Yang, Z.-Y., and Chen, M.-Y., 2012, "Experimental Study on Vibration-Assisted Grinding," Journal of Manufacturing Science and Engineering, 134(4), pp. 041009-041009.
[99] Yang, Z., and Yu, Z., 2012, "Grinding wheel wear monitoring based on wavelet analysis and support vector machine," Int J Adv Manuf Technol, 62(1-4), pp. 107-121.
[100] Arriandiaga, A., Portillo, E., Sánchez, J., Cabanes, I., and Pombo, I., 2014, "Virtual Sensors for On-line Wheel Wear and Part Roughness Measurement in the Grinding Process," Sensors, 14(5), pp. 8756-8778.
[101] Li, W., Winter, M., Kara, S., and Herrmann, C., 2012, "Eco-efficiency of manufacturing processes: A grinding case," CIRP Annals - Manufacturing Technology, 61(1), pp. 59-62.
[102] Peklenik, J., 1958, "Untersuchungen über das Verschleißkriterium beim Schleifen," Industrie-Anzeiger Essen, 27(April), pp. 397-402.
[103] Backer, W. R., and Krabacher, E. J., 1956, "New techniques in metal-cutting research," Trans. of the ASME, 78(Oct.), pp. 1497–1505.
[104] König, W., and Messer, J., 1981, "Influence of the Composition and Structure of Steels on Grinding Process," CIRP Annals - Manufacturing Technology, 30(2), pp. 547-552.

Figure Captions List

Fig. 1	Tool wear mechanisms after [21, 102]
Fig. 2	Typical wear behavior with three phases: initial wear (I), steady state wear (II), wheel collapse (III), after [46, 103]
Fig. 3	Wheels with similar G-ratio but different end of life
Fig. 4	Wheel A and B with similar G-ratio at similar workpiece volumes, but different wear profiles and wear stages

Table Caption List

Table 1	Taxonomy and types of wear mechanisms in the literature
Table 2	Sustainability concerns connected with tool wear

Fig. 1

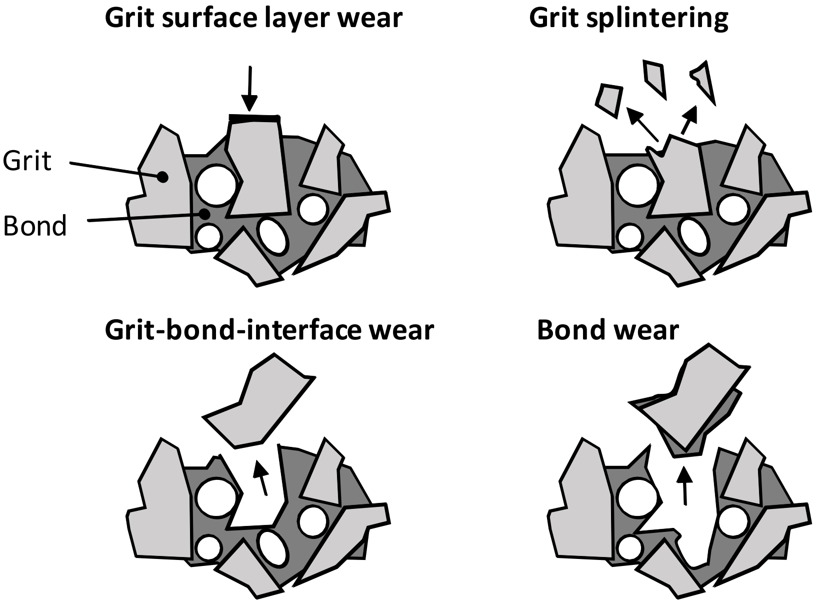
Grit surface layer wear
Grit splintering
Grit
Bond
Grit-bond-interface wear
Bond wear

Fig. 2

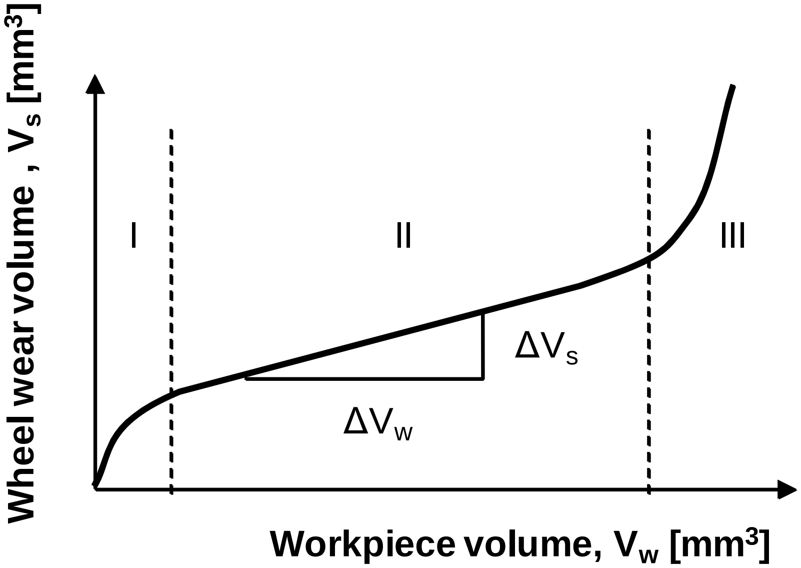
Wheel wear volume , V_s [mm³]
I
II
III
ΔV_s
ΔV_w
Workpiece volume, V_w [mm³]

Fig. 3

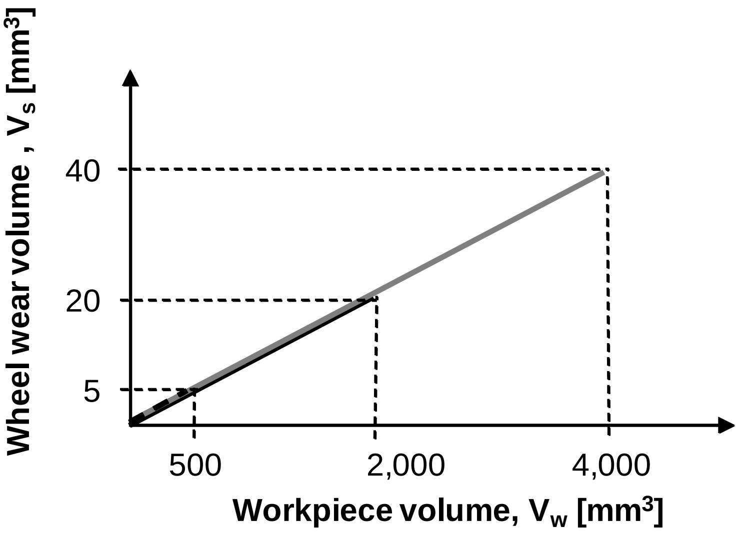
Wheel wear volume , V_s [mm^3]
40
20
5
500
2,000
4,000
Workpiece volume, V_w [mm^3]

Fig. 4

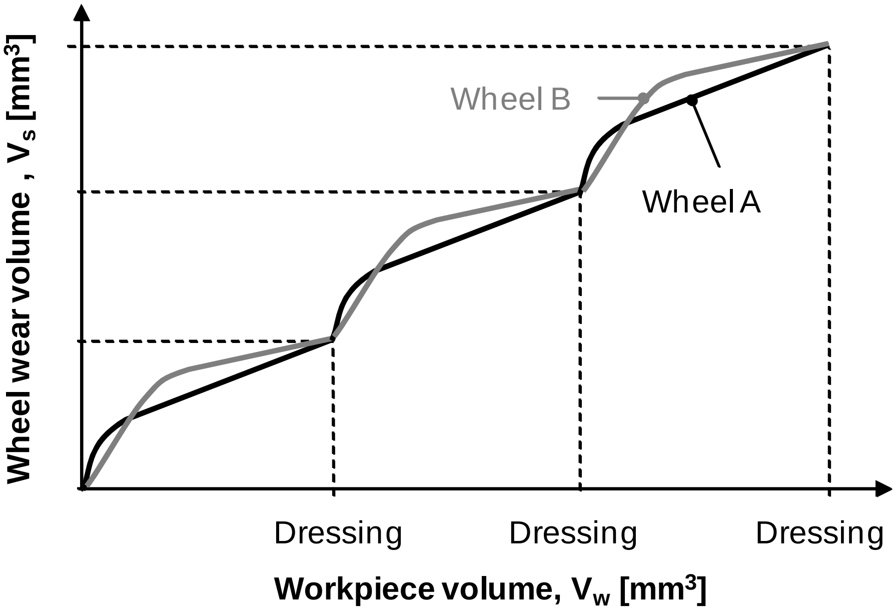
Wheel B
Wheel A
Wheel wear volume , V_s [mm³]
Dressing
Dressing
Dressing
Workpiece volume, V_w [mm³]

Table 1

	Grit surface layer wear	**Grit splintering**	**Grit-bond-interface wear**	**Bond wear**
Klocke, 2009 [3]	Compressive softening, chemical wear, abrasion	Micro-breakage, grit breakage		Bonding breakage, chemical and thermal wear of bonding
Koenig, 1981 [104]	Abrasion, micro-cracks, corrosion, diffusion	Micro-fracture, grain fracture		Bond fracture, chemical bond wear
Malkin 1968, 2008 [14, 46]	Attritious wear	Grain fracture		Bond fracture
Jackson, 2011 [22]	Abrasive wear (surface flats)	Fracture of abrasive grains	Fracture at interface grit/bond	Fracture of bond bridges
Borkowski, 1992 [37]	Attrition, surface microchipping	Grain chipping and cracking	Grit pull-out	Bonding bridge failure
Rowe 2009 [55]	Rubbing	Grain micro- and macro fracture	Grain pull-out	Bond fracture
Peklenik 1958 [102]	Compressive softening	Splintering of crystal clusters, partial grit break-out	Total grit break-out	

Table 2

Economic sustainability	**Environmental sustainability**	**Social sustainability**

• Tool costs per part
• Storage costs
• Tool investment
• Tool conditioning costs
• Process stability
• Savings from tool body re-use
	• Tool disposal:
	  • Waste regulations
	  • Take-back service
	• Embodied energy
	• Emissions from tool use
		• Worker safety and health
		  • Tool breakage
		  • Emitted particles
		• Hazards while using manual tools