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Sustainability concerns in the life cycle of bonded grinding tools

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Title: Sustainability Concerns in the Life Cycle of Bonded Grinding Tools

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Abstract

Manufacturing technologies need to become more sustainable, as do the tools used. Grinding is one of the most important finishing processes and grinding tools are complex products with a large variety of grit types, bond materials, and manufacturing routes. This study discusses the tool life stages from raw material production and tool manufacturing to tool use and end of life. The most important economic, environmental and social concerns are pointed out. This study highlights where more research and transparency in the supply chain is needed to achieve more sustainable grinding tools.

Highlights:

- Sustainability in grinding technology needs to include comprehensive studies on the life cycle of grinding tools.
- This paper addresses the most important economic, environmental and social issues throughout all life stages of a grinding tool and therefore sets the stage for future quantitative evaluations.
- This study highlights where more research and transparency in the supply chain is needed to achieve more sustainable grinding tools.

Keywords: Grinding, grinding wheel, grinding tool, sustainable development, sustainability, life cycle

1. Introduction

Manufacturing has to shift from non-sustainable mass production to a more sustainable, environmentally conscious one [1]. In this trend, the sustainability of abrasive processes sees considerable research efforts [2, 3]. Abrasive finishing operations such as grinding are often decisive for the functional performance of the product [3] and grinding tools are critical for the process performance. The 2013 CIRP keynote paper on "Sustainability of Abrasive Processes" revealed that only little information is available on the sustainability of grinding tools [3], so this study continues there and gives the first comprehensive study on tool life. 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" [4]. This statement is still true today and tool choice and design often rely on empirical knowledge.

This paper illuminates the three dimensions of economic, environmental and social sustainability for the life stages of grinding tools. Figure 1 shows the main operations involved in the life stages of a grinding wheel and in which section they are addressed in this paper. First, grit material production is discussed, followed by tool manufacturing strategies, which depend on the bond type. Then sustainability issues in tool use and end of life are addressed. It is emphasized throughout this study how different wheel types have different hot spots for improvement. The main findings are finally summarized and ideas are given on greener supply chains and life cycle concepts.

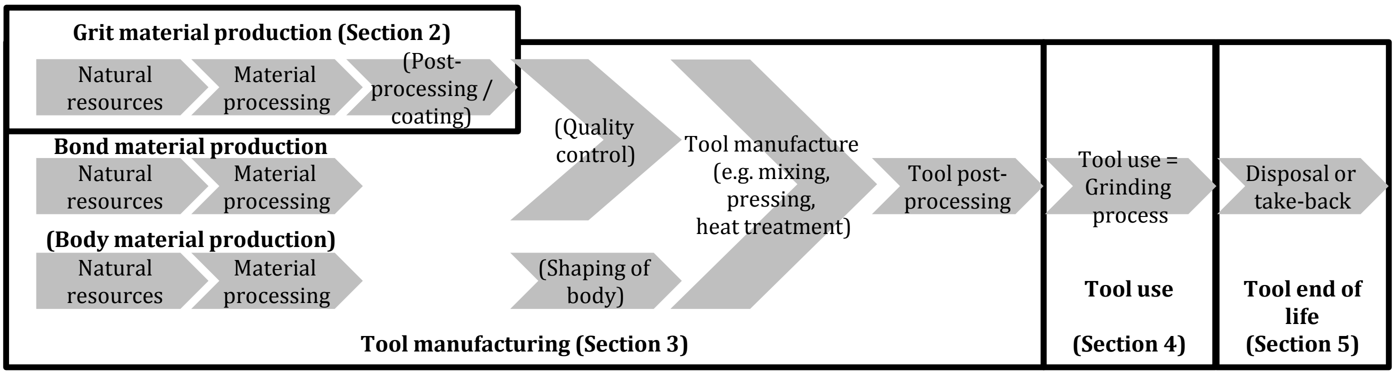

Figure 1 Grinding tool life cycle

2. Grit material production

In general, grit type and properties are chosen with regard to the machined material and desired workpiece quality. Abrasive grits for grinding tools can be subdivided into so called *conventional abrasives* (alumina (Al_2O_3) and silicon carbide (SiC)) and *superabrasives* (cubic boron nitride (CBN) and diamond). Superabrasives stand out by their higher hardness and wear resistance.

Though there are still some abrasive applications with natural materials, most grits for grinding tools are made of artificial materials [5]. The conventional grits are produced in large batch sizes. Fused or molten alumina is manufactured by electro-fusing bauxite, i.e. heating material through an electric arc, invented by Jacobs in 1897 [6]. The processing times depend on the applied method and furnace size and take several hours followed by days of cooling time [5]. The different types of fused alumina are produced by additional ingredients or changes in the fusion procedure. The worldwide production capacity of fused corundum grits totaled 1.19 Mt in 2011 [7]. Sintered alumina is sintered from unfused or fused alumina or from sol-gel alumina, which is produced by the chemical sol-gel procedure [5, 8].

Abrasive silicon carbide is molten from quartz sand in resistance furnaces by the Acheson process invented in 1891, with a worldwide production capacity of about 1 Mt in 2011 [7, 9]. In addition to the quartz sand, coke or coal, sawdust, and salt are placed around a conductive core [5]. Again heating and cooling takes place during several days. Conventional grits are often post-processed through crushing, heat treatment, chemical processes, and/or sieving [10].

Superabrasives are commonly produced by high-pressure high-temperature (HPHT) processes, although natural diamonds are still important for dressing tools. Since 1953, diamond has been synthesized from graphite with the help of metallic catalysts at pressures of 5 - 8 GPa and temperatures of around 1200 - 1800 °C [11, 12]. The worldwide production of synthetic diamond totaled 876 t in 2011 (excluding Germany and South Korea), but this number includes also diamond for wear-resistant coatings, electronic applications, and more [13]. Cubic boron nitride is synthesized since 1957 from boron and nitrogen with the help of catalysts such as elemental metal or metal nitrides [14]. The pressures lie between 4 - 6 GPa at temperatures between 1400 - 1700 °C [14, 15]. In 2008, around 25.1 t of CBN was produced worldwide (data error tolerance of 15 %) [16]. Diamond and CBN are synthesized in timescales shorter than an hour.

Grits are post-processed and sometimes coated with non-metallic coatings (e.g. SiH_4 on conventional grits) or metallic coatings (e.g. Ni on diamonds) for enhanced grit retention in the tool bond, grit protection, or heat transfer [8, 17]. The metallic coatings are applied through physical or chemical vapor deposition, as well as chemical or electrochemical processes [18]. The distribution of grit properties in a batch has direct impact on tool manufacturing and tool performance, but information on economic or environmental performance for sorting and analysis methods is not available.

Economic concerns: Location, low energy, and raw material costs are important factors for the competitiveness of grit producers [8]. Today, China is the leading producer of fused alumina, silicon carbide, and synthetic diamond [7, 19]. The grit price affects the later tool price strongly, in particular for superabrasives, so a low grit price is a competitive advantage for grit producers and tool manufacturers. Nonetheless, grit availability and quality have to be considered and grit wear behavior impacts the tool use stage.

Environmental concerns: The ecological hazard of abrasive grits themselves is minor with low potential for bioaccumulation for SiC and some alumina types [20]. More hazards arise from the mining of the raw materials and the grit production, such as emissions of particulate matter (PM) and carbon monoxide (CO) from the furnaces when producing conventional grits [21]. The production of alumina likely emits fluorides, sulfides, and metal constitutes of the raw materials [21]. Sol-gel processing of sol-gel corundum emits NOx [21]. The SiC production generates CO_2 and other gases that can be collected and used for energy production [22]. Solid waste materials such as metallic catalysts and refractories from HPHT synthesis or unreacted mass from producing conventional abrasives remain as well, but can partially be reused [23].

Processing energy is not only a main cost driver, but also a main environmental concern. The embodied energy describes the energy to create a defined volume of material including all processes and inefficiencies. The fusion of brown alumina is estimated with consuming 10.8 - 14.4 MJ/kg [24], while the whole production of Al_2O_3 (99.5 % purity) uses 49.5 - 54.7 MJ/kg [25]. The melting of SiC grit material is estimated to consume 28.8 MJ/kg [24], while the entire SiC processing is projected to use 70.2 - 77.6 MJ/kg [25]. The differences between the values come from including mining, transportation and other operations.

The large worldwide production numbers multiplied with the estimated embodied energies of the grit materials result in large total energies consumed (Table 1). This makes clear that higher energy efficiencies in grit production yield global benefits. More detailed data on producing abrasive grits and special grit types, e.g. fused, sintered or Sol-Gel alumina, as well as the boundary conditions are needed.

The superabrasives market is highly competitive and energy information is therefore not published. Expert interviews indicate that the synthesis of CBN from hexagonal boron nitride (HBN) consumes presumably much less energy than the initial HBN production, so the energy values for HBN (120 - 133 MJ/kg [25]) can be taken as first estimation for embodied energy of CBN grits.

Table 1 Production and estimated embodied energy of grit materials

	Grit material	Worldwide production /capacity	Estimated embodied energy
Conventional abr.	Al_2O_3	Capacity of 1.19 Mt of fused corundum grits in 2011 [7]	Production of Al_2O_3 (99.5 % purity): 49.5 - 54.7 MJ/kg [25]
	SiC	Capacity of 1 Mt in 2011 [7]	Production of SiC: 70.2 - 77.6 MJ/kg [25]
Superabrasives	CBN	Production of 25.1 t in 2008 (data error tolerance of 15 %) [16]	Production of HBN: 120 - 133 MJ/kg [25]
	Diamond	876 t in 2011 (inc. other applications)	Not available

Social concerns: Mining for raw materials is known for having many physical, chemical, biological, ergonomic and psychosocial occupational health hazards [26]. The emissions and particulate matter discussed above can be harmful to workers and the local community and produce lung diseases. The grits themselves can cause respiratory tract irritation, coughing, and shortness of breath; the human skin and eyes can be harmed by mechanical, abrasive action of grits [20].

3. Tool manufacturing

Grinding wheels with conventional grits are commonly monolithic tools composed of grits, bonding, and pores; grinding wheels with superabrasives consist of a thin abrasive layer on a wheel body because they are more expensive and wear-resistant. Common body materials are aluminum, steel, bronze, synthetic resin with metallic or non-metallic fillers, fiber-reinforced synthetic resin, or ceramics [5]. The main bonding systems for grinding tools are resin, vitrified, and metallic bonds. Resin and vitrified bonds are produced by mixing the bond ingredients with grits and fillers, molding, pressing, and heating. Resin bonds consist of phenolic, polyimide, polyamide, epoxy, or urethane resins [5, 6, 10]. The bond and grit mixture is hot or cold pressed and cured through a heating process of temperatures between 140 - 200 ^{o}C [10].

Cut-off wheels are reinforced with glass fibers, nylon discs, carbon, cotton cloth, linen, wood, silk, materials on aramide basis, or other materials [27, 28]. Vitrified bonds consist of silicates, kaolin, field spar, quartz, and frits, i.e. pre-molten bonding components, which are sintered at temperatures over 800 ^{o}C [8]. Metal bonded tools are either multi-layered (produced by sintering or infiltration) or single-layered (produced by electroplating or brazing) [6]. Metallic multi-layered bonding systems consist of copper, tin, cobalt alloys, tungsten carbides or alloys from the iron-copper-tin-system [5, 29]. Metallic single-layered bonds are mainly made from electroplated nickel or soldered alloys with titanium, nickel or others [6].

Economic concerns: The large product variety of grinding tools which can be offered as stock or customized products creates both challenges and opportunities for the manufacturers to be economically sustainable [30]. Customers might not be able to define the best product or they are not well informed about trade-offs between product cost and its features; the manufacturer needs to manage product variants, manufacturing equipment, lead times, and inventory [30].

The heat treatment processes are major cost factors within the tool manufacturing costs. For example, conventional resin bonds need to be cured at maximum temperatures of 190 ^{o}C for about 24 h, whereas vitrified bonds are sintered at temperatures up to 1,250 ^{o}C for up to 100 h [31]. The furnace size and type decide on production cycles and productivity. Stationary furnaces allow more flexible production planning but are not as cost-effective for mass production as the continuous tunnel furnaces. The furnaces are heated by electricity, gas, or oil [5]. The wheel body also adds to the price. For example, metal bodies are machined to high tolerances, which is a considerable portion of the tool manufacturing costs [32].

Environmental concerns: Bond ingredients might be hazardous or health endangering. Vitrified bonds can contain Li_2O, which might cause severe skin burns and eye damage [33], CaO, which causes skin irritation and serious eye damage, may cause respiratory irritation and is toxic to fish [34], or B_2O_3, which may damage fertility or the unborn child and is toxic to fish [35]. Metallic bonds contain heavy metals, such as Co or Ni which are classified as possibly carcinogenic to humans by the International Agency for Research on Cancer (IARC) [36].

Pre-processing steps such as frit manufacturing add to the embodied energy. The heat treatment processes for resin and vitrified bonds emit volatile organic compounds (VOC) and combustion products depending on the furnace energy source [21]. During the manufacturing of resin bonded tools, emissions form from formaldehyde and phenol [27]. Naphthalene is used as pore builder in vitrified bonded wheels and hazardous to workers and the environment. Researchers try to substitute naphthalene with renewable material, but the resulting wheel properties need to be consistent [37]. The electrolytic baths for producing single-layer metal bonded tools need to be maintained carefully to keep workers and local communities safe. In general, substituting risky ingredients might reduce the initial residuals intensity and hazards, but indirectly this might lead to higher tool manufacturing costs and new production strategies.

First estimates of the embodied energy of vitrified bonded grinding tools are given in [3] with both calculated and measured data approaches. The estimated embodied energy of 454 MJ of the vitrified alumina wheel (400 x 200 x 20 mm^3 (outer diameter x inner diameter x width) consists to 49 % of the grit material energy and 42 % of the sintering energy (Table 2). The embodied energy of 1257 MJ of the CBN wheel (same dimensions with a 5 mm abrasive layer on a low-carbon steel body) consists to 72 % of the embodied energy of the tool body, followed by body machining energy (16 %) and sintering energy (9 %)(Table 2) [3]. Re-using the body reduces the embodied energy of the superabrasive tool significantly.

Table 2 Embodied tool energy per workpiece volume

	Alumina wheel		CBN wheel	
Estimated embodied energy in grit material [3]	223		26	
Estimated embodied energy in bond material [3]	42		6	
Estimated sintering energy [3]	189		115	
Estimated embodied energy in body material [3]			910	
Estimated machining energy for body [3]			200	
Estimated embodied energy per wheel [MJ] [3]	454		1,257	
Max. useful volume [cm^3]	(used from 400 to 250 mm) 1,531		(used from 400 to 392 mm) 99.5	
G-ratio for steel grinding from [8, 45]	10	50	1,000	10,000
Embodied energy per workpiece volume for max. useful volume in [J/mm^3]	**29.6**	**5.9**	**12.6**	**1.2**
Embodied energy per workpiece volume in [J/mm^3] when tool body is reused five times			**3.7**	**0.4**

Social concerns: Besides worker health and safety, tool manufacturers have to embrace their wider social responsibility. Legislative regulations enforce disclosure and reduction of chemicals [1]. Supply chain management is very important for tool producers, since they might be held responsible for issues arising with upstream suppliers [38, 39]. Tool producers also need to be in a good service-relationship with the tool user. A transparent, green and socially friendly supply chain is beneficial to all stakeholders in the life cycle of grinding tools.

4. Tool use

Grinding tools are used in automated or manual settings. A life cycle inventory of the grinding process includes non-product material (metalworking fluid, tooling), incoming and machined part, energy, social aspects, grinding machine tool, and waste (solid and liquid waste, process heat and gaseous emissions) [3]. Tool specification, wear and conditioning define product quality, grinding forces and energy, and productivity, but a generic process model is still not available and existing models rely on empirical values [5, 6, 23, 40].

Economic concerns: The grinding costs per part enclose time-dependent costs (labor, machine) and time-independent costs (nonconformity, tooling, etc.). Increasing the material removal rate reduces processing time and time-dependent costs, but likely increases tool wear, scrap rate, and other load-dependent costs [32, 41]. It is therefore not easy to find an optimum process setup. For example, a superabrasive tool costs more than a conventional one, but the time-dependent costs are likely much smaller per part. This is due to fewer tool changes and dressing instances, longer cycle times, and higher process stability [42].

Environmental concerns: A study done at MIT in 2005 estimated that grinding consumes about 63 x 10^{15} J per year in the US alone [43]. Researchers measured specific energies for grinding including machine energy between 200 - 2000 J/mm^3 for grinding of steel with vitrified bonded alumina and CBN wheels at specific material removal rates from 19.2 - 0.12 mm^3/mms [2, 3, 44]. If G-ratios, i.e. ratio of machined part volume per consumed wheel volume, of 10 - 50 are assumed for steel grinding [8, 45] with the alumina wheel in the case study above (minimum outer diameter of 250 mm), the embodied energy from the grinding wheel per workpiece volume results in 29.6 - 5.9 J/mm^3 (Table 2). For the CBN wheel it is assumed that it will be used to an outer diameter of 392 mm and has a G-ratio of 1,000 - 10,000 [8, 45]. The embodied energy results in 12.6 - 1.2 J/mm^3 (Table 2). If the tool body is reused five times, the embodied energy for the CBN wheel decreases to just 0.4 - 3.7 J/mm^3.

In this case study, the embodied energies of the grinding tools are relatively small compared to the stated specific grinding energies. However, wheel wear and specific grinding energy have commonly opposing trends, so that they are hardly minimal at the same time. Additional aspects like dressability, flexibility, and achieved surface integrity and roughness have to be considered, which further complicates life cycle studies of grinding tools. An even broader scope can take the part life and performance into account, so that a leveraging effect between manufacturing and use phase can happen [3, 46]. New grinding process models for sustainability are needed [2, 47].

Social concerns: Workers need to be safe and healthy. Above a circumferential speed of 20 m/s, bursting grinding tools are potentially harmful to machinist and machine tool and appropriate machine encapsulation is necessary [6, 41]. Accidents with manual tools account for 2/3 of accidents with grinding equipment [48] and vibrations can cause permanent health effects. Emissions of particles and dust from the grinding process should be reduced. For example, glass fiber particles from cut-off wheels are carcinogenic, which is overcome by using natural fiber cloth as reinforcement which is under research [49]. Grinding operators might have a higher injury rate, but also require more training and higher salaries than lathe operators [50].

5. Tool end of life

The most important causes for end of grinding tool life are tool wear to the minimum abrasive layer dimensions or tool degradation at the end of shelf life. Today, abrasive tools are often disposed via household waste or special waste, which leads to waste combustion or landfill. Re-use of the abrasive layer is difficult, because inhomogeneous density and particle sizes decrease tool toughness and increase the danger of cracks and tool breakage in vitrified bonded tools [51]. The re-use of abrasive grits is not common. McClarence estimated in 2010 that only between 8 - 10 % of new diamond is reclaimed [52]. Conventional grinding wheels can be crushed and backfilled in roadworks. Worn superabrasive wheels can be returned to the manufacturer. For example, the steel bodies of electroplated grinding wheels are separated from the abrasive layer and can be re-plated up to six times [6].

Economic concerns: Disposal costs might be considerably high for the tool user and depend on tool bond and use conditions, in particular the metalworking fluid used and material machined. For example, metal bonds for diamond wheels are often considered hazardous waste [52].

Re-layering of the tool body brings economic benefits to both the user and tool manufacturer. Recovery costs for super-abrasives often offset the value of the reclaimed material [53].

Environmental and social concerns: Landfill is a global concern. The intrinsic energy of materials can be turned into heat through combustion. However, this option is only feasible for resin bonded tools. Epoxies give 30 - 31.5 MJ/kg combustion heat, phenolics around 31.5 - 33.1 MJ/kg [25]. In all cases, tool manufacturers have to obey the regional waste regulations if they take back used tools.

6. Conclusion and outlook

This study covers the life cycle of grinding tools comprehensively and enables an informed LCA or sustainability analysis of specific tool types. The main stakeholders in the life of grinding tools are grit, bond and other material suppliers, tool manufacturers, tool users and society in general (Figure 2 top). All life stages are dominated by several economic, environmental and social concerns (Figure 2 bottom). Sustainability in the tool end of life is not well realized yet. Only few social concerns, in particular safety and health, are addressed today.

The grinding tool market is highly competitive and data not very transparent. On the one hand, generic models are missing because grinding tools are often highly specialized. On the other hand, commercial tools to model manufacturing systems do not include environmental aspects sufficiently [54]. Energy and material costs are often substantial parts of the price and are therefore confidential. Higher data transparency and an environmentally and socially friendly supply chain, however, would give a competitive edge to tool supplier and user and create win-win-relationships [55]. Research alliances with universities and research institutions can boost research efforts on greener tooling options. Examples are tools with less hazardous ingredients or less processing energy needed. In addition, new tools should embrace design features for end of life.

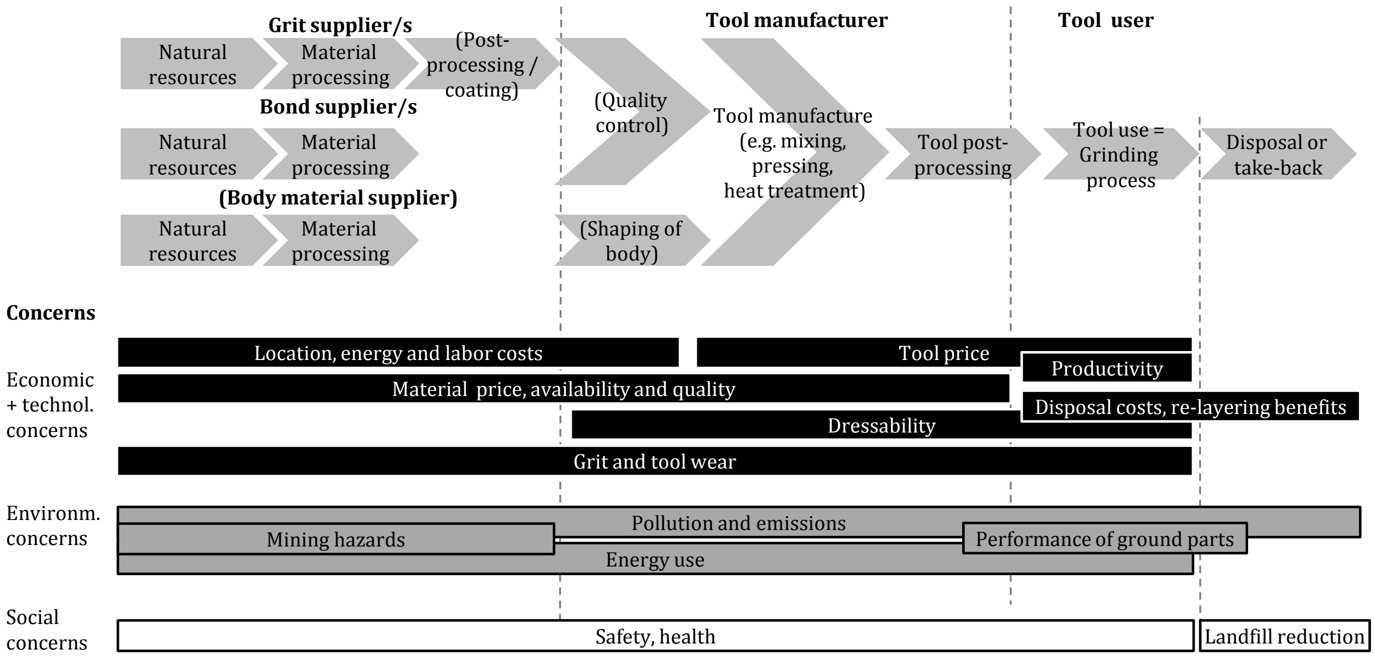

Figure 2 Stakeholders and sustainability concerns in the life of grinding tools

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References

[1] Umeda, Y., Takata, S., Kimura, F., Tomiyama, T., Sutherland, J., Kara, S., Herrmann, C., Duflou, J., 2012, Toward integrated product and process life cycle planning -An environmental perspective, Annals of the CIRP, 61/2:681-702.

[2] Li, W., Winter, M., Kara, S., Herrmann, C., 2012, Eco-efficiency of manufacturing processes: A grinding case, Annals of the CIRP, 61/1:59-62.

[3] Aurich, J., Linke, B. , Hauschild, M. , Carella, M., Kirsch, B., 2013, Sustainability of abrasive processes, Annals of the CIRP, 62/2:653-672.

[4] Malkin, S., 1968, The attritious and fracture wear of grinding wheels, PhD thesis at MIT, Boston.

[5] Klocke, F., 2009, Manufacturing Processes 2 - Grinding, honing, lapping, A. Kuchle (transl.), Springer.

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

[7] USGS, Olson, D., 2012, Minerals information: Abrasives (manufactured), Available from: http://minerals.usgs.gov/minerals/pubs/commodity/ abrasives/mcs-2012-abras.pdf [last access Dec 31, 2013].

[8] Jackson, M., Davim, J., 2011, Machining with abrasives, Springer.

[9] Moser, M., 1980, Microstructures of ceramics, Structure and properties of grinding tools, Akadémiai Kiadó, Budapest.

[10] Menard, J.-C., Thibault, N. , 2000, Abrasives, in: Ullmann's Encyclopedia of Industrial Chemistry.

[11] Wedlake, R. J., 1977, Diamond Synthesis, Industrial Diamond Review, June 1977: 196.

[12] Yin, L., Zou, Z., Li, M., Liu, Y., Cui, J., Hao, Z., 2000, Characteristics of some inclusions contained in synthetic diamond single crystals, Materials Science and Engineering, 293/1 - 2:107-111.

[13] USGS, Olson, D., 2012, 2010 Minerals Yearbook Diamond, Industrial [Advance Release], Available from: http://minerals.usgs.gov/minerals/pubs/commodity /diamond/myb1-2010-diamo.pdf [last access Dec 31, 2013].

[14] Wentorf, R., 1961, Sythesis of the cubic form of boron nitride, Journal of Chemical Physics, 34/3:809 ff

[15] Greim, J., Schwetz, K., 2006, Boron carbide, boron nitride, and metal boride, in: Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH.

[16] McClarence, E., 2010, Report - Trends for cubic boron nitride, The Abrasives Hub, 2010-09-01.

[17] Dyer, H., 1979, Ultra-hard abrasives in resin bond application, IDR Jan. 1979: 15-20.

[18] Kompella, S., Turner, D., Proske, K., 2005, Coatings for superabrasive crystals, Proc. of the Diamond At Work Conference, Oct 20- 21, 2005, Barcelona.

[19] Li, Z., Zhao, B., Li, L., Wong, J., 2011, China`s Diamond in the World Market, Key Engineering Materials, 487:526-532

[20] Washington Mills, 2012, Washington Mills Recycling Services, Available from: http://www.washingtonmills.com/documents/literature/, [last accessed September 4, 2012].

[21] US EPA, Midwest Research Institute, 1994, Emission Factor Documentation for AP-42, Section 11.31, Abrasives Manufacturing, Final Report, May 18, 1994, Available from: http://www.epa.gov/ttnchie1/ap42/ch11/bgdocs/b11s31.pdf [accessed October 22, 2012]

[22] Liethschmidt, K., Garbes, J., 2008, Silicon Carbide, in: Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH.

[23] Malkin, S., Guo, C., 2008, Grinding technology: theory and application of machining with abrasives, 2. Edition, Industrial Press.

[24] Tyrolit, 2003, Grindology Boxes, Accompanying notes to case “General Basics 1“, 2. Edition, company brochure.

[25] Granta CES Edupack 2010, Version 6.2.0, 2010, Granta Design Limited.

[26] Donoghue, A., 2004, Occupational health hazards in mining: An overview, Occupational Medicine, 54:283-289.

[27] Colleselli, K., Schwieger, K., 1988, 11.2. Schleifscheiben und Schleifkörper, in: Becker/Braun (ed.), Kunststoff-Handbuch 10 - Duroplaste, Hanser Verlag.

[28] Patent US 2010/0190424 A1 (Jul. 29, 2010) Francois, E., Zhang, G., Klett, M., Saint Gobain Abrasives Inc.: Reinforced bonded abrasive tools.

[29] Stockwell, B., 1986, Die Metallurgie der Metallwerkzeuge, Industrie Diamanten Rundschau 1/86:31-35.

[30] ElMaraghy, H., Schuh, G., ElMaraghy, W., Piller, F., Schönsleben, P., Tseng, M., Bernard, A., 2013, Product variety management , Annals of the CIRP, 62/2: 629-652.

[31] Tyrolit, 2003, Wie entsteht ein Tyrolit Schleifwerkzeug, Anhang 1, Anhang 2 (Z1), 2. Edition

[32] Metzger, J., 1986, Superabrasive grinding, Butterworth & Co.

[33] Sigma-Aldrich, Sept. 18, 2012, Material Safety Data Sheet Lithium oxide, Aldrich - 374725, available from: http://www.sigmaaldrich.com.

[34] Sigma-Aldrich, Sept. 19, 2012, Material Safety Data Sheet Calcium oxide, Aldrich - 451711, available from: http://www.sigmaaldrich.com.

[35] Sigma-Aldrich, Feb. 28, 2013, Material Safety Data Sheet Boric anhydride, Aldrich - 11615, available from: http://www.sigmaaldrich.com.

[36] United Abrasives Inc., Nov. 30, 2009, Material Safety Data Sheet Diamond Wheels, Prepared By: IH&SC Inc., Shelton, CT 06484.

[37] Davis, T., DiCorleto, J., Sheldon, D., Vecchiarelli J., Erkey, C., 2004, A route to highly porous grinding wheels by selective extraction of pore inducers with dense carbon dioxide, The Journal of Supercritical Fluids, 30/3: 349-358.
[38] Chen, Y., Simon, R., Reich-Weiser, R., Woo, J., 2013, Green supply chain, in : Dornfeld D. (ed.), Green Manufacturing: Fundamentals and Applications, Springer.
[39] Jayal, A.D., Badurdeen, F., Dillon Jr., O.W., 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):144-152.
[40] Brinksmeier, E. Aurich, J., Govekar, E., Heinzel, C., Hoffmeister, H.-W., Peters, J., Rentsch, R., Stephenson, D., Uhlmann, E., Weinert, K., Wittmann, M., 2006, Advances in Modelling and Simulation of Grinding Processes, Annals of the CIRP, 55/2: 667-696.
[41] Rowe, W., 2009, Principles of modern grinding technology, William Andrew.
[42] King, R., Hahn, R., 1986, Handbook of Modern Grinding Technology, Chapman and Hall.
[43] Baniszewski, B., 2005, An environmental impact analysis of grinding, B.Sc. thesis at the Massachusetts Institute of Technology.
[44] Aurich, J., Carella, M., Steffes, M., 2012, Evaluation of Abrasive Processes and Machines with Respect to Energy Efficiency, Proc. of the 19th CIRP Conf. on Life Cycle Engineering, Berkeley, CA, USA, 2012, May 23-25, p. 329 -333.
[45] Helletsberger, H., 2005, Grindology Papers G3 Schleifverhaeltnis/G-Faktor, Grindology College of Tyrolit Schleifmittelwerke Swarovski K.G.
[46] Helu, M., Vijayaraghavan, A., Dornfeld, D., 2011, Evaluating the relationship between use phase environmental impacts and manufacturing process precision, Annals of the CIRP, 60/1:49-52.
[47] Linke, B., Dornfeld, D., 2012, Application of Axiomatic Design Principles to Identify More Sustainable Strategies for Grinding, Journal of Manufacturing Systems, 31/4: 412-419.
[48] BG Vereinigung der Metall-Berufsgenossenschaften, Herbst, P., 2010, BG-Information Schleifer BGI 543, print 09.2010/3.900.
[49] Eschner, M., Fritzlar, B., Schnabel H.-D., Sedner, A., 2005, Untersuchungen zum Einsatz von Naturfasern in Phenolharzmatrix-Kompositen, Proc. of the 15th Symposium Verbundwerkstoffe und Werkstoffverbunde, Kassel, Germany, Apr. 6-8, 2005, p. 223-228.
[50] Araujo, J.B. de, Oliveira, J.F.G. de, 2012, Evaluation of Two Competing Machining Processes Based on Sustainability Indicators, Proc. of the 19th CIRP Conf. on Life Cycle Engineering, Berkeley, CA, USA, 2012, May 23-25, p. 317-322.
[51] Patent WO2011/092021A1 (Aug. 4, 2011) Behrens, B.-A., Kammler, M., Lange, F., Universitaet Hannover: Schleifkörper mit Zusatzpartikeln aus recycelten Schleifkörpern und Verfahren zur Herstellung hiervon.
[52] McClarence, E.: Diamond recovery -What`s it worth?, Diamond Tooling Journal, 70/626: 32-33.
[53] Saint-Gobain Abrasives: Recycle used diamond dressing rolls, 2011, available from: http://www.nortonindustrial.com/uploadedFiles/SGindnortonabrasives/ Documents/DressingRollRecyclingFlyer-8088.pdf
[54] Thiede, S., Seow, Y., Andersson, J., Johansson, B., 2013, Environmental aspects in manufacturing system modelling and simulation – State of the art and research perspectives, CIRP Journal of Manufacturing Science and Technology 6: 78–87
[55] Winkler, H., 2011, losed-loop production systems - A sustainable supply chain approach, CIRP Journal of Manufacturing Science and Technology 4: 243–246