Chapter 9
Future Prospectives

> *From the time we enter the world with the help of medical instruments, until our final tombstone, polished to a glittering hardness, we live in the shadow of the grinding wheel. Name the product. Somewhere there lurks an abrasive operation; this has been so since the cave man, millions of years ago sharpened his tools and weapons by rubbing them together.*
> [LEWI76, p. 3]

The preceding Chaps. 2–6 mapped out how abrasive tooling systems are designed, composed and manufactured. It then was explained how sustainability can be assessed with existing and new methods in Chap. 7, followed by case studies in Chap. 8. To gain an outlook on abrasive tooling systems, the general market trends for abrasive tools and grit material need to be examined. It will then be shown how recent research and innovations lead to more sustainable tools. Service options for tool manufacturers will be discussed followed by a comprehensive, concluding summary of sustainability of abrasive tooling systems for all main stakeholders.

9.1 Market Trends for Abrasive Tools and Grit Material

The global market for abrasive products is tied to the overall economic activity. The production of abrasives by industrial nations is moving to the developing countries such as China and India [ASAM10, p. 313]. In 2010, China consumed about 20 % of the world's abrasives [MCCL10]. The main markets for abrasives in 2008 were metallic abrasives and fused corundum; the application of superabrasives was almost negligible [MCCL10]. Common types of metallic abrasives are steel shots and grits to be mostly used for blast cleaning. The Taiwanese company FACT predicts a worldwide trend that the consumption and manufacturing of diamond tools will shift massively from Europe and the USA to Asia and China [FACT12].

The Asian market for abrasives will grow with increasing grit quality. Already in 2011, China was the world's leading producer of fused corundum and silicon carbide, challenging the abrasive grit producers in other countries (Figs. 9.1 and 9.2)

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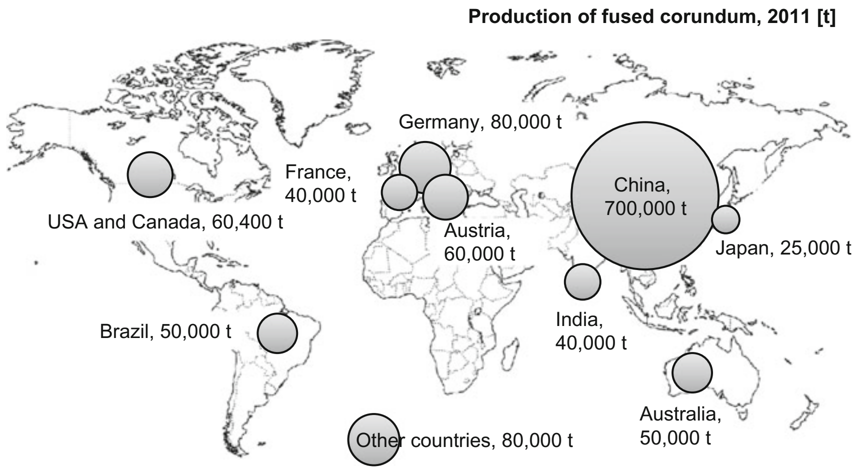

Fig. 9.1 World wide production capacity of fused corundum in 2011, total of 1.19 Mio t [USGS12A]

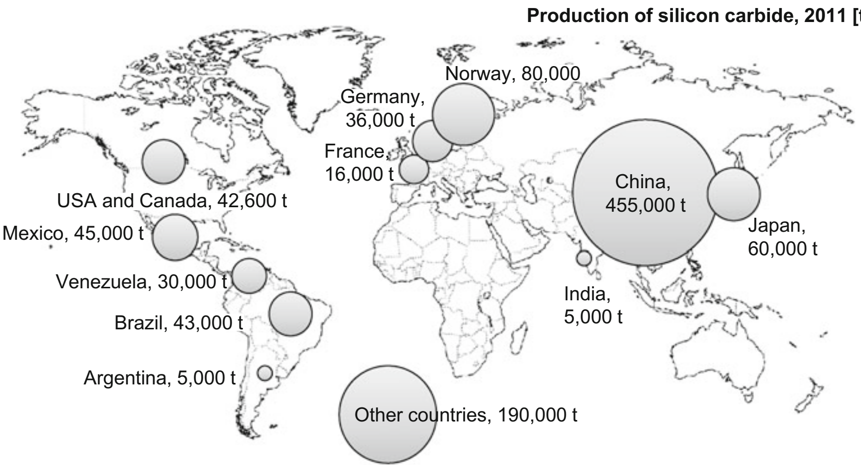

Fig. 9.2 World wide production capacity of silicon carbide in 2011, total of more than 1 Mio t [USGS12a]

[USGS12A]. In addition, China has become the biggest producing country of synthetic diamond (Fig. 9.3) [LIZH11]. One reason is the close or equal quality of Chinese diamonds compared to the Western products; another reason is the low price (Table 9.1) [LIZH11].

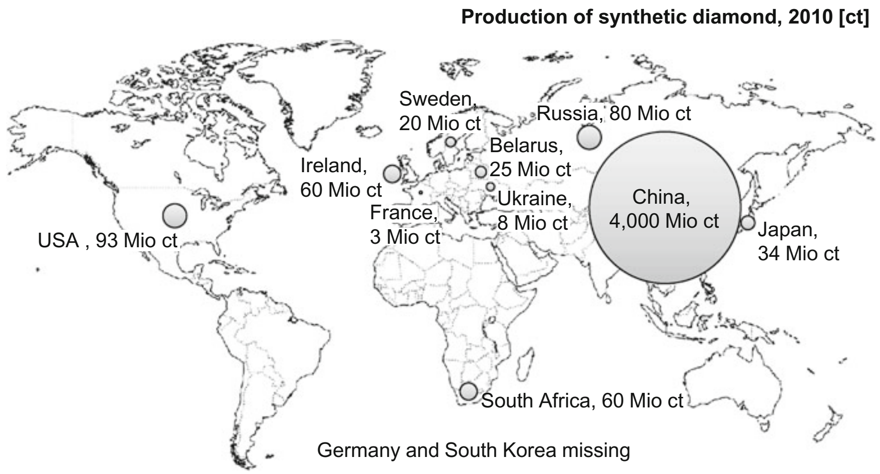

Fig. 9.3 World wide production of industrial diamond in 2010, values of Germany and South Korea are missing, total of 4383 Mio ct = 876 t [USGS12B]

Table 9.1 Approximated costs of abrasive grit material in US$

	Appr. costs per kg in 1976 [LEWI76, p. 36]	Appr. costs per kg in 2007–2012
Corundum	$0.55	$1.3 (high-purity) in 2011 $0.60 (regular) in 2011 [USGS12A]
SiC	$0.77	$0.55 in 2007 to $1.25 in 2011 [USGS12A]
Zirconium corundum	$1.32	$1.00–5.80 in 2012
Diamond	$5512.00	$250.00 in 2011 [LIZH11]
CBN	$5512.00	$450.00 in 2012

The amount of synthetic diamond shown in Fig. 9.3 include more uses than abrasive grits, such as wear-resistant coatings, electronic applications, etc. [USGS12B]. Li et al. [LIZH11] anticipate that producers of superhard materials will rather focus on more technical and knowledge intensive areas such as the production of PCD and PCBN than try to compete with the Chinese diamond grit manufacturers. Not discussed here is the mining and production of natural diamonds. Dressing operations will likely still use natural industrial diamond [USGS12B]. Figure 9.4 shows that the CBN market is still dominated by Europe and North America.

Fig. 9.4 World wide production of CBN in 2008, total of 125.5 Mio ct = 25.1 t, error tolerance for the data is ±15 % [MCCL10c]

9.2 Innovative and More Sustainable Tools

9.2.1 Future Requirements

Common trends in grinding technology are tighter form and size tolerances, smaller surface roughness, engineered surface textures, higher productivity, and smaller process costs [KRAF08]. There is a natural trend towards higher grinding wheel speeds and higher grinding performance [KREB06].

New products and new applications demand for adjusted tools designs. The tool user demands for higher bonding strength of vitrified bonding bridges, as well as harder and more porous vitrified bonds [KRAF08, KREB06]. This can happen through recrystallization or embedding of disperse particles, leading to new production steps for vitrified bonding in the areas of bonding preprocessing or sintering technology [KREB06].

9.2.2 Developments in Tool Design

9.2.2.1 Engineered Tools

The grinding tool can be designed to be similar to a milling tool with defined distances between the grits (Fig. 9.5) [OKAM78]. Grinding wheels with defined grit distribution and defined grit orientation reduce the randomness in grinding [WEBS04]. Hand set superabrasive grits allow for a defined grit pattern on grinding wheels [AURI03]. In the case of grinding belts, oriented grits have been used for decades.

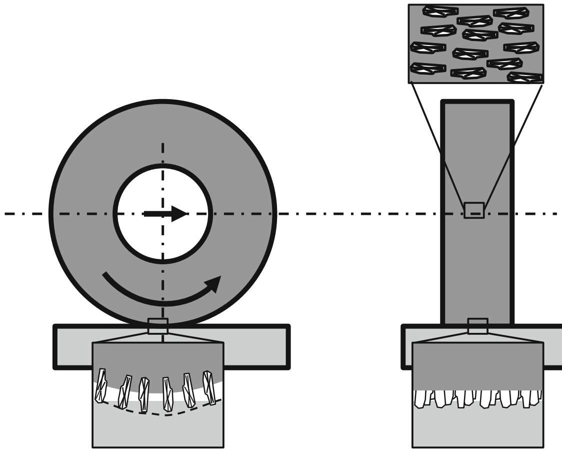

Fig. 9.5 Model of surface generation with an engineered grinding wheel after [BORK92, p. 119]

Burkhard and Rehsteiner [BURK02] developed a brazing technology to produce single-layer tools with arranged grits. Honing tools with a single layer of CBN grits in a defined pattern were applied successfully in single-stroke operations on case-hardened steels, and showed a 10 fold increase in tool life [BURK02].

For glass grinding, Brinksmeier et al. [BRIN12] successfully applied coarse-grained, single-layered, metal-bonded diamond grinding wheels. Both stochastically distributed and placed diamond grits were used. After dressing, the favorable ductile removal mode and optical surface quality were achieved [BRIN12].

The workpiece surface finish is a strong function of the axial offset between adjacent rows of grits in an engineered tool [KOSH03]. Aurich and Kirsch [AURI12] give a recent overview on simulation for engineering tools.

9.2.2.2 Slotted Tools

Slotted tools or so-called segmented tools consist of a discontinuous abrasive layer either with geometrically defined or undefined cavities [KIRC10, p. 9]. Grooves can be perpendicular to the wheel perimeter or inclined.

The so-called T-Tool wheel consists of a metal bonded, segmented superabrasive layer and can significantly reduce forces and temperatures in SiC grinding compared to the process with a non-segmented wheel [TAWA11]. Kirchgatter [KIRC10] examined several different designs for slotted grinding tool in outer diameter grinding applications. He highlighted that improper slot design can lead to dynamical problems in the grinding process, but proved a lower thermal damage of the workpiece. Slotted wheels allow for reduced cooling lubricant flow [UHLM10].

9.2.2.3 Controlled Abrasive Clusters

Yuan et al. [YUAH10] invented an electroplated tool with controlled abrasive clusters (CAC) and used it successfully to grind carbon/epoxy composites with reduced wheel loading. The use of covers during the electroplating process allows the control of shape and pattern of superabrasive grit clusters.

9.2.2.4 Internally Cooled or Lubricated Wheels

The pores of vitrified grinding wheels may be filled with lubricants such as sulfur, wax, or resin after sintering [MARI07, p. 113, KING86, p. 79]. Sulphur is in use as high-temperature extreme pressure lubricant in internal grinding operations in the bearing industry; yet, the use is declining because of environmental considerations [MARI07, p. 113].

Other concepts for internal tool cooling involve coolant supply through the tool body. Aurich et al. [AURI11] present a channel design similar to centrifugal pump impellers in a steel body. Nguyen and Zhang [NGUY08] invented a tool body with a coolant chamber for grinding operations on aerospace alloys.

9.2.2.5 Sensor Integrated Grinding Wheels

Many grinding machinists still rely on their sense of hearing for monitoring, for example, to define the contact position between dressing tool and grinding wheel or find out if the dressing tool is in continuous contact with the grinding wheel. In the case of superabrasives and small depths of dressing cut, it is very hard to hear the contact between dressing and grinding tool, so automatic sensors become necessary [STUC88, p. 107 f.].

Besides acoustic emission, grinding wheel spindle power is the main control parameter in grinding [BRIN07]. The spindle power relates to the tangential grinding forces (Eq. 7.2). Direct force measurement gives higher resolution, but sensors might be hard to apply to the workpiece, e.g. in external grinding. Brinksmeier et al. [BRIN07] successfully integrated force sensors and temperature sensors into a grinding wheel.

Miniaturized sensors can be integrated in grinding tools to form an “intelligent grinding tool”. Superabrasive tools with a reusable body are a special case, and can hold temperature, acoustic emission or force sensors. Challenges lie in the wireless data and energy transfer to the rotating tool [KARP01, p. 190 ff.].

9.2.2.6 New Wheel Bodies

Yan et al. [YAN12] invented a bamboo charcoal composite that has vascular bundles as pores and is coated with abrasive particles in a metal bond layer around the vascular bundles. The advantage is claimed to be an easy fabricating process with low cost and high quality; the abrasive tool can be used for polishing operations [YAN12].

9.2.2.7 Deposition of Diamond Layers

Directly deposited diamond can act as abrasive layer [WEBS04]. Brinksmeier et al. [BRIN12] produced chemical vapor depositioned (CVD) diamond coated wheels. The CVD process achieved equal sized grits with a uniform distribution in a grit size between 0.5 and 30 μm [BRIN12]. Good results with small chip thicknesses were obtained in ultra-precision glass grinding [BRIN12].

Gäbler et al. produced abrasive pencils (burs) with a rough CVD diamond layer [WEBS04, GÄBL03]. They varied substrate diameters down to 60 μm, coating time between 10 and 90 h, and coating temperatures and achieved different crystal sizes.

9.2.2.8 Micro Tools

Aurich et al. [AURI09] produced micro grinding tools with a diameter down to 20 μm for tool grinding. They developed a desktop sized precision machine to electroplate the diamond tool and produce a defined cutting tool.

9.2.2.9 Ice Bonded Tools

Mohan and Ramesh Babu [MOHA11] developed an ice bonded abrasive polishing process for flat surfaces. The process kinematics are close to those of chemical mechanical polishing (CMP). The tool itself consists of a frozen slurry and is cooled by liquid nitrogen. The slurry composition and freezing methods play a significant role on how the abrasives are distributed in the ice matrix [MOHA11].

9.2.2.10 Magnetic Abrasive Particles

Magnetic abrasive finishing was first mentioned by Coats in a patent filed in 1938 [COAT40, SINL10]. It is a finishing method for flat, cylindrical, and ball grinding and especially suited for hard to machine materials [SINL10]. The magnetic abrasive particles can be produced by sintering, adhesive based processes, plasma based process (powder melting or plasma spraying), mixing (loose bonding), or other methods [SINL10]. Sing et al. [SINL10] summarize exisiting production methods.

Magnetorheological abrasive flow finishing is one variant that works with magnetorheological effects exhibited by carbonyl iron particles along with abrasive particles in a non-magnetic base viscoplastic medium [JHA06]. Magneto-abrasive machining is used to prepare defined cutting edges at HSS drills so that the run-in phase of the drill can be avoided and tool life is increased [KARP09].

9.2.2.11 Vortex Machining

Vortex machining is a new abrasive process for nano applications and works with vortices that are caused by an oscillating fiber in colloidal abrasive slurry [HOWA12]. The fiber is close to the workpiece surface (about 20 μm), but does not touch it. The resulting material removal footprints have micrometer sized lateral dimensions and nanometer depths [HOWA12].

9.2.3 Options for Tool Manufacturers

In the long run, the manufacturing paradigm has to shift from non-sustainable mass production, mass consumption, and mass disposal to sustainable environmentally conscious ones [UMED12]. The eco-efficient layout of manufacturing processes and products will be a core competency for engineers in the future.

It is important to integrate all the life cycle phases from the product development phase to the end-of-life phase, including closed-loop supply chain management [UMED12]. A holistic life cycle management aims to minimize costs, optimize revenues and reduce risks and impacts on environment in all product life cycle phases and beyond individual enterprises [HERR10, p. 96]. The tool manufacturer can act as a life cycle partner for the tool user. The manufacturer can support process ramp-up, monitor tool condition and process performance, and support production output [SCHH10].

9.2.3.1 Service Options, End of Life and Incentives

Grinding tool manufacturers could offer a “greener” tool option, which might cost more than the comparatively not so green version, but have a certified smaller impact on environment and society. Green in this context would be a tool with less hazardous ingredients or less sintering energy needed.

Several studies have investigated the environmental behavior of consumers. For example, in hotels, it was found that in-room signs and messages could create awareness and induce environmentally friendly behavior such as reusing towels [BACA13]. Even more, letting the consumers choose to sign a commitment statement or receiving a pin as symbol for environmental commitment increased the positive behavior, here reusing towels [BACA13]. Abrasive tool manufacturers could offer to display the name of companies, which buy the “greener” tools. The tool users could also pride themselves with using greener abrasive tools.

Rickli and Camelio [RICK10] investigated how incentives affect the consumer's decisions on the product's end of life. Buy-back incentives, such as a monetary amount, encourage consumers to voluntarily return a product [RICK10]. This is an easy means to be implemented for abrasive tools and take-back options.

9.2.3.2 Labelling and Customer Information

Labelling is important for the consumer to decide if a product is green. Customers are more likely to buy environmentally friendly products if they know about those attributes in the use phase which are both environmentally friendly and of high quality [ABEL05, p. 173].

Table 9.2 Global model of grinding tool sustainability

<table>
<tr><th></th><th></th><th>Grit manufacturer and other raw materials manufacturers</th><th>Tool manufacturer</th><th>Tool user (Machine tool manufacturer)</th><th>Society and local community</th></tr>
<tr><td rowspan="6">Raw material processing and tool manufacturing</td><td>Techn.</td><td colspan="2">Material availability and quality</td><td>Dressability</td><td></td></tr>
<tr><td rowspan="3">Econ.</td><td>Production location</td><td></td><td></td><td></td></tr>
<tr><td>Energy costs, labor costs</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Material price</td><td>Tool price</td><td></td></tr>
<tr><td>Env.</td><td>Mining hazards (env., soc.)</td><td></td><td></td><td rowspan="2">Mining hazards, emissions (env., soc.)</td></tr>
<tr><td>Soc.</td><td colspan="2">Worker health, protection measures, legislation</td><td></td></tr>
<tr><td rowspan="7">Tool use</td><td rowspan="3">Techn.</td><td>Grit wear</td><td colspan="2">Tool wear</td><td></td></tr>
<tr><td></td><td></td><td>Machine tool, max.cutting speed, dressability</td><td></td></tr>
<tr><td></td><td></td><td></td><td>Product life, product performance</td></tr>
<tr><td rowspan="2">Econ.</td><td></td><td colspan="2">Tool price</td><td></td></tr>
<tr><td></td><td></td><td>Competitiveness</td><td></td></tr>
<tr><td>Env.</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Soc.</td><td></td><td colspan="2">Safety</td><td></td></tr>
<tr><td rowspan="4">Tool end of life</td><td>Techn.</td><td></td><td></td><td>Tool wear, shelf life (techn., econ.)</td><td></td></tr>
<tr><td>Econ.</td><td></td><td colspan="3">Re-layering, recycling, take-back service (techn., env., econ.)</td></tr>
<tr><td>Env.</td><td></td><td></td><td colspan="2">Disposal costs, waste reduction, waste regulations (env., econ.)</td></tr>
<tr><td>Soc.</td><td></td><td></td><td></td><td></td></tr>
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9.3 Conclusion on Abrasive Tool Sustainability

Global trends on raw material pricing and availability drive tool manufacturers and raw material suppliers to strive for new materials and tool designs. Research alliances with universities and research institutions boost these efforts.

Sustainability can be regarded in four dimensions: economics, environment, society, and technology. Different stakeholders are interested in the grinding tool life cycle. Most important stakeholders are the grit manufacturers, other raw material suppliers, tool manufacturers, tool user, society and local communities. Machine tool manufacturers have similar concerns as the tool user. Table 9.2 summarizes the most important aspects for these stakeholders along the four life stages of abrasive tools.

Today, environmental sustainability in tool use or social sustainability in tool end of life are rarely regarded (Table 9.2). Tool manufacturers who incorporate these aspects can therefore gain a competitive edge.

Furthermore, raw material manufacturers are rarely concerned with tool use and tool end of life. The tool manufacturer is also only involved in few tool use and end of life aspects (Table 9.2). A close cooperation between material suppliers, tool manufacturers, tool users and machine tool manufacturers help to enhance overall tool sustainability. In particular, the functionality of the machined part is very important to consider for resource efficiency and offers a new perspective to global sustainability in production engineering.