Chapter 1
Introduction

> *Das 21. Jahrhundert fuehrt die Menschheit an ihre natuerlichen Grenzen. […] Welche Moeglichkeiten haben die Unternehmen des produzierenden Gewerbes, durch effizientere Technologien sowohl Kosten als auch Ressourceneinsatz und Emissionen zu reduzieren? […] An die Stelle von «maximaler Gewinn aus minimalem Kapital» muss «maximaler Gewinn aus minimalen Ressourcen treten».* [FHG08]
> *Translation:* "*The 21th century leads humanity to its natural limits. […] What options do manufacturing companies have to reduce costs, resource use and emissions through more efficient technologies? […] «Maximum profit from minimum capital» needs to be replaced by «maximum profit from minimum resources».*" [FHG08].

Looming shortages of resources and energy induce a growing importance of sustainability in manufacturing. In the long run, the manufacturing paradigm has to shift from non-sustainable mass production to a sustainable environmentally conscious one [UMED12]. Furthermore, producers will have higher responsibility for the product life cycle in the future. Manufacturers may have to manage various legislative restrictions on product ingredients [e.g. the European REACH initiative (Registration, Evaluation, Authorization and restriction of Chemicals]) [UMED12]. In addition, customers increasingly demand greener products, which leads to more competition in the sustainability and manufacturing of the products. The World Commission on Environment and Development, also known as the Brundtland Commission, coined the definition of sustainable development as meeting the needs of the present without compromising the ability of future generations to meet their own needs [UN87].

Abrasive processes, also called machining with geometrically undefined edges, represent a key technology with high performance, process stability, and quality tolerances. Abrasive processes are applied in nearly every production, even if this includes the manufacturing of the mold. Abrasive processes are also core technologies in developing new energy systems as well as in improving efficiency of existing products. Nevertheless, the consideration of sustainability aspects in abrasive machining is just arising, but has a high recognition by the industry [OLIV09].

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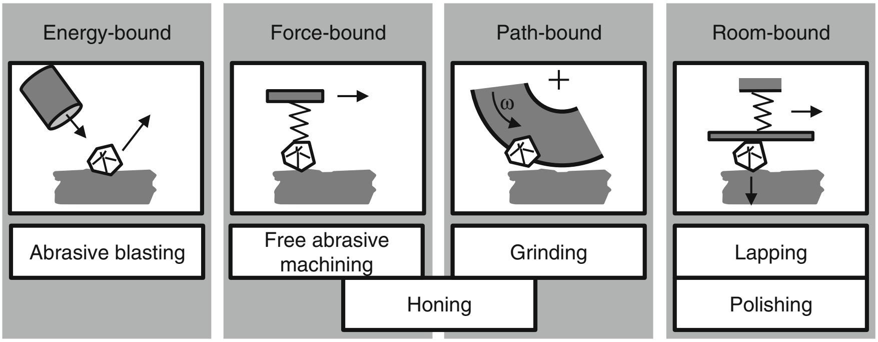

Fig. 1.1 Grit engagement principles after [KLOC09]

Abrasive processes use grits to remove material. The engagement physics of grit and workpiece can be energy-bound, force-bound, path-bound, or room-bound grits (Fig. 1.1). Except for the energy-bound principle, all processes use abrasive tools consisting of abrasive grits in a bonding or a slurry paste. The abrasives should be harder than the workpiece material to form chips. Splintering of dull grits leads to self-sharpening and can be forced by proper abrasive grit design. In the case of path-bound grits, bonding has to hold the grits until they are too blunt, then relieve them and expose new sharp grits. The pores in a bonded or coated tool are important to supply cooling lubricant and remove chips from the contact zone. The abrasive layer might be attached to a body or backing material. All components and their composition affect the sustainability of the abrasive tools and abrasive processes. This work focusses on grinding tools.

The advantages and problems of abrasive tools arise from their often undefined cutting edge shapes, edge orientation, and number. Due to the high number of active cutting edges in the grinding tool, grinding is advantageous as it is not ruined by failure of a single cutting edge, like cutting [WERN73, p. 67]. However, the choice of an appropriate abrasive type is difficult because the interaction between abrasive grit, workpiece material, and the machining result is fairly unknown [LUDE94, p. 1].

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” [MALK68]. This statement is still true today. The design of grinding tools holds the dilemma of providing either a cheap, mass-produced product versus an expensive, customized product. The range of machinable workpiece materials for a certain wheel has to be balanced against the tool performance. In addition, the possible workpiece geometries depend on the flexibility of the tool, e.g. the dressability of conventional wheels against pre-profiled superabrasive tools. As consequence, a mass produced tool can be used for several applications, but will never be as effective as a tool designed for one special purpose.

Several milestones in the development of abrasive grit materials and bonding systems, and the refinement of the tool components and manufacturing processes have led to large improvements in process performance (Fig. 1.2). The life of the grinding tool is intertwined with the life of the product produced by grinding (Fig. 1.3). Similar to the manufactured product, an abrasive tool life has four phases: raw material extraction, manufacturing, use, and end of life. The use phase coincides with the machining process of another product. This thesis will discuss all life cycle phases of a grinding tool.

Abrasive tool compositions and manufacturing techniques are widely company proprietary and development is still in progress. As the design process of a grinding tool relies on the expertise of the tool manufacturer, it is often not a transparent procedure to the customer. Therefore, it is hard to comprehend considerations on sustainability. This thesis summarizes publicly available knowledge and unveils how it relates to sustainability.

Traditionally, sustainability has been viewed in tree categories or pillars: economy, environment, and society. However, this is not sufficient because it

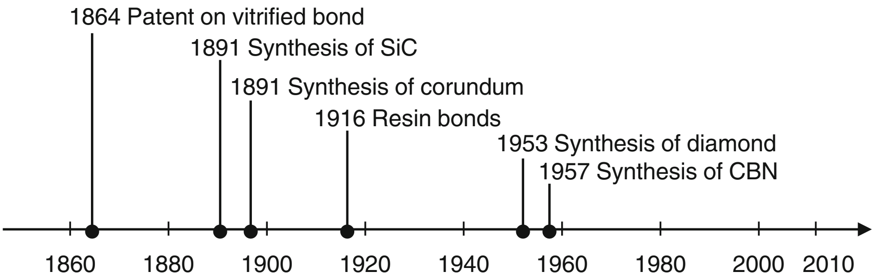

Fig. 1.2 Some milestones in the development of grinding tools

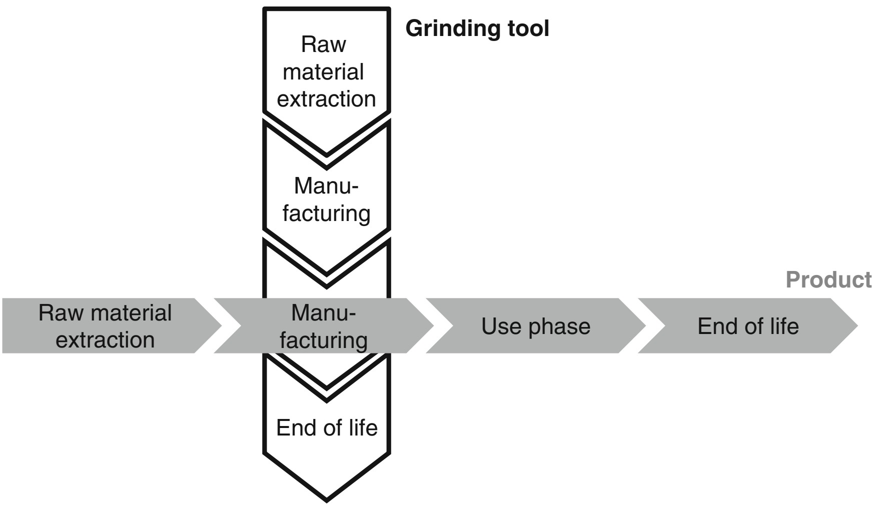

Fig. 1.3 Life cycle perspective of grinding tools and ground products

disregards many decisions heavily based on technological considerations. For example, choice of grit size does not translate easily into one of the traditional three pillars of sustainability but depends on part surface roughness which is a technological factor. Therefore, in this work sustainability for abrasive tools is viewed under the following four aspects:

- Economics in terms of productivity and costs
- Environment in terms of energy use, materials use, waste, recyclability, emissions, etc.
- Society in terms of worker safety, health, and education
- Technology in terms of feasibility, workpiece quality, best practice, performance

This thesis revises the state of the art of research and common practice in the field of abrasive tooling systems for fine machining applications. Despite the diverse technical terms used in the literature, this thesis uses uniform terms.

Life cycle considerations and sustainability aspects in grinding are trend-setting perspectives, which are discussed in this thesis for the first time comprehensively throughout. All Chaps. 2–5 end with an interim model on technological, economic, environmental, and social sustainability.

Chapter 2 "Abrasives" analyzes the grit materials including their chemical composition, chemical and physical properties, material processing, and abrasive process performance. The knowledge of grit materials is crucial to understand the life cycle of abrasive tools holistically—where do the materials come from, how are they processed and what performance do they imply for the abrasive tool.

In a similar way, the bonding system defines tool performance and the tool manufacturing route. Therefore, Chap. 3 "Bonding Systems" explains different bond types, their ingredients, processing, and resulting tool performance.

Different abrasive applications need distinct tool designs as described in Chap. 4 "Abrasive Tool Types". There is hardly ever only one perfect tool type, but tools can be used interchangeably affecting process performance and product quality. Moreover, the tool type affects the tool end of life significantly in terms of recyclability, re-use, or disposal.

The implications of the tool design and tool fixture specific to grinding tools are discussed in Chap. 5 "Grinding Wheel Macro-design—Shape, Body, and Qualification". The shape and material of the tool affect its manufacture, raw materials, its use and end of life. In addition, the tool microstructure as explained in Chap. 6 "Grinding Wheel Micro-design—Abrasive Layer and Wear" changes tool performance and tool manufacture. The structure defines the tool topography that interacts with the workpiece surface and the wear phenomena, and affects sustainability since the grinding tool needs to be consumed during its use phase. Lower wear might yet lead to lower energy efficiency of the grinding process. Tool conditioning is an important method to adjust and regenerate tool profile and topography.

Having introduced the main factors of tool design, this knowledge needs to be tied back to sustainable grinding technology. Therefore, Chap. 7 "Sustainability of Grinding" first explains methods of Life Cycle Engineering (Life cycle assessment (LCA), Life cycle costing (LCC), Social life cycle assessment (SLCA), and Sustainability Indicators). Then a generic life cycle inventory of grinding processes is gathered to show the state of the art in grinding process sustainability. In addition, a new approach to understand and dissect grinding processes is explained and applied. This so called axiomatic grinding process model visualizes how process setup and tool design are connected to traditional quality indicators and newer sustainability indicators.

Chapter 8 “Sustainability Case Studies” then uses the concepts from the former chapter to discuss several examples: Vitrified bonded grinding wheels with corundum and CBN are compared with regard to their manufacturing strategies and energies; Hardturning and grinding are more or less favorable in terms of sustainability depending on the criteria. The example of leveraging gear grinding focuses on how the manufacturing process can improve the product performance towards higher overall energy efficiency, even if the gear grinding procedure consumes more energy. In a similar way, speed stroke grinding can improve product quality through a more sophisticated manufacturing process.

The final Chap. 9 “Future Prospectives” explains the actual market situation for grit material and introduces new abrasive tool concepts with potentially higher sustainability. All interim models from Chaps. 2 to 5 are combined to a generic model allowing for final conclusions on abrasive tool life cycle and sustainability.

The aims of this work are to

- Educate students and tool users on abrasive tools,
- Help tool manufacturers to emphasize sustainability in tool manufacturing,
- Help tool users to evaluate sustainability in tool use.

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