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Review

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.

Contents

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

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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. Fig. 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.

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 and 6 GPa at temperatures between 1400 and 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

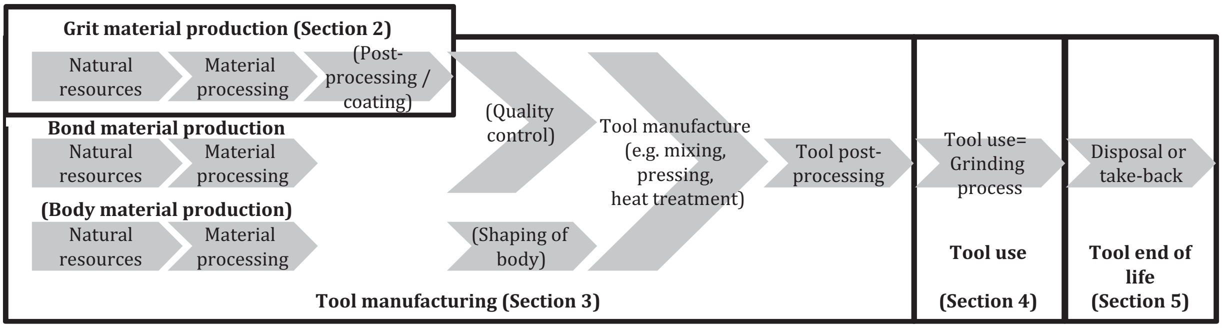

Fig. 1. Grinding tool life cycle.