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Fixed abrasive machining of non-metallic materials

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ABSTRACT

This paper summaries advancements in fixed abrasive machining of non-metallic materials, which include reinforced concretes, stones, rocks, carbon fiber reinforced plastic, metal and ceramic matrix composites, wood, wood-fiber plastic composite, biomaterials (bone, plaque, and enamel), and structural and electronic ceramics. The broad impacts, diverse applications, and innovations of fixed abrasive machining processes are presented. Benefits of the engineered deterministic distribution of abrasive grain grinding tools are demonstrated. Industrial perspectives and future research on innovative fixed abrasive machining technologies that enable new processes and improve the productivity are highlighted.

1. Introduction

Novel advanced materials with unique properties for superior performance during use are the enabling technology and source of innovations for new products and services. The evolution of material utilization in our society is illustrated in Fig. 1 for four types of material: ceramics, composites, polymers, and metals. Ceramics and polymers (including wood, skins, and fibers) were dominating materials before 5000 BC. Metals had a growing relevance until the 1950s. Since then, the utilization of non-metallic ceramics, composites, and polymers has steadily grown in electronic, medical, energy, aerospace, construction, and other industries. This trend of increasing use of non-metallic materials reflects in manufacturing research. The focus of this paper is to summarize advancements of fixed abrasive machining processes for non-metallic materials, which have a trend of increase utilization in broad applications.

New abrasive materials, such as the synthetic diamond and cubic boron nitride (CBN), are great inventions that have enabled better productivity and quality and created new applications. For non-metallic work-materials, the pace of new discovery and application is rapid. New non-metallic work-materials often require the abrasive machining to achieve precise shape, good surface integrity, and specific functional requirements. Due to the distinct material properties, most of these non-metallic materials are difficult-to-machine and require abrasive machining processes.

This paper covers the fixed abrasive machining processes for eight non-metallic materials listed in Fig. 2. While these processes differ significantly in tool design, they share the same abrasive machining principles and material removal mechanisms. In this paper, these eight non-metallic materials are the section titles. Within each section, various fixed abrasive machining processes are subsection titles. Each section starts with an introduction and technical challenges of this non-metallic material in fixed abrasive machining and concludes with the summary of innovations and future research.

2. Reinforced concretes and stones

Natural and artificial stones are often machined by cut-off grinding processes, including the disk sawing, cable sawing, and core hole drilling [54]. Most of the tools are based on metal-bond synthetic diamond in segments, which are welded onto circular (disk sawing) or tube-shaped (core hole drilling) base bodies or spaced on stranded steel cables (cable sawing). The segments engage with the workpiece according to specific process kinematics (Fig. 3). The diamond grain performs the work-material removal while the bond provides the right level of grain retention forces and wear resistance for optimal tool performance, which is characterized by a sensitive balance of the diamond wear and a timely set-back of the bonding, known as the self-sharpening-effect (Fig. 3) [49]. The tool can be adjusted by bond composition

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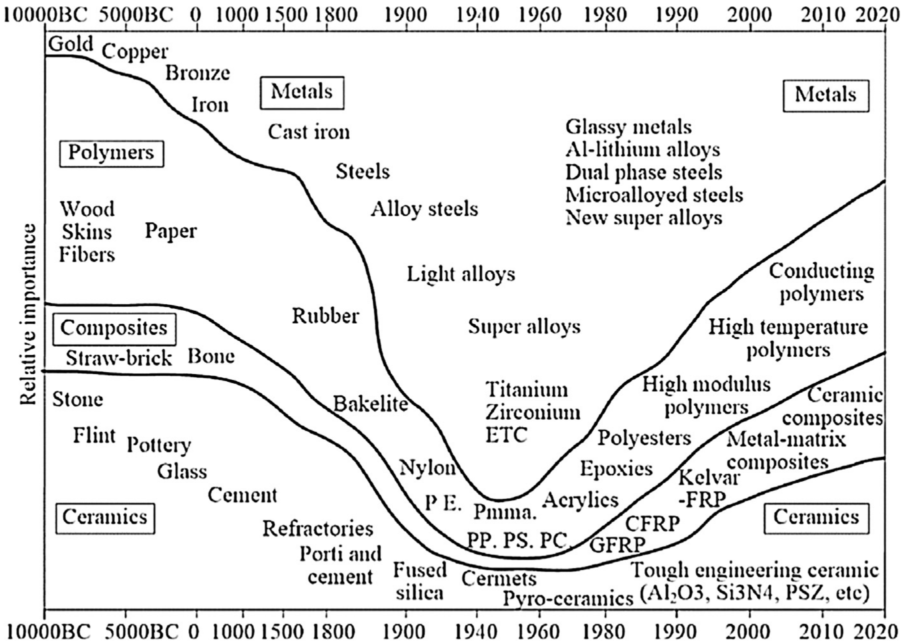

Fig. 1. The evolution of materials utilization in the society [7].

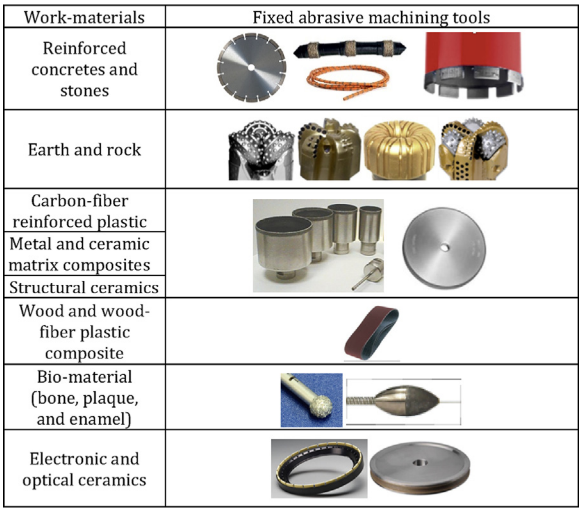

Fig. 2. Type of fixed abrasive grinding for non-metallic materials.

and diamond grain size, concentration, and distribution in accordance with the work-material and application. Tools with engineered deterministic grain distribution have been studied and demonstrated in practical applications with success. The process parameters are crucial to provide an ideal condition of constant grain protrusion throughout the grinding operation.

2.1. Disk sawing

Cut-off grinding disks are predominantly applied in the fabrication of slabs and tiles from natural stone and cutting of pure and reinforced concrete. This is traditionally performed using resin bonded Al_2O_3 grinding discs. The diamond grinding disks and processes have advanced for disk sawing.

2.1.1. Tool technology

The process step with the highest added value in natural stone processing is the fabrication of slabs and tiles. The G-ratio (volume of work-material removed vs. volume of wear in the tool) of about 1.7 is the state-of-the-art [43,145]. An approach to improve the G-ratio and reduce kerf waste and energy expenditure is the application of thinner cut-off grinding disks. Denkena et al. [43] proved that it was possible to reduce the waste by more than 30% while still meeting tile quality requirements. This was achieved by thinner cutting segments and parallel/conical core, higher cutting speed, and a new cutting segment design (Fig. 4). In order to compensate the reduced stability and increased tool deflection of conical steel core, a stronger steel alloy with the disk thickness $w_{d,i}$ = 3.3 mm at flange and $w_{d,a}$ = 3.0 mm at outer rim were applied [68]. Bockhorst [16] showed that an increased cutting speed (v_c) from 32 to 50–60 m/s further contributed to the dynamic stabilization of the thin rotating disk (Fig. 4).

To withstand higher grinding loads and reduce the tool deflection (w_p), the cutting segment composition and structure were adjusted. As shown in Fig. 5, Glatzel [68] investigated the sandwich segment with a higher bonding hardness (+2 to 3 HRC) and abrasive grain concentration (+15 to 20%) on both sides and a lower hardness and grain concentration in the middle. This design enabled an inner groove formation on the radial face. A guide was formed during cutting and contributed to a reduced tool deflection (w_p). Li et al. [110] studied the geometry and structure of diamond segments to reduce the tribological interactions between the tool and workpiece in disk sawing of granite by adding side slots in cutting segments and optimizing the process parameters and retention of the diamond. An enhancement of the tool life could also be achieved by a high pressure water supply, which injected the water into the contact zone at a speed matching to that of the grinding wheel surface speed (Fig. 5) [39].

An innovation that has been adopted commercially is the cutting segments with systematically arranged abrasive grains, also referred to as engineered grinding tools (EGT) or blazed diamond grid [76], to achieve the constant single grain chip thickness for every diamond grain in cut-off grinding (Fig. 6) [46]. The single layer EGT can achieve increased material removal rate (MRR) and tool life [174]. Denkena et al. [41] confirmed these results in disk sawing of reinforced concrete and observed lower adhesion wear on EGTs compared to stochastic tools with equal grain concentrations. The engineered cut-off grinding tools with optimized grain distribution in EGT are available in the market and have been adopted for practical applications with success.

To find the optimal grain distributions, Denkena et al. [46] utilized and extended the material removal simulation CutS® to model 3D grain arrangements of sintered EGT (Fig. 7). CAD-models of real diamond grains, geometric parameters for 3D grain arrangement, and algorithms for stochastic distributions, material removal, and grain wear were implemented. The material