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Recent developments in grinding machines

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ABSTRACT

Grinding is often the final step in the process/manufacturing chain, meaning that no subsequent post-grinding correction of the surface and geometry is performed. This imposes strong requirements on grinding-machine technology and on the understanding of this finalising process. While grinding has unique capabilities it is nevertheless in competition with other machining processes. The evolution of grinding machines is driven by process requirements like accuracy, MRR, and subsurface integrity. The regeneration of the tool on the machine with dressing devices is to be regarded as unique for grinding machines, hence a grinding machine always runs two separate processes. The high accuracy of grinding has, in fact, been an obstacle to simply adopting developments from other machining processes. Also, a lack of experienced machinists and a general trend towards individualized products and one-piece flow has required a transition from an experience-based approach to a science-based approach. Development is further driven by market demands, such as cost-reduction in terms of CAPEX, footprint, TCO versus quality, and throughput, which affect business models and the machine's design and construction. Moreover, the current mega-trends – such as resource efficiency, individualization, ergonomics and Industry 4.0 – are changing the appearance of grinding machines, which is also affected by the availability of new technologies, especially sensors, actuators and the control or machine intelligence. This paper reviews the most-relevant technologies, assesses their impact and the readiness of industry to adopt them, identifies the still-open issues, and concludes with future research requirements.

1. Introduction

1.1. Importance of grinding machines

Grinding is one of the oldest manufacturing techniques ever used by humans. Although the process is to a great extent driven by centuries of experience, it is still an important process and represents a vital field of cutting-edge research. Today grinding spans from very crude and rough applications in cutting of materials at high material-removal rates (MRR) to finishing and ultraprecision processes. The latter can achieve surface roughness values in the range of Ra = 0.3 nm and accuracy, planarity and size of geometrical features in the range of 10 nm. Due to process capabilities covering a broad range of MRR and accuracy, the expectation is to further extend the grinding operation from rough geometries to finishing. Moreover, requirements from the parts point of view are not only accuracy, but also surface topography, where grinding can achieve unique properties. Research in grinding tries to enhance economic and ecological properties and performance to extend grinding applications in the overall process chain—on the one hand, in the direction of increased MRR, avoiding turning and milling, and on the other hand, in the direction of fine finishing, thus making further abrasive finishing processes such as lapping and polishing obsolete. Fig. 1 shows the principal role of grinding in the process chain as well as research directions.

In many industrial applications, grinding processes are the final step in the process chain towards finished workpieces. This encompasses two aspects:

- As visible surfaces the appearance of ground areas presented to the customer. Hence, the tolerance for faults and marks and all other deviations from the intended surface characteristics is limited, whereas other processes only need to deliver surfaces suitable for a subsequent grinding or other manufacturing process.

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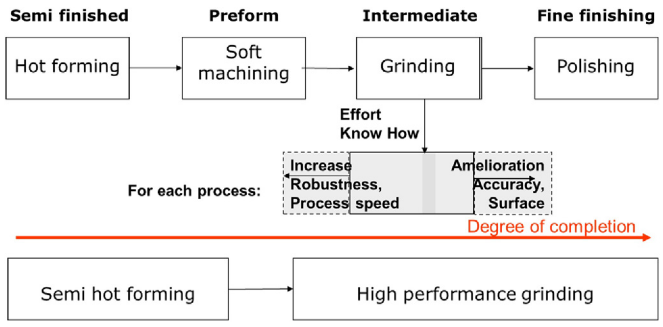

Fig. 1. Role of grinding research in the process chain.

- A workpiece to be ground has usually already passed most steps of a process chain. At this degree of maturity, it incorporates the maximum value created. Scrap in grinding is the most expensive and must be avoided.

Nevertheless, grinding today still requires test pieces to begin a long process run, which clearly indicates the necessity of grinding research and development in grinding machines.

Manufacturing processes are competing in terms of cost, quality, time, throughput, flexibility and, increasingly, ecological footprint. Grinding is suitable for manufacturing in hard and brittle materials because of the abrasive grains' hardness and their stout cutting wedges with negative rake angles. The abrasive tool may wear, but an essential feature of all grinding machines is a dressing device to regenerate the abrasive-tool geometry and cutting ability. When correctly profiled, the grinding wheel is capable of significant material removal before its geometry deteriorates and requires reconditioning. This enables grinding even of materials with the same hardness as the abrasive grains themselves. Furthermore, it is possible to generate surface topographies that cannot be produced by other manufacturing processes. Also the subsurface integrity can be beneficially influenced by grinding. By combined ploughing and cutting, minimal dimensional changes are possible, which makes grinding so unattainable precise compared to other operations. Grinding processes are highly reliable, as no catastrophic wear can occur after run-in.

In addition, other machining technologies have improved as well, imposing pressure for further advances in grinding, particularly advances in laser technology [270]. Laser manufacturing in ultra-hard materials such as diamond, which is achieved without wear and minimal geometric restrictions, is a strong competitor to grinding. However, it still has higher costs and is therefore restricted to geometries that cannot be produced by grinding. Also, some challenges can be regarded as indirect. For example, tools with geometrically defined cutting edges can be manufactured by using ultra-short pulsed lasers, which can sometimes replace geometrically non-defined cutting in materials which were formerly the sole domain of grinding.

Cost, productivity and quality have been major target parameters for several decades. A comparison between grinding and hard-turning is available in Refs. [68,152] and has shown superior reliability and quality for grinding, but better flexibility and energy efficiency for hard-turning, depending on the application. Also, compared to hard-turning, grinding is disadvantageous with respect to resources, material and energy consumption, and emissions as shown in Ref. [68]. However, due to the relatively low cost of these resources, grinding is overall more economical.

1.2. Classification of grinding machines

Grinding machines can be classified according to Ref. [274] and with respect to Ref. [272] in correlation to the classification of the different process technologies with geometrically non-defined cutting edges as it is given in DIN 8589, parts 11, 12, and 13. Fig. 2 shows the upper hierarchical level.

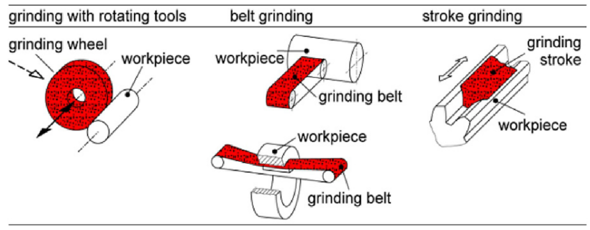

Fig. 2. Different grinding processes. according DIN 8589, 11-13, defining grinding machines.

Belt-grinding machines use a flexible belt. A multitude of grains with geometrically non-defined cutting edges are affixed to the belt by a supporting bond material. The belt, driven by at least two pulleys, is pushed against the workpiece by a supporting structure, which can be the pulley itself or a contact shoe. The supporting structure may be a curved surface, giving the workpiece its final shape.

A further level of classification for grinding machines with rotating tools distinguishes between cylindrical-planar, generative-gear, coordinate and tool-grinding machines as well as grinding machines with non-defined feed and special-purpose machines [68]. An additional criterion for differentiation is the machine kinematics.

1.3. Peculiarities of grinding machines

In Ref. [218], the industrial challenges in grinding are outlined in a global view. The process properties of grinding are significantly different from milling, which explains the differences in architecture, layout and equipment of grinding machines, all of which manifest themselves in the process chain according to [274]:

- Cutting speeds in grinding are 5–10 times higher than those typically used in machining operations with geometrically defined cutting edges, which means large tool diameters and/or high spindle speeds.
- The normal forces on the grinding wheel are significantly larger than the tangential forces, typically several times larger.
- Grinding machines need massive protections against failure of the grinding wheel.
- Grinding machines have CNC-driven dressing devices to generate and regenerate grinding-wheel profiles on the machine. Dressing is usually done in a separate dressing cycle. but occasionally, with difficult-to-grind materials, simultaneously with grinding.
- The quality of axes, rotational accuracy of main and auxiliary spindles are typically higher than for machines for the material removal with geometrically defined cutting edges.
- Balancing devices are often needed due to the high centrifugal forces resulting from the high spindle speeds.
- The heat generated by high forces and high cutting speeds in the grinding zone and originating from the negative rake angles and wear flats must be dissipated by the use of metal working fluids (MWF). Thus the energy required for running the grinding process might be dominated by the coolant supply.
- Grinding machines using oil coolant require fire protection.
- Grinding machines are preferably equipped with an acoustic-emission (AE) contact-recognition sensor to detect wheel-workpiece contact.
- For high-quality parts, measuring devices for in-situ measuring of the part geometry and direct iterative correction have been developed.
- Higher requirements have developed for sealing off machine parts from abrasive removed from the wheel, from wheel wear and/or dressing.

1.4. Structure of the paper

This paper is related to several CIRP Keynote papers [45,120,129,154,201,213,275], and focuses on topics related to