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Abrasive fine-finishing technology

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ABSTRACT

Abrasive fine-finishing technology is often applied as a final finishing process, and the selection of the right technology is crucial to obtaining the desired performance of functions such as fatigue life. This paper begins with classifications of the technology along with fundamentals and brief histories of the individual methods. The material removal mechanisms, specific energies, and finishing characteristics of the various technologies are summarized giving assessments of the surfaces created by them. Guidelines developed for selecting the appropriate methods, and case studies illustrate the effectiveness of various methods. This paper ends with a discussion of the future prospects of the technology.

1. Introduction

For production of critical parts, the manufacturing processes turning raw materials into finished components typically consist of material-conversion processes and finishing processes (Fig. 1). The material-conversion processes usually start with a forging or forming process followed by soft (green) machining to create the desired form and geometry. If applied, heat-treatment processes control the microstructure and mechanical properties of machined components. It is crucial to select the right technology for the material-conversion processes, which determine the hardness, the residual stress condition, and the amount of stock removal in subsequent processes. Accordingly, the material-conversion processes have a significant influence on the productivity, quality, and cost of finishing processes.

Following material-conversion processes such as grinding and hard-turning, the hard stock is further processed to meet specifications including geometrical tolerances, accuracies, and surface topography. In many cases, particularly in the production of critical components, abrasive fine-finishing processes are applied to improve the surface or sub-surface functions beyond the degree accomplished in preceding operations. In addition, abrasive fine-finishing processes meet desired specifications that are too difficult or too expensive to meet using only the preceding processes.

In this paper, abrasive fine-finishing technology is defined as a technology following grinding/hard-turning that adds value by imparting desired functionality to the surface by using abrasive grains to enhance the surface characteristics and integrity. The material removal and surface-generation mechanisms of abrasive fine-finishing technology are quite different from those of grinding. The differences are summarized as follows:

(1) Abrasive fine-finishing technology utilizes a pressure-copying principle as the material removal process (The stock removal capability of the abrasive fine-finishing is far lower than grinding, and it is limited to controlling dimensional accuracies, such as sizes, taper, roundness etc.).
(2) It utilizes a more sophisticated (compared with grinding) relative motion between work surface and abrasive tool.
(3) It does not utilize grinding wheels, and the cutting speed is significantly lower than in grinding.

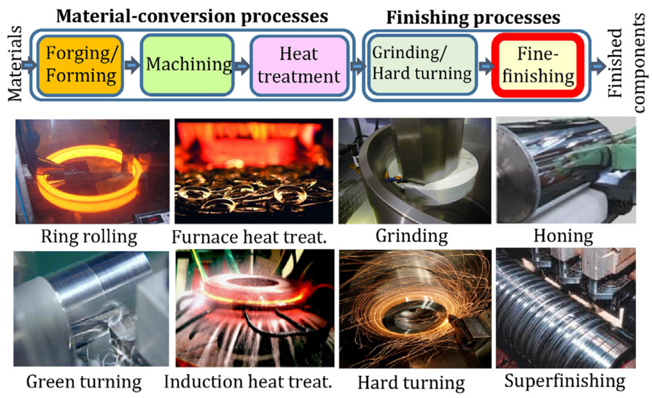

Fig. 1. Typical manufacturing processes from raw material to finished components.

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Abrasive fine-finishing technology has unique capabilities [47], which attract considerable attention in industry. Among the advantages are the following:

(1) Surface modification in texturing and topography.
(2) Damage-free surface generation without a heat-affected zone.
(3) Enhancement of surface integrity and the creation of compressive residual stresses in most of cases.
(4) Improvement of geometrical accuracies, such as roundness, profile, etc.
(5) Enhancement of visual factors such as uniformity, light-reflection, brightness, etc.

Fig. 2 shows examples of components finished by various abrasive fine-finishing technologies. In the case of bearing components, the fatigue life, motion accuracy, and sound performance are significantly improved when superfinishing is used. The honed bores of engine block cylinders have surfaces with low sliding friction and high wear resistance. Precision mechanical components finished with mass finishing provide a low torque performance and a long service life. The fatigue strength of turbine blades is improved by blasting. Optical components and silicon wafers processed with lapping and polishing have damage-free mirror surfaces. Jewels finished with polishing and buffing have mirror surfaces with high brightness. Abrasive flow machining (AFM) enables the finishing of holes with complex paths and geometries. Manifolds finished with AFM show improved flow through the passages.

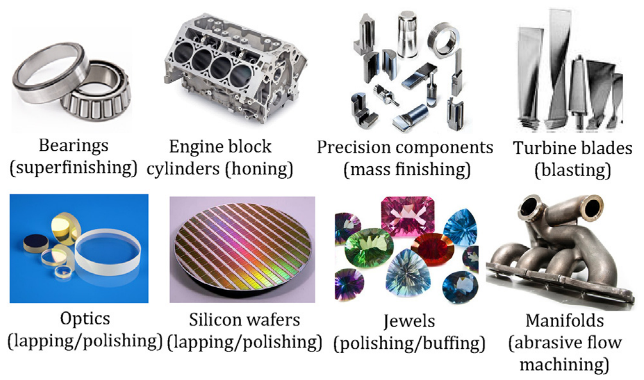

Fig. 2. Samples of critical components finished by abrasive fine-finishing technology.

Abrasive fine-finishing technologies use a wide variety of tools with various shapes and grain states under different operational conditions. Distinct empirical rules are implemented for each process to control the finishing characteristics, and finishing conditions must be selected by skilled operators. This is due to a lack of scientific understanding of the fundamentals of those processes. However, a comparison of parameters common to those processes would allow engineers to analyze them and choose the optimum process for a given application.

This paper will clarify the fundamentals of abrasive fine-finishing technology through the establishment of common parameters, which enables a scientific assessment of each process as well as providing a baseline for comparison. The fundamental understanding of each process helps optimize the design of manufacturing processes to produce components that meet desired specifications and achieve performance.

CIRP (*Collège International pour la Recherche en Productique*) has made significant contributions to scientific knowledge-building regarding abrasive fine-finishing technology. There have been 54 relevant papers published from 1960 to 2015 by the Scientific Technical Committee-Abrasive Process (STC-G) in the Annals of CIRP Vol. 1. The breakdown by the finishing method is: 25 papers on lapping/polishing [12,13,20,25,42,43,45,71,77,78,82,89,92,95,109,125,144–146,149,175,185,191,199,220], 8 in honing [24,41,61,111,128,148,183,204], 8 on magnetic abrasive finishing (MAF) [52,85,163,173,187,210,211,215], 4 on coated abrasives [16,97,158,176], 3 on jet finishing [14,76,87], 3 on superfinishing [28,133,195], and 3 on mass finishing [65–67]. In addition to those, there have been three CIRP keynote papers regarding polishing technology, which have provided invaluable technological overviews. In 1997, Komanduri et al. [98] summarized fine abrasive processes, with an emphasis on material removal of brittle materials, and described the process modeling of various fine-abrasive methods, such as ultra-precision grinding, polishing, elastic emission machining, erosive jets, magnetic field-assisted finishing, etc. In 1998, Venketesh et al. reviewed chemical-mechanical polishing (CMP) technology for semiconductor materials and discussed ductile-regime machining and modeling [197]. In 2003, Evans et al. described the material removal mechanism in lapping and polishing [44]. They characterized polishing via fundamental interactions between four critical elements – workpiece, fluid, granules, and lap – of the process and provided comprehensive overviews of polishing technology. These keynote papers focused primarily on polishing technologies for brittle materials.

In 1988, Salje presented a CIRP keynote paper describing the relationship between grinding, honing and lapping using fundamental parameters such as chip thickness, specific energy, etc. [147]. This paper provided crossover understanding of the material removal mechanism between bonded- and unbonded-abrasive finishing processes and made a bridge between grinding and abrasive fine-finishing technologies. The authors of the present paper intend to extensively expand Salje's approach to all abrasive fine-finishing processes using fundamental parameters.

This paper will begin by classifying each abrasive fine-finishing technology. Subsequently, the background and the origin of each technology will be presented in a historical review. The fundamentals of the various abrasive fine-finishing technologies will then be discussed describing the material removal mechanisms, specific energies, and surface characteristics (topography and integrity) created. The assessment of the effects of the surface topography and integrity on the performance of components will help develop the guidelines for appropriately selecting the technology and designing the finishing processes. This paper will end by illustrating the state of the art in industry-applied abrasive fine-finishing technology and discussing the future directions of research and development (R&D) in this field.

2. Classifications and descriptions of abrasive fine-finishing technologies

2.1. Classifications

Fig. 3 shows the classifications of abrasive finishing technologies. Based on the processing principle, abrasive finishing technologies (including grinding) can be classified into two categories: motion-copying processes and pressure-copying processes [79]. Motion-copying processes remove material to a given depth of cut. This enables the control of form accuracy and dimensions. For example, the grinding process using bonded abrasive wheels is a motion-copying process. In contrast, pressure-copying processes have no given depth of cut but instead remove material by means of the pressure of the tools against the workpieces. This is suitable for obtaining desired surface geometries and surface integrity and for improving form accuracy but not for controlling dimensional accuracy. Abrasive fine-finishing technologies such as superfinishing, honing, lapping, polishing, and buffing are representative of pressure-copying processes and are often used as post-grinding processes.

Abrasive fine-finishing technologies can be classified based on the following criteria: (1) abrasive state, (2) tools used for the processes, and (3) finishing methods. There are two abrasive states: bonded and unbonded. In the bonded-abrasive (i.e., *fixed*

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