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Research on Abrasive Flow Polishing Processing and Technical Development of Slender-Hole Parts

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Abstract

In response to the continuously rising requirements for inner wall machining accuracy and surface quality of slender-hole parts in fields such as aerospace and hydraulic transmission, this paper systematically reviews the development history and research status of abrasive flow polishing technology. It elaborates the machining mechanism and process characteristics of abrasive flow polishing, focuses on analyzing the influence laws of abrasive properties, process parameters and flow channel structure on the inner wall polishing effect of slender holes, and summarizes the latest progress of this technology in terms of processing equipment, medium research and development, and process optimization. Furthermore, it points out the future development trend and application prospects of abrasive flow polishing technology for slender holes, which can provide reference for the selection of precision machining technologies for similar parts.

Keywords

Slender Hole; Abrasive Flow Polishing; Surface Quality; Process Optimization.

1. Introduction

Hole machining is a vital machining process that accounts for a considerable proportion in mechanical manufacturing. According to statistics, hole machining makes up approximately one-third of the total machining workload and one-quarter of the total machining time. Among all hole machining operations, the fabrication of small holes is the most challenging. Generally, holes with a diameter ranging from 0.5 mm to 3 mm are collectively defined as small holes[1].

With the development of aerospace, energy equipment, automobile manufacturing, precision hydraulic equipment and other industries, parts with slender hole structures have been applied more and more extensively. Such parts are typically characterized by small aperture, large depth-to-diameter ratio and complex geometry. As a result, their inner hole surfaces are prone to oxide scale, burrs and various machining defects during processing, which seriously deteriorate the assembly accuracy, service performance and service life of the parts.

Abrasive flow machining (AFM) is a non-traditional machining method. It employs viscoelastic fluid loaded with abrasive particles that reciprocates through the inner bore of the workpiece under pressure, achieving material removal through the micro-cutting and extrusion effects between abrasive grains and the workpiece surface. At its initial stage, AFM was mainly used for deburring the surfaces of cross holes, valve bodies, molds and other components in the aerospace sector[2]. The machining parameters of AFM and the rheological properties of the abrasive medium are two critical factors affecting the machining performance. Medium viscosity and working pressure exert significant influences on the metal removal rate and surface roughness[3-6].

Benefiting from its favorable fluidity and flexibility, abrasive flow can reach narrow holes that are inaccessible to conventional cutting tools. Furthermore, with its unique process advantages of fluidity and formability, it has shown increasingly prominent strengths in the grinding and polishing of

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special-shaped holes, thin-walled parts, complex cavities, and workpieces with large-scale complex curved surfaces[7-8].

2. Research Status of Finishing and Polishing for Slender-Hole Parts at Home and Abroad

Inner wall finishing and polishing of slender holes is a common technical challenge in the high-end equipment manufacturing field. At present, domestic and international research mainly focuses on three major technical routes: abrasive flow polishing, magnetic-assisted finishing, and composite field-enhanced polishing. Among them, abrasive flow polishing has become the mainstream technical route for ultra-precision machining of slender holes due to its advantages of adapting to complex inner cavities and no cutting force deformation[9].

2.1 Overseas Research Status

Overseas research on slender hole finishing technology started earlier, and a complete system covering basic mechanism, process optimization to equipment R&D has been formed. The research entities are mainly universities and scientific research institutions in the United States, Germany, Japan, India and other countries.

2.2 Basic Process and Mechanism Research of Abrasive Flow Polishing (AFP)

Abrasive flow polishing technology originated in the US aerospace field in the 1960s. It was initially used for deburring of valve bodies and cross holes, and then gradually expanded to precision polishing. In terms of basic process, Singh et al. applied traditional AFP to inner surface polishing of 316L stainless steel microholes with a diameter of 850 μm, and successfully reduced the surface roughness Ra from 1.4 μm to 150 nm, verifying the feasibility of abrasive flow in machining micro slender holes[10]. Sharma et al. developed an ultrasound-assisted abrasive flow machining (UAAFM) method. By introducing ultrasonic vibration during machining, abrasive grains are forced to impact the workpiece surface vertically, which adds extra radial cutting force and significantly improves the machining efficiency and surface quality of deep holes[11].

In terms of machining mechanism and simulation, overseas scholars carried out research on flow field dynamics and material removal mechanism earlier. Li et al. took a servo valve housing as the research object and used a solid-liquid two-phase flow model to conduct numerical simulation of the abrasive flow machining process. It was found that when the outlet back pressure diameter was 3.3 mm, the dynamic pressure in the channel and wall shear force reached peak values, achieving optimal machining efficiency and surface quality[12]. Junye Li et al. simulated the nanometric cutting process of single-crystal copper by SiC abrasive grains through molecular dynamics (MD) simulation, revealed the influence law of cutting angle on cutting force and surface defects, and proved that a small cutting angle is more conducive to improving surface quality and reducing subsurface damage[13].

2.3 Composite Field-Enhanced Polishing Technology

To break through the bottlenecks of low machining efficiency and poor uniformity of traditional abrasive flow in slender holes with large depth-to-diameter ratios, overseas scholars have developed various composite finishing technologies. Hybrid processes such as electrochemical abrasive flow machining (ECAFM), magnetic field-assisted abrasive flow machining (MAFM), and rotary abrasive flow machining (RAFM) have emerged one after another. By coupling external field energies such as electric field, magnetic field and rotary motion, the cutting action of abrasive grains is strengthened, and the flow field distribution in deep hole regions is improved[14].

In the field of magnetic-assisted finishing, Japanese scholars are in a leading position. Hanada et al. prepared spherical iron-based composite magnetic abrasives loaded with diamond particles via plasma spraying technology, with particle size controlled within 10 μm. The abrasives were successfully applied to ultra-precision finishing of capillary inner walls, solving the problem of

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insufficient machining accuracy of traditional irregular magnetic abrasives[15]. Verma et al. from India designed a magnetic abrasive finishing tool based on dual permanent magnets. Polishing experiments on the inner wall of stainless steel pipes showed that magnetic flux density is the most significant parameter affecting surface roughness, and nanoscale surface quality can be achieved after process optimization[16].

2.4 Equipment and Industrial Applications

Overseas has realized serialization and intellectualization of abrasive flow finishing equipment. Representative enterprises include Extrude Hone (USA) and Otec (Germany). Their equipment can realize closed-loop control of pressure, flow rate and temperature, and are widely used in mass production of slender hole parts such as aero-engine fuel nozzles and hydraulic valve sleeves. In recent years, with the development of MEMS and microfluidic technology, overseas research has further extended to sub-millimeter and micrometer-scale slender holes, focusing on the development of low-viscosity water-based abrasives and nanoscale abrasive grains to meet the finishing requirements of smaller-sized holes.

2.5 Domestic Research Status

Domestic research on slender hole finishing technology started relatively late. However, driven by demand from aerospace, hydraulic transmission and other fields, it has developed rapidly over the past two decades, and numerous achievements have been made in process optimization, flow field simulation, composite technology and other aspects. The core research institutions include Nanjing University of Aeronautics and Astronautics, Northwestern Polytechnical University, Dalian University of Technology and Harbin Institute of Technology[17].

2.6 Process Optimization and Uniformity Control of Abrasive Flow Polishing

Aiming at the uniformity problem of "over-polishing at the inlet and outlet" and "under-polishing in the middle section" of slender holes, domestic scholars have carried out extensive process innovations. Cao Wentao et al. from Nanjing University of Aeronautics and Astronautics proposed a bidirectional abrasive flow finishing mode for additive-manufactured internal microchannels, and comparatively studied the machining effects of silicon carbide and alumina water-based abrasives. The results show that bidirectional machining can reduce the inlet-outlet reaming difference of the channel from 51 μm to 27 μm, significantly improving the polishing uniformity of slender channels[18].

Cai Zhijie et al. from Northwestern Polytechnical University carried out orthogonal experiments on EDM-machined surfaces of common rail pipe microholes using abrasive flow polishing, and established a surface roughness prediction model based on response surface methodology. The influence laws of polishing pressure, abrasive concentration and machining time were clarified. Under optimal parameters, the channel Ra can be reduced from 1.31 μm to 0.20 μm, with a prediction accuracy of over 99%[19]. In addition, domestic scholars have also studied methods such as back pressure adjustment, variable-diameter flow guiding and abrasive grading for slender holes with large depth-to-diameter ratios, which effectively improve the axial machining uniformity of channels.

2.7 Magnetic-Assisted and Composite Finishing Technology

China has also formed a characteristic research direction in the field of magnetic finishing. Liu Tongyi et al. proposed a magnetic honing process for the inner surface machining of slender stainless steel pipes. The process is divided into three stages: oxide scale removal, semi-finishing and finishing. Through parameter optimization via response surface methodology, the inner wall surface roughness Sa of the pipe can be reduced from 4.351 μm to 0.071 μm, meeting the high-precision requirements of aerospace, medical and other fields[20]. In addition, a self-pressurized high-speed magnetic abrasive flow polishing device has been developed domestically, which forms a flexible polishing brush through the magnetorheological effect. It can realize deterministic polishing of millimeter-scale and micrometer-scale slender holes while avoiding subsurface damage[21].

2.8 Technology Development Trends and Deficiencies

At present, domestic slender hole finishing technology is developing in four directions:

(1) Intellectualization:：integrating online detection and adaptive parameter adjustment to realize closed-loop control of "machining-detection".

(2) Miniaturization: developing nanoscale abrasives and low-viscosity media for MEMS microchannels.

(3) Greenization: developing degradable polymer matrix materials and recyclable abrasive grains.

(4) Hybridization: coupling multi-field energies such as ultrasound, magnetic field and electrochemistry to break through the machining bottleneck of holes with large depth-to-diameter ratios.

However, on the whole, domestic research still has three main deficiencies: Research on the machining mechanism and uniformity control of abrasive flow for slender holes with a large depth-to-diameter ratio (>20:1) is still insufficient. There are few self-developed high-end finishing equipment, and core components rely on imports. Research on abrasive medium formulation and rheological properties lags behind, with insufficient customization degree.

3. Summary

This paper systematically reviews the research status and development trajectory of inner wall finishing and polishing technology for slender-hole parts. Focusing on abrasive flow polishing technology, it comparatively analyzes the research progress and technical characteristics at home and abroad from four dimensions: machining mechanism, process optimization, composite field enhancement, and equipment industrialization. The research shows that abrasive flow polishing has become the mainstream technical route for ultra-precision machining of slender hole inner walls due to its unique advantages of no cutting force deformation and adaptability to complex inner cavities and large depth-to-diameter ratio structures. Scholars at home and abroad have achieved fruitful results in the rheological properties of abrasive media, the influence law of process parameters, and the axial uniformity control of channels. The development of new processes such as ultrasonic assistance, magnetic field assistance, and electrochemical compounding has further expanded its machining boundary and performance upper limit.

However, there are still three core shortcomings in current research: the control mechanism of axial machining uniformity for slender holes with large depth-to-diameter ratios is still unclear, the supply of independent high-end finishing equipment and core components is insufficient, and the research on the formulation and rheological properties of customized abrasive media lags behind. In the future, abrasive flow polishing technology for slender holes will evolve towards intelligent closed-loop machining, micro-nano scale adaptation, green medium development, and multi-field composite strengthening. Relevant research can provide theoretical reference and technical support for the selection of precision machining technology and process innovation of slender hole parts in aerospace, hydraulic transmission and other fields.

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