Editorial

Sustainable Machining for Difficult-to-Cutting Materials

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Under the international strategic framework for addressing the global carbon neutrality goal, green manufacturing technology has become a core issue in the development of modern industry. As an important thermal management method in the metal processing process, the application of cutting fluids can effectively control the temperature in the processing area and prevent thermal damage to the workpiece. However, the environmental problems brought about by the traditional formula of cutting fluids have become increasingly prominent. According to statistics, more than 4 million tons of cutting fluids mainly based on mineral oil are consumed globally each year. These non-renewable resource derivatives not only increase the ecological burden but also pose a serious challenge to the sustainable development of the manufacturing industry. Minimal quantity lubrication (MQL) as an innovative solution can reduce the consumption of cutting fluids by more than 90% and has been preliminarily verified and gradually replaced traditional flood cooling lubrication. However, the characteristic of MQL technology relying solely on air cooling for heat dissipation makes it perform well in low specific energy processing of common materials but difficult to cope with high energy density processing scenarios. Especially in the precision processing of difficult-to-machine materials (including high-toughness metals such as nickel-based high-temperature alloys/titanium alloys, hard and brittle materials such as engineering ceramics, and multi-component composite structural materials) widely used in strategic fields such as aerospace and marine engineering, MQL technology still faces the bottleneck of insufficient heat transfer efficiency. To break through this technical barrier, several innovative research directions have emerged in the academic community in recent years: including nano-biological MQL lubricants, multi-physical field (ultrasonic field, electromagnetic field, magnetic field) collaborative processing, laser-assisted processing technology, and micro-textured tools and grinding wheels surface engineering technology. These cutting-edge technologies improve the processing energy efficiency ratio through interdisciplinary methods and show significant advantages in improving processing quality and suppressing process defects. Based on this, the author team has specially planned a special issue on "Sustainable Machining for Difficult-to-cutting Materials", focusing on exploring key scientific issues such as the penetration and film formation mechanism of biological lubricants, the material removal mechanism of multi-energy field-assisted processing, and the preparation process of micro-textured tools and grinding wheels, aiming to provide theoretical support and technical solutions for the green manufacturing of strategic emerging materials.

From the perspective of multi-energy fields, methods such as low-temperature cold air, magnetic fields, and ultrasonic vibration can effectively enhance processing performance. However, the atomization performance of MQL technology is relatively poor, which has a certain impact on the heat transfer performance of the lubricant. Therefore, auxiliary technologies can be employed to enhance the cooling and heat transfer capabilities of the lubricant. Liu's group [1] based on the Rehbinder effect theory, investigated the processing performance of cold plasma jet (CPJ) assisted micro-milling of 30CrMnSiNi2A high-strength steel. The effects of CPJ-assisted processing, dry processing, and nitrogen-assisted processing were compared. Through single-crystal diamond scratch tests and orthogonal micro-milling experiments, the influence of CPJ on material removal behavior, cutting force, and surface quality was analyzed. The experimental results showed that CPJ reduced the surface energy of the material through active particles, promoting brittle fracture, and increasing the material removal efficiency from 0.433 to 0.895 under a 400 mN load. Under the

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optimal processing parameters, the cutting forces F_z, F_x and F_y in CPJ-assisted micro-milling are reduced by 26.5%, 24.8% and 31.3%, the surface roughness *Sa* reduced by 19.3%, and plastic flow and burrs were effectively suppressed. The research confirmed that CPJ-assisted processing can significantly improve the processing efficiency and surface quality of high-strength steel, providing a new method for ultra-precision manufacturing. Sun's group [2] investigated the shear stress prediction problem of high volume fraction (30–40%) magnetorheological fluids (MRFs) based on the dipole interaction theory and the classical single-chain model. The study compared the traditional single-chain model with the newly proposed distance-weighted correction model. Through Monte Carlo simulation and energy barrier analysis, the performance of the models under different volume fractions and magnetic field intensities was verified. The experimental results showed that the new model significantly reduced the prediction error by introducing distance-weighted parameters, dynamic chain reconfiguration mechanisms, and lateral magnetic field overlap corrections. The root mean square error (RMSE) of shear stress decreased from 27.40 kPa to 7.76 kPa (a reduction of 71.7%), and the R-square value increased from −0.9236 to 0.8457. The research revealed the amplification effect of lateral magnetic field overlap caused by chain aggregation on shear stress and confirmed that local dipole rearrangement dominates the macroscopic rheological response, providing a theoretical basis for the design and engineering application of high-concentration magnetorheological fluids. Zhu's group [3] systematically reviewed and analyzed the current application status of ultrasonic vibration-assisted grinding technology in the processing of advanced materials. It provides a detailed introduction to ultrasonic processing, covering its basic principles, ultrasonic vibration systems, classification of ultrasonic vibrations, processing characteristics and effects of ultrasonic processing, aiming to offer theoretical insights and practical references for future research and engineering applications.

In terms of the removal mechanism of difficult-to-process materials, the dynamic tool wear caused by coupling thermal interaction and the integrity deterioration of machining interface have become the key problems restricting the improvement of process performance. In-depth analysis of the co-regulation mechanism of micromechanical response characteristics and surface shape during material removal is the core scientific problem of constructing an integrated grinding process system with high precision, high efficiency, low energy consumption and low carbon emissions, and has important engineering value for promoting the development of green precision manufacturing technology. Li's group [4] proposed grinding force prediction models for bone, bioinert ceramics and bioalloys based on different material removal mechanisms. The application and experimental verification of the grinding force prediction model are summarized. It explores the influence and mapping relationship between different machining parameters. To provide theoretical guidance and support for improving the processing quality of bone tissue and its alternative materials during grinding. Sun's group [5] explored in depth the mechanism leading to grinding heat generation and its related heat transfer mechanism, and analyzed the motion mechanism, modal analysis and grinding force mechanism of the double-end grinding process. Then finite element method was used to solve the instantaneous temperature field during the grinding process. The micro and macro profile height of machined workpiece surface is measured and analyzed. The research can determine the optimum process parameters of the processing technology. This in turn improves the efficiency of machining and the consistency of the product.

From the analysis of lubricant preparation, the nano-fluid lubricant can effectively improve the friction performance and processing capacity. Huang's group [6] synthesized two graphene oxide (GO) based nanosuspensions by dispersing GO nanosheets into water or diamond nanoparticles into GO aqueous solutions via ultrasonic waves. The tribological and processability of developed GO and diamond-GO nanosuspensions in silicon single crystal grinding and polishing of C and silicon surface silicon carbide single crystal were evaluated. The processing mechanism involved in these processes is revealed.

Through the statistical analysis of the literature in the field of machining, tool surface wear prediction and workpiece surface roughness optimization are the current research hotspots. Based on bibliometrics, Li's group [7] studied trends in the application of digital twins and artificial intelligence in machining. By comparing 464 articles in the Web of Science database from 2018 to 2024 and using VOSviewer to visualize the data, it is found that the number of relevant studies has increased significantly since 2018 (up to 80 in 2024). China (49.78%), India (14.44%) and the United States (10.13%) were the top three countries in terms of number of publications. The results show that the research heat in this field continues to increase, and tool wear prediction, surface roughness optimization and energy efficiency are the core research directions.

Zhu's group [8] synthesizes and critically discusses the advantages and limitations inherent in the research findings, while constructing a model-control-vibration suppression closed-loop optimization system designed to facilitate ultra-precision vibration control of wafer handling robots under highly dynamic operating conditions. By clarifying the bottlenecks that exist in existing technologies and the trajectory of future interdisciplinary integration, this work provides theoretical support for the intelligent development of wafer processing robots and facilitates the rapid and reliable development of wafer transfer systems.

In summary, the intervention of low temperature, multi energy fields, nanoparticles, etc. can effectively improve the cutting and grinding performance of difficult-to-cutting materials, providing theoretical guidance and technical support for high-performance manufacturing of difficult-to-machine materials

Declaration of Competing Interest

The authors declare that they have no known competing financial interests.

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