

Advances in Robot-Assisted Gas Bag Polishing for Precision Manufacturing

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Abstract - The increasing demand for high-precision components in aerospace, automotive, biomedical, mould and die, and optical industries has intensified the need for advanced polishing technologies capable of producing superior surface quality on complex free-form surfaces. Conventional polishing methods are often labor-intensive, time-consuming, and highly dependent on operator expertise, resulting in inconsistent surface finishes and limited process repeatability. Robot-assisted polishing has emerged as a promising solution by offering enhanced automation, precise motion control, and consistent polishing performance. Among the various compliant polishing techniques, gas bag polishing has gained significant attention due to its flexible contact characteristics, ability to conform to complex geometries, and capability to maintain uniform contact pressure during polishing. This paper reviews the recent advancements in robot-assisted gas bag polishing, including its working principle, abrasive particle behavior, magnetorheological and magnetic abrasive gas bag polishing, pulse-assisted polishing, and related flexible polishing technologies. Furthermore, the review highlights the influence of process parameters, compliance control, and tool design on polishing performance. Finally, current research challenges and future directions, including intelligent force control, artificial intelligence-based process optimization, digital twin technology, and adaptive robotic polishing systems, are discussed to provide insights into the future development of precision manufacturing technologies.

Key Words: Robot-assisted polishing, Gas bag polishing, Free-form surfaces, Precision manufacturing, Flexible polishing, Magnetorheological polishing, Surface finishing, Process optimization.

1. INTRODUCTION

The increasing demand for high-quality surface finish in industries such as aerospace, automotive, biomedical, mould and die, and precision engineering has driven the development of advanced polishing technologies. Many engineering components possess complex free-form surfaces that require excellent surface integrity, dimensional accuracy, and low surface roughness for improved functional performance. However, conventional manual polishing is labor-intensive, time-consuming, and highly dependent on operator skill, making it difficult to achieve consistent polishing quality on complex geometries.

Robot-assisted polishing has emerged as an effective alternative by providing accurate tool-path control, improved repeatability, and automated operation. Among various compliant polishing techniques, gas bag polishing has attracted considerable attention due to its flexible rubber gas bag, which

conforms to the workpiece surface and maintains uniform contact pressure during polishing.

This compliant behavior enables efficient polishing of free-form surfaces while minimizing surface damage and improving surface finish. This paper presents a concise review of recent advances in robot-assisted gas bag polishing, focusing on its working principle, recent technological developments, related flexible polishing techniques, current challenges, and future research directions for precision manufacturing applications.

2. WORKING PRINCIPLE OF ROBOT-ASSISTED GAS BAG POLISHING

Robot-assisted gas bag polishing is a compliant surface finishing technique designed for polishing complex free-form surfaces with high accuracy and consistency. The system typically consists of an industrial robot, a gas bag polishing tool, a controller, an air supply system, and a polishing slurry containing free abrasive particles, as shown in Fig. 1. The polishing tool incorporates a flexible rubber gas bag that is inflated with compressed air, enabling it to conform to the local curvature of the workpiece. The industrial robot guides the polishing tool along a predefined trajectory while maintaining the desired contact force and orientation throughout the polishing process.

The flexible gas bag acts as a compliant interface between the polishing tool and the workpiece. Pneumatic pressure inside the gas bag provides the necessary stiffness and controls the contact pressure at the polishing zone. A slurry containing free abrasive particles, such as diamond abrasives, is continuously supplied between the gas bag and the workpiece surface. During polishing, the abrasive particles become trapped within the contact region and remove material through micro-cutting, micro-ploughing, and rolling actions. Owing to the elastic deformation of the gas bag, the contact area automatically adapts to variations in surface geometry, resulting in uniform pressure distribution, reduced surface damage, and improved polishing quality.

The robot executes precise tool motions, including spindle rotation and feed movement, to ensure uniform material removal over the entire surface. By controlling polishing parameters such as spindle speed, feed rate, contact pressure, and abrasive size, robot-assisted gas bag polishing can achieve excellent surface finish while maintaining high repeatability and process stability. These characteristics make the technique particularly suitable for precision polishing of free-form components used in aerospace, mould and die, biomedical, and optical manufacturing. Abrasive particles remove material through two primary mechanisms: sliding, which causes micro-cutting and micro-ploughing, and rolling, which induces micro-fatigue and micro-cracking. The combined action of these mechanisms enables controlled material removal while producing a smooth surface with minimal subsurface damage.

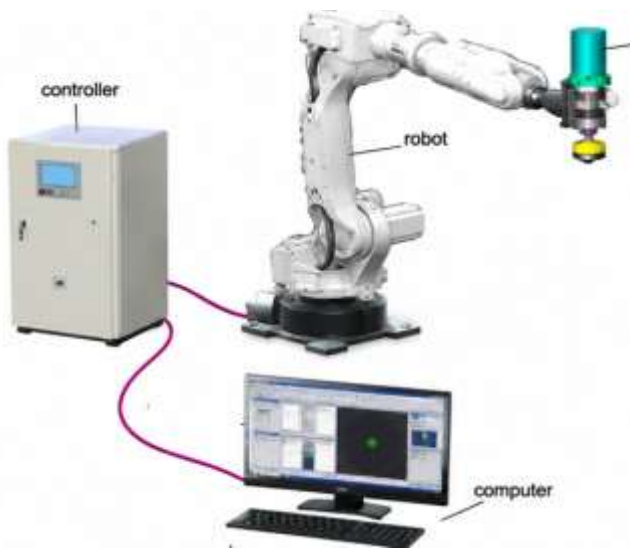


Fig -1: Schematic diagram of a robot-assisted gas bag polishing system

3. FLEXIBLE POLISHING TECHNOLOGIES

Several flexible polishing technologies have been developed to overcome the limitations of conventional rigid polishing tools for machining complex free-form surfaces. Among these, pneumatic wheel polishing, bonnet polishing, magnetic polishing, and gas bag polishing are the most widely investigated due to their excellent compliance and ability to produce high-quality surface finishes.

Pneumatic wheel polishing employs an air-inflated elastic wheel embedded with abrasive particles, allowing the polishing tool to conform to varying surface curvatures while maintaining relatively uniform contact pressure. This technique offers good polishing efficiency and is particularly suitable for moulds and free-form surfaces. However, abrasive wear and degradation of the wheel binder may affect polishing consistency over prolonged operation.

Bonnet polishing utilizes a flexible spherical membrane inflated with compressed air to generate a compliant polishing interface. The bonnet continuously adapts to local surface geometry, enabling deterministic material removal with excellent surface quality and dimensional accuracy. Owing to its high precision, bonnet polishing is extensively used for finishing optical components, moulds, and aspheric surfaces, although it generally requires sophisticated tool-path planning and process control.

Magnetic polishing, including magnetic abrasive finishing and magnetorheological polishing, employs magnetic fields to control abrasive particles within a polishing medium. The magnetic field forms a flexible abrasive brush or stiffens the polishing fluid, resulting in stable contact conditions, improved material removal, and nanometer-level surface finish. Despite its superior polishing quality, the technique involves relatively complex equipment and higher operational costs.

Among these methods, gas bag polishing combines the advantages of flexibility, simplicity, and robotic automation. The inflatable rubber gas bag provides excellent compliance, enabling uniform contact pressure over complex free-form surfaces while free abrasive particles perform controlled material removal.

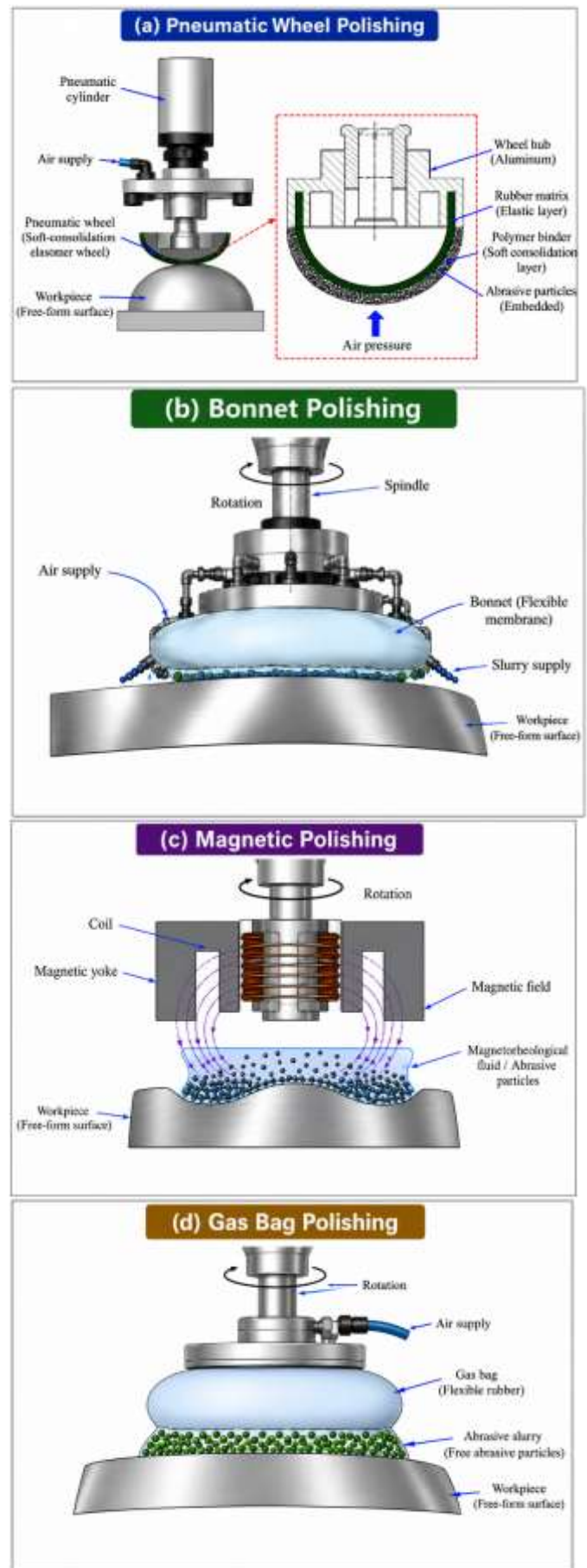


Fig -2: Free Form surface polishing techniques

Compared with other flexible polishing techniques, robot-assisted gas bag polishing offers lower tooling cost, greater

adaptability to different workpiece geometries, and easier integration with industrial robotic systems. These advantages make it a promising polishing technique for precision manufacturing applications, particularly in aerospace, automotive, mould and die, and biomedical industries.

4. CHALLENGES AND FUTURE RESEARCH

Despite significant advancements, several technical challenges remain in robot-assisted gas bag polishing that limit its widespread industrial adoption. One of the primary challenges is achieving precise force control, as maintaining a constant contact pressure on complex free-form surfaces is essential for uniform material removal and superior surface quality. Variations in surface curvature and tool deformation often result in inconsistent polishing performance. Therefore, advanced force-control strategies, such as impedance and adaptive force control, are required to enhance process stability.

The integration of artificial intelligence (AI) and machine learning offers promising opportunities for intelligent polishing systems capable of automatically optimizing process parameters and predicting polishing outcomes. Similarly, the development of digital twin technology can enable real-time monitoring, simulation, and optimization of the polishing process, thereby reducing trial-and-error experimentation and improving manufacturing efficiency. Machine vision systems combined with in-process sensors can facilitate automatic defect detection, workpiece localization, and online inspection of surface quality.

Future research should also focus on adaptive tool-path optimization to improve polishing efficiency on complex free-form geometries while minimizing cycle time. Adaptive pressure control based on real-time feedback can ensure uniform contact conditions throughout the polishing process. Furthermore, the development of hybrid gas bag polishing techniques, incorporating magnetorheological fluids, magnetic abrasive brushes, ultrasonic vibration, or compliant pneumatic tools, has the potential to enhance both material removal rate and surface finish. In addition, real-time surface roughness prediction using sensor data and data-driven models will enable closed-loop polishing systems capable of autonomously adjusting process parameters. The convergence of these technologies with smart industrial robots and Industry 4.0 frameworks is expected to transform robot-assisted gas bag polishing into a highly intelligent, autonomous, and efficient precision manufacturing process.

5. CONCLUSIONS

Robot-assisted gas bag polishing has emerged as a promising flexible polishing technology for precision manufacturing, particularly for complex free-form surfaces. Its compliant polishing mechanism enables uniform contact pressure and improved surface quality compared with conventional rigid polishing methods. Recent developments, including magnetorheological and magnetic abrasive gas bag polishing, have significantly enhanced material removal efficiency, polishing stability, and surface finish. Although considerable progress has been achieved, maintaining accurate contact force and pressure remains a critical challenge for achieving consistent polishing performance on complex geometries. Future advancements are expected to focus on intelligent force control, AI-based process optimization, digital twin technology, machine vision, and real-time surface roughness

prediction. The integration of these technologies with smart robotic systems will enable autonomous, adaptive, and highly efficient polishing processes, making robot-assisted gas bag polishing a key technology for next-generation precision manufacturing applications.

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