Mechanism and Study on Ball End Magnetorheological Fluid Finishing Process

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Abstract:
The primary object of this research is to explore the capacities of BEMRF. Traditional polishing methods for glass commonly face challenges in reaching nanoscale precision and uniformity. In BEMRF, by controlling rheological properties of the MR fluid, we can tackle these challenges and potentially surpass the limitations of conventional techniques. The study includes the application of magnetorheological (MR) fluid with suspended magnetic particle abrasives to accomplish precision finishing by the manipulation of magnetic fields.

Keywords: Ball End Magnetorheological Finishing (BEMRF), MR fluid, Magnetic Particle Abrsaives

1. Analysis on BEMRF Technique

Ball-end magneto-rheological finishing (BEMRF) is a cutting-edge method of refining surfaces that employs intelligent fluids to regulate the forces involved in finishing. This allows for extremely precise finishing down to the nanometer scale on a variety of surfaces, all while avoiding any potential damage. It's designed to work on flat, contoured, and intricate 3D surfaces, ensuring exact surface topography across different materials. BEMRF has proven to be effective in minimizing surface roughness and enhancing material removal rates, making it a valuable technique in the finishing process.

Studies have concentrated on understanding how materials are removed during the BEMRF process, emphasizing the influence of magnetorheological fluids in managing finishing forces and attaining superior surface quality. Additionally, research has delved into creating tailored polishing fluids to elevate the nanofinishing of materials such as copper, showcasing the flexibility and suitability of BEMRF across various uses.

Moreover, research has been carried out to analyze the parameters and assess the performance of the BEMRF process, focusing on its capability to attain accurate surface finishes and manage residual stresses. The introduction of automated CNC systems for BEMRF has facilitated the nanofinishing of intricate 3D surfaces with tailored controllers, demonstrating the prospect of achieving meticulous finishing in manufacturing contexts.

In summary, BEMRF stands as an innovative technology within finishing processes, providing a blend of precision, control, and adaptability to attain superior surface finishes across different materials. Through the utilization of magnetorheological fluids and advanced polishing methods, BEMRF holds the promise of transforming surface finishing practices across diverse industries.

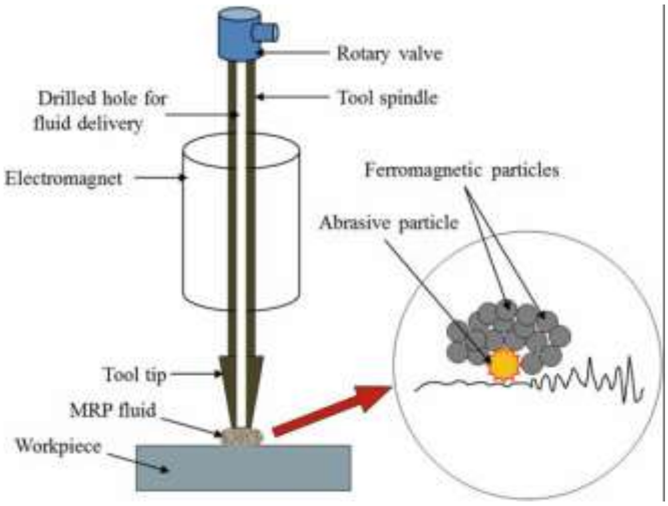


Fig.1. BallEnd MRF model

2. Some limitations on Ball End Magneto Rheological Finishing

Traditional techniques used for finishing semiconductor wafers, lenses, and ceramics are both labor-intensive and challenging to control, in addition to being costly. One of the primary challenges in manufacturing highly precise lenses lies in their composition, often being made of glass—a brittle material prone to cracking during machining. Even a minuscule crack can significantly impair the functionality of the lens, rendering it entirely ineffective for its intended application.

The MRF process stands out as an innovative precision polishing technique capable of refining flats, spheres, and aspheres [1]. It employs a specialized stiffened magnetorheological (MR) polishing fluid, consisting of micron-sized Carbonyl Iron Particles (CIP) and non-magnetic abrasives uniformly dispersed in a carrying medium along with additives. Operating as a sub-aperture process, MRF achieves remarkable precision, reaching accuracies of 30 nm peak to valley and surface roughness below 1 nm on various optical glasses, glass ceramics, and hard crystals [2] . However, its application is limited to specific geometries such as concave, convex, flat, and aspherical shapes due to constraints on relative movement between the finishing medium and workpiece.

To address these constraints, a new precision finishing method called ball end Magnetorheological finishing (Ball end MRF) has been developed for nano-finishing flat and 3D surfaces of both magnetic and non-magnetic materials [2]. In this technique, a small hemispherical ball-shaped MR polishing fluid is formed at the tool tip through variations in the magnetic field, which is then utilized to abrade the material from the workpiece. Controlled by a computer-controlled 3-axis motion controller, this process exhibits potential applications in various industries including automotive, aerospace, mold manufacturing, semiconductor, and optics machining.[3]

Mori [4] investigated the magnetic field dynamics and acting forces, offering a foundational understanding of the process mechanism in Magnetic Abrasive Finishing (MAF). They elucidated the formation of the magnetic abrasive brush, emphasizing the energy involved in brush formation. Kim and Choi [5] devised a surface roughness model for the MAF process, aiming to predict the finishing time required for removing existing scratches. Their model, rooted in micro cutting mechanisms, assumes a uniformly profiled workpiece surface without statistical distributions of initial surface roughness, with abrasives moving along the length of the scratches. Jha and Jain [6] proposed a model for the arrangement of Carbonyl Iron Particles (CIP) chains based on microscopic observations, analyzing the potential configurations of CIP and abrasives of varying sizes within the MR polishing fluid. Their simulations underscored the significant role of the CIP-to-abrasive ratio in determining final surface roughness in the Magnetic Abrasive Flow Finishing (MRAFF) process. Sidpara and Jain [7],[8] introduced a theoretical model detailing the normal and tangential forces acting on the workpiece during MR fluid-based finishing, corroborating it through experimental validation. They further presented two distinct theories to characterize the influence of abrasive particle concentration in the MR polishing fluid, calculating normal and tangential forces while accounting for centrifugal and Coriolis forces, respectively.

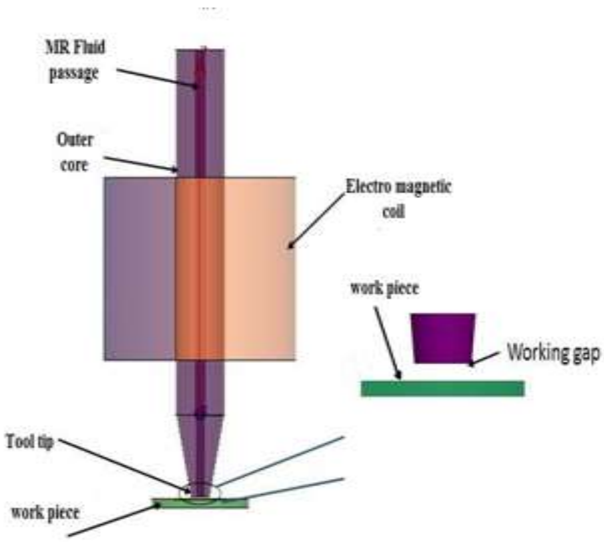


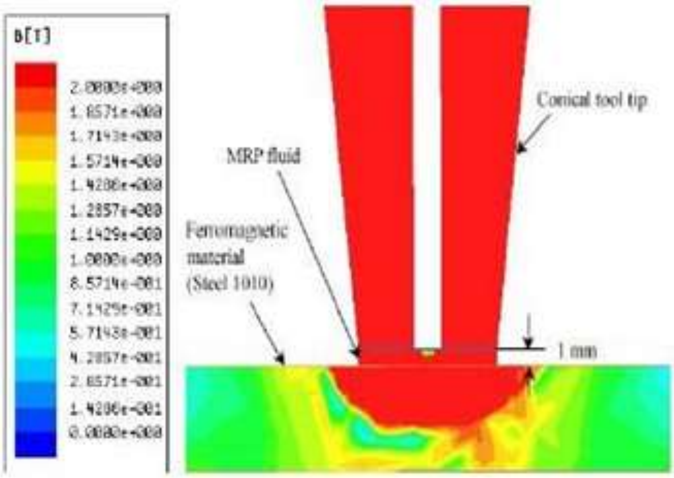
Fig.2. Finite element model of Ball endMRF

2.1 Some more studies on BEMRF process

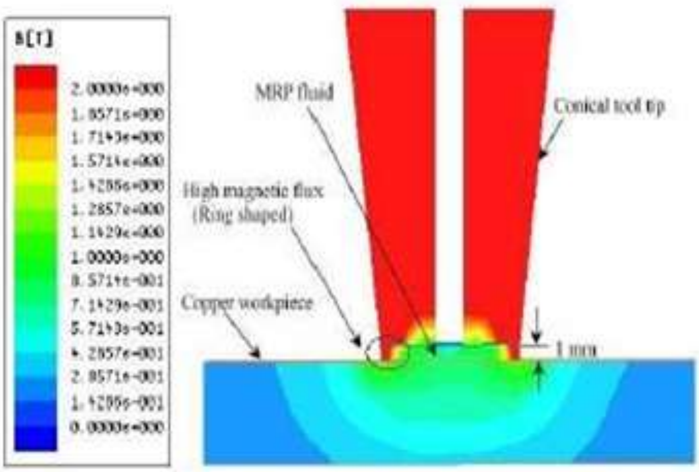
In a separate study by Khan et al.[9] focusing on copper as the workpiece material, magnetic simulations revealed a significant and irregular decline in magnetic flux density during the BEMRF process. Moreover, Singh et al.[10] observed that the inclusion of a center hole inside the rotating core, facilitating the flow of MR fluid in the Ball-end Magneto-Rheological Finishing (BEMRF) setup, resulted in a non-uniform magnetic flux density at the tool tip. This non-uniformity could potentially lead to variations in surface roughness during spot finishing. Since copper is non-magnetic, unlike magnetic materials with two poles, only one magnetic pole formed between the tool tip and the workpiece surface, causing the decrease in magnetic flux density. A slight improvement in magnetic flux density was observed over a copper workpiece surface when supported by a mild steel base, but a more substantial enhancement was achieved by placing a layer of a permanent magnet beneath the copper workpiece. This enhancement in magnetic flux density with the presence of a permanent magnet was experimentally validated using a gauss meter.

In order to ensure consistent magnetic flux density at the tip of a rotating finishing tool, essential for achieving uniform surface finishes during spot finishing operations on precision components, researchers replaced the rotating core with a solid version devoid of a central hole. A comparative analysis was conducted to assess the magnetic flux density when using the solid rotating core versus the one with a central hole. Finite element analysis results revealed that the magnetic flux density at the end surface of the solid rotating core tool was more uniform compared to its counterpart with a central hole (see Figure 4a & 4b)[11]. This uniform magnetic field across the entire end surface of the solid rotating core facilitated uniform strength of the MR polishing fluid, ensuring consistent application of magnetic normal force during spot nano-finishing on the workpiece surface.

In the BEMRF process, manual removal and cleaning of the workpiece are required to calculate surface roughness. However, to automate this process, it's essential to automatically remove the MR fluid adhering to the workpiece surface after finishing, enabling automatic measurement of surface roughness. Iqbal et al.[12] attempted to develop an automated system for cleaning the workpiece to facilitate surface roughness measurement for feedback control of the BEMRF process. This automation involved three phases: designing a cleaning strategy, developing the cleaning system, and automating the cleaning process. Various tests were conducted to design the cleaning strategy, including air spray, water jets, surfactant solutions, and kerosene jets for workpiece cleaning.

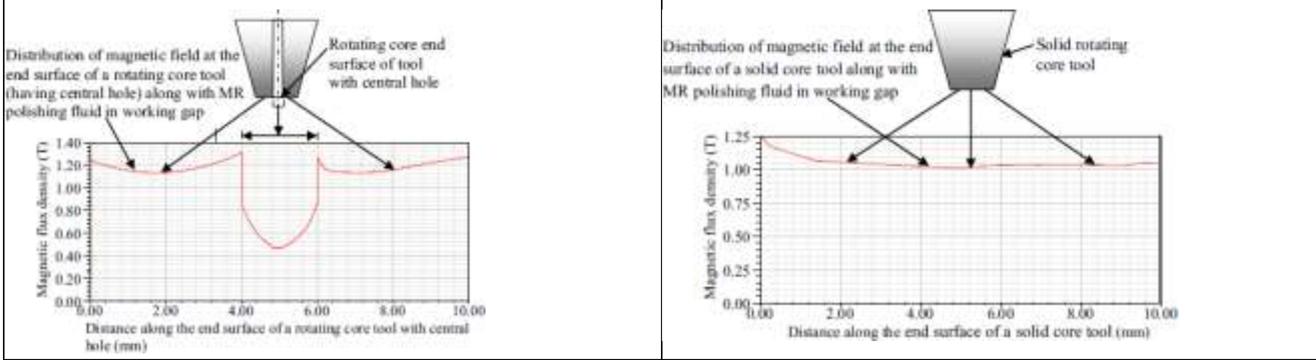


(a)



(b)

Fig. 3 Magnetic flux density distribution for (a) ferromagnetic material and (b) copper [13]



(a)	(b)

Fig. 4 Distribution of magnetic field at the end surface of (a) rotating core tool with central hole and (b) solidrotating core tool [11]

Kumar et al.[13] conducted both analytical and experimental investigations to examine the impact of Magnetorheological (MR) fluid composition and finishing duration on the Ball-end Magneto-Rheological Finishing (BEMRF) of polyactic acid (PLA) workpiece material. The PLA workpiece, generated through fused deposition modeling (FDM), underwent preliminary finishing using conventional facing and lapping processes. During the study, three types of abrasives—Alumina (Al2O3), Silicon carbide (SiC), and Boron carbide (B4C)—were mixed with Electrolytic iron particles (EIPs) and water as the base fluid. Alumina (Al2O3) was identified as the most suitable abrasive for finishing PLA workpiece material. Experimental findings revealed that the percentage change in surface roughness (%ΔRa) initially increased with an increase in abrasive concentration in the MR polishing (MRP) fluid, but beyond a certain concentration, it started to decrease due to the elevated number of cutting particles hindering the finishing process. Moreover, an increase in EIP concentration in the MRP fluid led to an increase in %ΔRa, as EIP played a crucial role in the magnetorheological effect, enhancing the fluid's magnetic properties and improving abrasive particle grip during finishing. An optimized composition of the MRP fluid, comprising 16.7 vol% abrasives, 25 vol% EIP, and 58.83 vol% distilled water, was determined for finishing PLA workpiece material.

In a separate study, Garg et al. [14] utilized Comsol Multiphysics to model and analyze the influence of a strong magnetic field on the flow behavior of MR fluid in the BEMRF process. Simulation analysis revealed that the MR fluid stiffened at the tool tip, forming an almost hemispherical shape due to the concentration of magnetic flux density, providing the necessary stiffness for polishing various materials. The intensity of the magnetic field at the tip was observed to depend on factors such as magnetizing current, number of copper turns, magnetic permeability of the MR fluid, and iron core.

Furthermore, Singh et al.[15] explored the effect of different mesh sizes and volume percentage contributions of abrasives in MR fluid on the surface roughness of ferromagnetic materials using the BEMRF process. They employed Silicon carbide abrasives with mesh sizes ranging from 400 to 1200 and volume percentages ranging from 5 to 25 vol%. The MR fluid, comprising 20 vol% CIP particles and mineral oil as the base fluid, exhibited varying volume percentages depending on the abrasives used. Results indicated that the percentage change in roughness value decreased with an increase in abrasive mesh size, while it increased with an increase in percentage volume contribution. An optimal composition of the MR fluid was identified through analysis, resulting in a surface finish value of 82 nm from an initial value of 214 nm under specified machining conditions.

A study that focussed at the reduction of surface roughness using the BEMRF process is conducted during the finishing of EN-31 steel. The optimization of machining parameters, including magnetizing current, working gap, and spindle speed, was carried out using a 3-factor central composite design technique.[16] Each selected parameter set underwent a fixed finishing cycle of 40 minutes, with surface roughness measured after each cycle. The study established a transient phenomenon of surface roughness reduction in the BEMRF process, noting that the effectiveness of certain parameter sets diminishes over time.

Additionally, Alam et al.[17] investigated the effects of polishing fluid composition on finishing forces, specifically normal and shear forces. They varied the volume percentages of magnetic and non-magnetic abrasives in the MR polishing fluid across different samples. Experimental results obtained during the finishing of mild steel using the BEMRF process revealed that increasing the concentration of magnetic Carbonyl Iron Particles (CIPs) in the MR fluid led to an increase in both normal and shear forces. This was attributed to the higher magnetic permeability of the MR fluid resulting from a higher volume percentage of CIPs, which increased viscosity when electrically energized.

On the other hand, as the concentration of non-magnetic abrasives in the MR fluid increased, the magnitude of forces initially rose before declining after a certain threshold. This trend may be explained by the initial filling of voids between CIP chains by the abrasives, strengthening the chain structure of the MR fluid. However, beyond a certain concentration of abrasives, hindrance to chain formation occurred, leading to an increased number of broken chains and subsequently decreasing force magnitudes during finishing.

3. Surface Finish Modeling

For the analysis of material removal and surface finish in Ball end MRF process of EN material, the following assumptions are considered.

- In practical scenarios, the assumption of all Carbonyl Iron Particles (CIPs) and abrasives being of uniform size and uniformly distributed in the Magnetorheological Polishing (MRP) fluid to create a uniform body-centered chain structure may not hold true.
- While the shape of abrasives and CIPs is typically assumed to be spherical, microscopic observations reveal that they often have rounded shapes with irregularities and lack sharp cutting edges.
- Each abrasive grain is considered to have a single effective cutting edge; if multiple cutting edges exist on one grain, there may not be enough space for chips to accumulate between them.
- It is assumed that every abrasive grain achieves the same penetration depth under the applied force for a given workpiece material.
- When there is interference between abrasive grains and the workpiece, material removal is presumed to occur through indentation and translation of abrasive grains on the workpiece surface. This mode of material removal is assumed to simplify the analysis.

4. RESULTS AND CONCLUSION

- As the gap between the workpiece and the core, known as the working gap, widens, the magnetic field intensity decreases, as they are inversely proportional. Consequently, the percentage variation in surface roughness diminishes with an increase in the gap between the tip surface of the tool core and the workpiece surface. With a greater working gap, the magnetic field intensity of Carbonyl Iron Particles (CIP) in the finishing spot of the MR polishing fluid decreases, leading to a reduction in the abrasive holding pressure of CIP chains and consequently resulting in decreased finishing action.

- As the magnetizing current rises, there is a corresponding increase in the percentage variation in surface roughness. This is because with higher current supplied to the electromagnetic coil, the magnetic field intensity of Carbonyl Iron Particles (CIP) in the finishing spot of the MR polishing fluid escalates. Consequently, CIP chains grip abrasives more securely, leading to an intensified finishing action.
- Bimodal Magnetorheological (MR) polishing fluids have the potential to enhance the surface finish of diverse materials. Yet, there is a lack of extensive research regarding the finishing of non-magnetic materials using bidisperse MR fluids.
- The current research indicates that the Ball-end Magneto-Rheological Finishing (BEMRF) process is employed to achieve exceptionally high-quality surface finishes on a wide range of workpiece materials. Furthermore, it is noted that the magnetic field intensity plays the most significant role in influencing the yield stress and viscosity of the Magnetorheological (MR) fluid.
- While the majority of research attention is directed towards the finishing of metals or non-metals utilizing the BEMRF process, there is a notable lack of studies concerning the finishing of composite materials.

REFERENCES

1. W. Kordonski and D. Golini, "development update in magnetorheological completing," worldwide journal of contemporary Physics B, vol. 13, no. 14n16, pp. 2205-2212, 1999.
2. A. Kumar Singh, S. Jha, and P. M. Pandey, "design and improvement of nanofinishing technique for 3D surfaces the use of ball stop MR finishing tool," global magazine of system tools and Manufacture, vol. 51, no. 2, pp. 142-151, 2// 2011.
3. A. k. Singh, S. Jha, and P. M. Pandey, "Magnetorheological Ball end completing technique," substances and production approaches, vol. 27, no. four, pp. 389-394, 2012/04/01 2011
4. T. Mori, ok. Hirota, and Y. Kawashima, "rationalization of magnetic abrasive completing mechanism," magazine of materials Processing generation, vol. 143, pp. 682-686, 2003.
5. J.-D. Kim and M.-S. Choi, "Simulation for the prediction of surface-accuracy in magnetic abrasive machining," magazine of substances processing era, vol. 53, no. 3, pp. 630-642, 1995.
6. S. Jha and V. k. Jain, "Modeling and simulation of floor roughness in magnetorheological abrasive flow completing (MRAFF) procedure," wear, vol. 261, no. 7–eight, pp. 856-866, 2006
7. A. Sidpara and V. okay. Jain, "analysis of forces on the freeform floor in magnetorheological fluid primarily based completing technique," worldwide journal of system tools and Manufacture, vol. sixty nine, pp. 1-10, 2013
8. A. Sidpara and V. K. Jain, "Theoretical analysis of forces in magnetorheological fluid based finishing method," international journal of Mechanical Sciences, vol. fifty six, no. 1, pp. 50-fifty nine, 2012
9. Khan, D. A., Kumar, J., & Jha, S., Magneto- rheological nano-completing of polycarbonate, international journal of Precision generation, Vol. 6, No. 2, 2016, pp. 89-a hundred.
10. Singh, A. K., Jha, S., & Pandey, P. M., layout and improvement of nanofinishing method for 3-D surfaces the usage of ball stop MR finishing tool, worldwide magazine of device gear and Manufacture, Vol. fifty one, No. 2, 2011, pp. 142-151.
11. Khurana, A., Singh, A. K., & Bedi, T. S., Spot nanofinishingn the usage of ball nostril

magnetorheological strong rotating center tool, The global magazine of advanced manufacturing technology, Vol. 92, No. (1-4), 2017, pp. 1173-1183.

12. Iqbal, F., Rammohan, R., Patel, H. A., & Jha, S., layout and improvement of computerized workpiece cleaning device for ball end magneto-rheological finishing manner, In international conference on Advances in substances & manufacturing, 2016, pp. 289-295.
13. Kumar, A., Alam, Z., Khan, D. A., & Jha, S., Nanofinishing of FDM-fabricated components the use of ball stop magnetorheological finishing process, substances and production methods, Vol. 34, No. 2, 2019, pp. 232-242.
14. Garg, H., Negi, V. S., Kharola, A. S., & Sharma, R., effect of Magnetic discipline on MR-Fluid in Ball cease Magnetorheological completing, In COMSOL convention, 2014.
15. Singh, A. k., Jha, S., & Pandey, P. M., overall performance analysis of ball cease magnetorheological finishing manner with MR polishing fluid, materials and manufacturing procedures, Vol. 30, No. 12, 2015, pp. 1482- 1489.
16. Iqbal, F., & Jha, S., Experimental investigations into temporary roughness reduction in ball-stop magneto-rheological completing process, substances and production methods, Vol. 34, No. 2, 2019, pp. 224-231.
17. Alam, Z., Khan, D. A., Iqbal, F., & Jha, S., impact of sharpening fluid composition on forces in ball stop magnetorheological finishing manner, international journal of Precision era, Vol. eight, No. (2-4), 2019, pp. 365- 378.