International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 - 5161

Available at http://inpressco.com/category/ijcet

Review Article

Magnetorheological Finishing: A Review

K.Saraswathamma[Å*]

[Å]Mechanical Engineering Department, Osmania University, Hyderabad, India.

Accepted 10 January 2014, Available online 01 February 2014, **Special Issue-2, (February 2014)**

Abstract

Surface quality is one of the most important properties of the precision devices. Poor surface quality of engineering products results in various problems during operations, such as malfunctioning, excessive wear, geometric inaccuracy, etc. The surface quality of a product is mostly determined during the manufacturing process. The traditional fishing process does not offer a flexible, cost effective option for finishing small precision devices. Magnetorheological fluid assisted finishing processes are one such kind of finishing processes, which has greater flexibility towards process control and one can finish with close tolerances and without damaging surface topography. Hence, this paper gives the review of abrasive flow finishing, magnetorheological finishing(MRF), Magnetorheological jet finishing (MR Jet,)magnetorheological abrasive flow finishing(MRAFF), Magnetorhological honing(MRAH), and Ball end Magnetorheological Finishing(Ball end MRF), . This article provides a comprehensive literature review of Magnetorheological finishing process in terms experimental investigation, and rheological characterization of Magnetorheological fluid. This article deals with various advancements in MRF process and its allied processes have been discussed.

Keywords: *Precision finishing, Magnetorheologcal fluid, Magnetorheological finishing processes.*

1. Introduction

Precision finishing of internal surfaces and complex geometries is always of concern being labour intensive and difficult to control. Abrasives with small multiple cutting edges are generally employed to get desired surface finish characteristics and geometrical accuracy by removing unwanted material from the workpiece. The Traditional finishing processes such as Grinding, Lapping and Honing works on this mechanism of finishing. But due to the development of new materials which are difficult to machine and complex geometrical shapes of engineering components, the available traditional finishing processes are alone not capable of producing required surface finish and other characteristics of the product and also processing of these require wide ranging equipment’s usage and more labour.

Developments in advanced finishing processes in the last few decades have attributed to the relaxation of limitations of tool hardness requirement i.e in EDM, ECM, USM, AJM etc.. Predefined relative motion of the cutting edge with respect to the workpiece surface is a major limitation in finishing complex geometries. To overcome this limitation, the multiple cutting edges in some loosely bonded from are directed to follow the intricate geometries to be finished. But due to the lack of control over the finishing forces, these possess the limitation for finishing complex geometry and moreover sometimes these processes impart surface and subsurface damages. Many advanced finishing processes have been developed to tackle these issues. Magnetorheological fluid assisted finishing processes are one such kind of finishing processes, which has greater flexibility towards process control and one can finish with close tolerances and without damaging surface topography. Many newly developed Magnetorheological fluid assisted finishing processes make use of magnetorheological fluid (MR fluid) to externally control the finishing forces on abrasive particles. Center for optics manufacturing (COM) in Rochester, N.Y. has developed automate MRF Process for finishing lens (Kordonski and Golini 1999).Since then, more number of polishing techniques are evolved using magnetorheological fluid. Few of them are Magnetorhelogical finishing (MRF), Magnetorheological jet finishing (MRJF), Magnetorheological abrasive flow finishing (MRAFF), Magnetorheological abrasive honing (MRAH), and ball end magnetorheological finishing (ball end MRF).

This paper provides a comprehensive literature review of Magnetorheological finishing process in terms of advancements of the process, magnetorheological fluid, experimental investigation, and applications. The developments of magnetorheological finishing and its allied processes have been discussed.

2. Magnetorheological finishing(MRF)

MRF is a magnetic field assisted precision finishing

*Corresponding author: **K.Saraswathamma**

process developed and commercialised by QED Technologies Inc.(Kordonski and Jacobs 1996; Jacobs, Kordonski et al. 2000). MRF is a precision technology that may produce surface accuracy on the order of 30nm peak to valley and surface micro-roughness less than 10Å rms(Kordonski and Jacobs 1996). MRF can be used for variety of materials raging from optical glasses to hard crystals.

MRF was initiated in Minsk, Belarus by Kordonski, Prokhorov, Gorodkin, and coworkers in 1988. Then MRF process fundamentals were transferred to the Centre for Optics Manufacturing (COM) in 1994. In 1996 , MRF which was shown in fig. 1&2 was invented and commercialized at COM in 1996(Jacobs and Arrasmith 1999). In 1999, MRF was fully commercialised by QED Technologies. In MRF, the MR polishing fluid is deposited by a nozzle on the rim of a rotating wheel, which transports the fluid to the workpiece surface (fig.1a). The wheel rim and the surface to be polished form a converging gap exposed to a magnetic field. The moving wall, which is in the rim surface, generates a flow magnetically stiffened MR polishing fluid through converging gap. The magnetically stiffened MR fluid generates a unique pressure distribution in the gap that is associated with an unsheared fluid, which is attached to the moving wall (fig.1b). A quasi –solid moving boundary is effectively formed very close to the surface of the workpiece resulting in the high shear stress in the contact zone and material removal over a portion of the workpiece surface. This area is designated as polishing spot. The material removal is enhanced by nonmagnetic abrasive particles, which are constitutes of the slurry and forced out to the polishing interface by a magnetic field gradient. When the MR fluid mixed with abrasives flows over specimen surface, the shear stress of the fluid generates a drag force to move the abrasives, which results in material removal(Kordonski and Golini 1999; Kordonski and Golini 1999; Shorey, Jacobs et al. 2001)

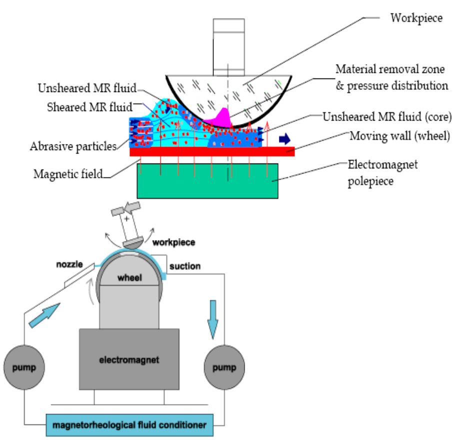

Fig1.aMagnetorheological finishing bMagnetorheological Finishing Machine (Kordonski and Golini 1999)

In MRF, the magnetic-field-dependent yield stress and viscosity of magnetorheological polishing (MRP) fluid are controlled by controlling magnetizing current in the electromagnet coils producing magnetic field across the finishing zone. The MRP fluid comprises of carbonyl iron particles (CIPs) and very fine abrasives dispersed in the carrier fluid, which exhibits unique reversible change in its rheological properties on the application and removal of external magnetic field. The carbonyl iron particles acquire magnetic dipole moment proportional to field strength and aggregate into interconnected chain-like columnar structure aligned in the field direction, embedding non-magnetic abrasive particles in between or within. The rheological characteristics and bonding strength gained by abrasive particles in presence of CIPs and magnetic field play an important role in MRF action.

QED technologies developed wheel kind of MR Finishing tool. In this the magnetorheological polishing fluid circulated continuously during the MRF process. Due to the magnetic field, the fluid adheres the periphery of the wheel. The shape of the fluid is determined by wheel speed, the magnetic field strength, gap between the workpice and wheel, and fluid flow rate(Schinhaerl, Smith et al. 2008). Researchers have tried different variants in wheel type MRF both include using permanent magnets and electromagnets. Due to the lack of the space , only few of them are discussed in this paper.

Cheng et al(Cheng, Yam et al. 2009) were introduced a novel design of polishing tool comprising of a self-rotating wheel and brass wire coils aligned to the direction of its rotating axis as shown in Fig 2. And also they presented an experimental study to determine the magnetic fluid viscosity as a function of the applied electric voltage through generation of magnetic field. They observed that viscosity would increase with the driving voltage. They also conducted experimental study using this wheel to polish K9 mirror and MR fluid composition taken as 33.84% CI particle, 57.34% silicone oil, 2.82% stabilizing agent, and 6% CeO_2. Surface accuracy is improved over three times with abrasives in the fluid compared to the without abrasives.

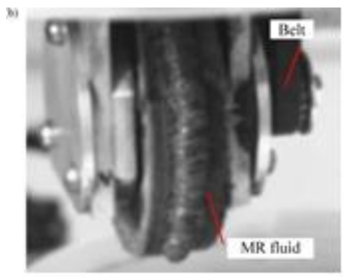

Fig. 2 The MRF under the action of the magnetic field(Cheng, Yam et al. 2009)

In the next paper (Cheng, Feng et al. 2009)the authors are conducted experimental study on the reaction- bonded SiC components using Magnetorheological finishing. In this case the authors used MR fluid composition as Carrier fluid (water-55%), Magnetic particles (CI particles-36%) and abrasive particles (cerium oxide, alumina and diamond-6%) and stabilizer (silicon oil-3%) in Vol%. They observed that Diamond particles are giving higher material removal rate compared to CeO_2 and Alumina. Additionally by adding small amount of CeO_2 to the diamond based MR fluid, they observed significant change in surface finish.

Using MRF technique with different polishing tool the researchers conducted experimental study on polishing of SOI (silicon-on insulator) wafer, conductor surface fabricated with an electroplating process on a CMOS grade silicon substrate with a polyimide interface layer and three-dimensional Silicon micro channel structures. According to their results, surface finish was improved significantly (Tricard, Dumas et al. 2003; Tricard, Dumas et al. 2003; Kim, Lee et al. 2004; Lee, Park et al. 2005; Tricard, Kordonski et al. 2006)

MR jet finishing technology(Kordonski, Shorey et al. 2005; Tricard, Kordonski et al. 2006)was one of the variant in MRF which is used to finish the Conformal (or freeform) and steep concave optics which are difficult to finish using conventional techniques due to mechanical interferences and steep local slopes. The researchers experimentally shown that a magnetically stabilized round jet of magnetorheological (MR) polishing fluid as shown in fig.3 generates a reproducible material removal function (polishing spot) at a distance of several tens of centimeters from the nozzle.

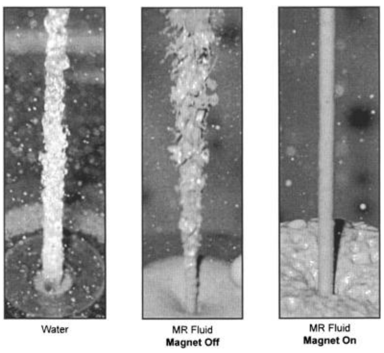

Fig.3 Jet snapshot images ,velocity=30 m/s, nozzle diameter=2 mm(Kordonski, Shorey et al. 2005)

Chinlin Miao et al(Miao, Shafrir et al. 2009) carried out situ experiment to measure the drag and normal forces in MRF using spot taking machine. Their approach experimentally addresses the mechanisms governing material removal in MRF for optical glasses in terms of the hydrodynamic pressure and shear stress, applied by the hydrodynamic flow of magnetorheological fluid at the gap between the part surface and the STM wheel. Their work reveals that the volumetric removal rate shows a positive linear dependence on shear stress. Shear stress exhibits a positive linear dependence on a material figure of merit that depends upon Young's modulus, fracture toughness, and hardness. A modified Preston's equation is proposed for estimating the MRF material removal rate for optical glasses by incorporating mechanical properties, shear stress, and velocity.

$\mathrm{MRR_{MRF}}=\mathrm{C'_{p,MRF}} \cdot \frac{\mathrm{E}}{\mathrm{K_c H_V^2}} \cdot \tau \cdot \mathrm{V}$----------------------1

$\mathrm{C'_{p,MRF}}$ is modified Preston coefficient, E is young's modulus, $\mathrm{H_v}$ is Vickers hardness, τ is shear stress i.e drag force divided by spot area and V is the relative velocity between part and tool.

JongwonSeok et al (Seok, Lee et al. 2009) proposed semi empirical material removal model for the description of the tribological behavior of the MR fluid in the MR finishing process by considering both the solid and fluid like characteristics of the fluid in a magnetic flied. Their main assumptions in modeling material removal rate are the wear behavior follows Archard's law of wear and shear stress imposed on the workpiece by MR fluid is represented by the superimposition of shear stress components due to the solid and liquid like contacts.Material Removal rate $\frac{dz}{dt}=\alpha(\mu_s P V_p+\mu_l V_p^2)=$ k$(P V_p+\frac{\mu_l}{\mu_s} V_p^2)$----------------------2

Where μ_l is the proportional constant determining the weight of V_p^2 with respect to the shear work done by the normal pressure on MRR. K and $\frac{\mu_l}{\mu_s}$ are treated as constant parameters to be determined from experiments.

3. Magnetorheological fluid abrasive flow finishing process(MRAFF)

The MRAFF process depends on extrusion of a magnetically stiffened slug of MRP fluid back and forth through or across the passage formed by workpiece surface and fixture(Jha and Jain 2004). The mechanism of process was shown in Fig. 4. The abrasive particles embedded between iron particle chains under the axial extrusion pressure performs the finishing action of MRAFF. This working process is similar to the Abrasive flow finishing(AFM) process. AFM process has the capability of finishing any geometry by allowing abrasive laden polymeric medium to flow over it. In AFM Process, the abrading forces are mainly depends on putty (polymeric medium) rheological behaviour, which has least control by the external forces, hence lacks determinism. In order to introduce determinism and controllability of the rheological properties of the abrasive medium , a new hybrid process " Magnetorheological abrasive flow finishing process was developed(Jha and Jain 2004).

Jha and Jain(Jha, Jain et al. 2007) were carried out experiments to study the effect of Extrusion pressure, magnetic flux density, and number of finishing cycles on the change in surface roughness. From the investigation, they concluded t that magnetic flux density was the main contributor in improving surface finish. As the magnetic flux density increases, CIP chains hold abrasives more firmly and result in faster finishing action. Another important finding from the experiments that surface roughness value progressively decreases with increase in finishing cycles till the critical surface finish is achieved (Jha, Jain et al. 2007).

MRAFF is capable of super finishing hard materials such as silicon nitride (Si3N4) using boron carbide, silicon carbide, and diamond abrasives(Jha and Jain 2006). In MRAFF process, magnetic field is applied to the cylindrical fixture with two cores of an electromagnet which are placed opposite to each other. Due to this, magnetic field in front of the core material is high and it becomes very low on either side of the core material. Least magnetic field is observed on the cylindrical fixture at a point which is perpendicular to the line joining these two core materials of the electromagnet. Hence, workpiece kept in this zone, comparatively less finished than the one kept in the zone in front of the core material. To enhance the process performance, researchers have modified the existing MRAFF setup as shown in fig.5 and optimised the polishing conditions. In modified MRAFF process, the polishing medium is rotated around the axis of the cylinder by imparting a rotational motion to the permanent magnets surrounding the workpiece fixture along with the reciprocating motion. By superimposing these two motions ,researchers achieved a higher relative velocity and higher finish rate(Das, Jain et al. 2010).

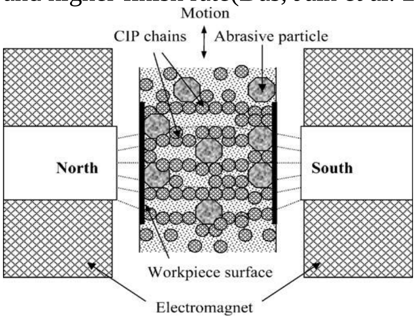

Fig.4 Mechanism of MRAFF(Jha, Jain et al. 2007)

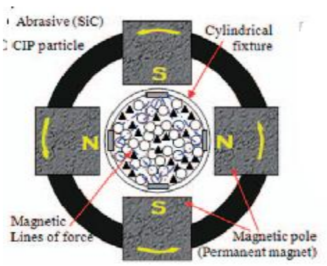

Fig.5 Mechanism of R-MRAFF(Das, Jain et al. 2010)

4. Magnetorheological abrasive honing(MRAH)

Sadiq and Shunmugam(Sadiq and Shunmugam 2009) developed a finishing process which is similar to the conventional honing except the workpiece is given rotation while in conventional the stone was rotated. The workpiece is rotated within the medium and at the same time a reciprocating motion is provided to the medium. Experiments were performed on stainless steel and Aluminium workpiece. From the experiments, the researchers are concluded that surface finish was improved by increasing the magnetic field density as the fluid develops greater yield strength to remove the surface irregularities. And also they found improvement in surface finish at higher rotation speed of the workpiece. Finite element analysis was also performedto understand the nature of magnetic field likely to be produced to calculate the axial stress due to the flow of MR fluid, and to predict final surface roughness value (Ra)(Sadiq and Shunmugam 2009). The comparison of results reveals just satisfactory agreement. However, this analysis did not consider radial stresses developed in the medium. A detailed computational fluid dynamics (CFD) simulation of the polishing medium is essential for in-depth understanding of the process.

5. Ball End Magnetorheological finishing(BEMRF)

MRF, MR jet finishing processes which are limited to specific geometries only such as concave, convex, flat and aspherical shapes due to restriction on relative movement of finishing medium and workpiece. These are incapable of finishing of 3D intricate shaped surfaces. To overcome these limitations, A Kumar etc al. developed a new precision finishing process for nano finishing of 3D surfaces using ball end MR finishing tool(Kumar Singh, Jha et al. 2011) . As shown in Fig.6 the pressurized MRP fluid enters from the top end of the central rotating core when there were no magnetic field. As soon as it reaches the tip surface of the tool magnetic flux density was provided. A ball end shape of the finishing spot, with semi-solid structure, is formed at the tip surface of the rotating core. Like conventional ball end milling, in this process also the tool was rotated and reciprocating motion (longitudinal feed and cross feed) was provided to the workpiece.

The researchers (Kumar Singh, Jha et al. 2012) were conducted experiments to study the effect of number of finishing passes on final surface roughness. They achieved the surface finish as low as 16.6nm, 30.4nm , 71nm and 123nm on flat,30, 45, and curve surfaces of the 3D workpiece. And also they found the performance of the finishing on ground surface was better compared to the milled surface.

The researchers(Singh, Jha et al. 2012)] were also conducted experiments on fused silica glass using cerium oxide abrasive powder and studied the effect of finishing time on final surface roughness. Significant improvement in surface roughness (Ra), root mean square (RMS), and Rmax value has been obtained after 90 min of finishing. Ra as low as 0.146nm was achieved from initial value of 0.74 nm.

In order to understand the material removal process and wear behavior during finishing, different modes of abrasive-workpiece interaction have been analysed by the researchers(Singh, Jha et al. 2013)with respect to measured magnetic normal forces. They developed mathematical model to predict magnetic normal finishing force and compared with the experimentally obtained results.

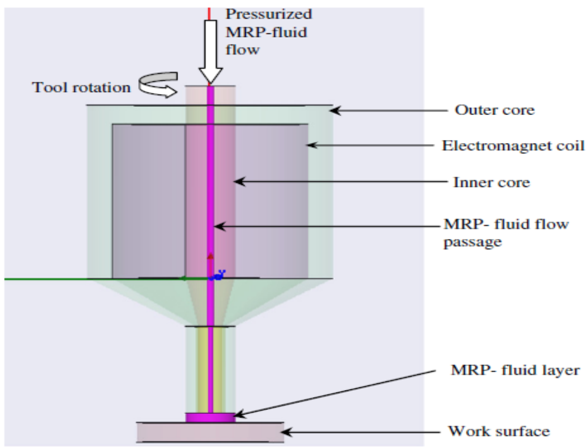

Fig.6 Ball End MRF Tool (Kumar Singh, Jha et al. 2011)

6. Magnetorheological fluid

All magnetorheological finishing processes relies for its performance on magnetorheological effect exhibited by carbonyl iron particles along with abrasive particles in non-magnetic carrier medium. So, magnetorheological fluid and its composition are crucial in MRF processes. Magentorheological fluids are smart fluids are discovered by Rabinow in 1948 , that responds to an applied magnetic field in their rheological behaviour(Rabinow 1948). MR fluids are suspensions of micron sized magnetic particles in a viscoelastic base medium such as water, glycerol, silicone oil, paraffin oil with some additives. In the absence of magnetic field, these fluids exhibits non Newtonian behaviouri.e weak Bingham behaviour. On the application of magnetic field, these fluids become stiffer and large shear force is required to make the fluid flow. The ultimate strength of MR fluid is limited by magnetic saturation.

The selection of the carrier liquid determines the temperature ranges in which the MR fluid can be utilized. Even though silicone oil is the most frequently used carrier liquid, hydrocarbon oil has some advantages due to its low viscosity, better lubrication properties and suitability for high shear-rate applications. Moreover, a hydrocarbon oil-based MR fluid has lower zero field viscosity, which is about 0.6 times less than the silicone oil-based MR fluid. On the other hand, a water-based MR fluid can minimize waste disposal problems and allows the particles to be easily recycled from the material(Ginder 1998; Phulé 2001).

Due to remnant magnetization of the particles, undesired particle aggregation arises in concentrated MR fluids. As a result, the formation of stiff sediments, which are very difficult to redisperse, is facilitated. In order to reduce particle aggregation and settling, different procedures have been proposed: (1) adding thixotropic agents (ex. Carbon fibers, silica nanoparticles)(Bossis, Volkova et al. 2003; De Vicente, López-López et al. 2003); adding surfactants(ex Oleic or stearic acid)(Phulé and Ginder 1999); (3) adding magnetic nanoparticles(Chin, Park et al. 2001; López-López, de Vicente et al. 2005); (4) the use of viscoplastic media as a continuous phase (Rankin, Horvath et al. 1999) and (5) water-in-oil emulsions as carrier liquids (Park, Chin et al. 2001). Glycerol and surfactants are used in water based fluid as stabilizers. Alkaline also helps to improve the stability and resistance to rust (Kordonski and Golini 1998) .

JM Ginder ,L.C.Davis and L.D.Elie(Ginder, Davis et al. 1996) developed numerical and analytical models of a magnetorheological fluid phenomena that account especially for the effects of magnetic nonlinearity and saturation. In this they calculated interparticle magneto static force and the resulted shear stress. They conducted FEA calculations to find the effect of shear stress on magnetic nonlinearity and saturation in MR fluids. From their results, the maximum shear stress of the particles increases as square of the saturation magnetization of the particles.

Jolly et al(Jolly, Carlson et al. 1996) developed a quasi-static, one-dimensional model to examine the mechanical and magnetic properties of magnetorheological materials. This model attempts to account for magnetic non-linearities and saturation by establishing a mechanism by which magnetic flux density is distributed within the composite material.

Very few researchers have focused on the characterization of MR Polishing fluid. Jha and Jain (Jha and Jain 2009)developed hydraulically driven capillary rheometerto characterize the polishing fluid and three constitutive models, viz. Bingham plastic (BP), Herschel–Bulkley (HB) and Casson fluid (CF) are used to characterize the rheological behavior of MR Polishing fluid. Their findings reveal that due to nonlinearity in flow curve, the MRP fluid cannot be characterized as Bingham plastic fluid. The behavior of all MRP fluids observed is of shear thinning viscoplastic nature due to rupturing of CIP chains at faster rate at high shear rates. The presence of non-magnetic abrasives of different sizes affects significantly the rheological properties and makes it difficult to predict the nature of such fluids. The strength of the MR fluid increases nonlinearly as the applied magnetic field increases, since the particles are ferromagnetic in nature and magnetization in different parts of the particles occurs non-uniformly.

Sidpara and Jain(Sidpara, Das et al. 2009) also done characterization study using parallel plate magnetorheometer for water based MR polishing fluid. Their findings also shows that MRP fluid follows shear thinning and Herschel-Bulkley was best model to fit the flow curve.

Conclusions

The state of the art review of MRF, MRAFF, MRAH, and Ball end MRF is presented in this paper. Following conclusions can be drawn from the presented discussion.

The MRF is an effective super finishing process for optical materials with variety shapes such as flat, spherical. Concave, and convex.Surface finish up to nanometer level is achieved without sub surface damage.

MRAFF and R-MRAFF process has been developed as a new deterministic finishing process. This processes also possesses the ability to correct roundness error of hard cylindrical stainless tubes. This process is still under development stage, and it can be further improved after overcoming its existing limitations. Further, 3D CFD simulation of MRP fluid in the finishing zone and simulation of surface roughness will help to automate R-MRAFF process for better finishing performance.

The ability of newly developed ball endMRfinishing tool to reduce surface roughness and improve the surface characteristics of a workpiece is demonstrated and this confirms that the present developed method of finishing process is capable of performing the nanofinishing action on plane and 3D groove surfaces of ferromagnetic as well as nonferromagnetic work materials. Magnetostatic simulation of the variation of magnetic flux density in the finishing region indicates clear formation of ball end finishing surface. The smart behaviour of MR polishing fluid is utilized to precisely control the finishing forces, hence final surface finish..

References

Bossis, G., O. Volkova, et al. (2003), Magnetorheology: fluids, structures and rheology,Ferrofluids, Springer,202-230.

Cheng, H. B., Y. P. Feng, et al. (2009),Material removal and micro-roughness in fluid-assisted smoothing of reaction-bonded silicon carbide surfaces, Journal of Materials Processing Technology,209(9), 4563-4567.

Cheng, H. B., Y. Yam, et al. (2009), Experimentation on MR fluid using a 2-axis wheel tool, Journal of Materials Processing Technology ,209(12–13), 5254-5261.

Chin, B. D., J. H. Park, et al. (2001), Rheological properties and dispersion stability of magnetorheological (MR) suspensions, Rheologica Acta ,40(3),211-219.

Das, M., V. Jain, et al. (2010),Nano-finishing of stainless-steel tubes using rotational magnetorheological abrasive flow finishing process, Machining Science and Technology,14(3),365-389.

De Vicente, J., M. López-López, et al. (2003),Rheological study of the stabilization of magnetizable colloidal suspensions by addition of silica nanoparticles, Journal of rheology ,47,1093.

Ginder, J. (1998),Behavior of magnetorheological fluids, MRS Bulletin-Materials Research Society,23(8), 26-29.

Ginder, J., L. Davis, et al. (1996), Rheology of magnetorheological fluids: models and measurements, International Journal of Modern Physics B,10(23n24), 3293-3303.

Jacobs, S. and S. Arrasmith (1999),Overview of magnetorheological finishing(mrf) for precision optics manufacturing, Ceram. Trans,102, 185-199.

Jacobs, S. D., W. Kordonski, et al. (2000). Deterministic magnetorheological finishing, Google Patents.

Jha, S. and V. Jain (2004),Design and development of the magnetorheological abrasive flow finishing (MRAFF) process, International Journal of Machine Tools and Manufacture, 44(10), 1019-1029.

Jha, S. and V. K. Jain (2006), Nanofinishing of silicon nitride workpieces using magnetorheological abrasive flow finishing, International Journal of Nanomanufacturing,1(1), 17-25.

Jha, S. and V. K. Jain (2009),Rheological characterization of magnetorheological polishing fluid for MRAFF,The International Journal of Advanced Manufacturing Technology , 42(7-8), 656-668.

Jha, S., V. K. Jain, et al. (2007),Effect of extrusion pressure and number of finishing cycles on surface roughness in magnetorheological abrasive flow finishing (MRAFF) process, The International Journal of Advanced Manufacturing Technology,33(7-8), 725-729.

Jolly, M. R., J. D. Carlson, et al. (1996), A model of the behaviour of magnetorheological materials, Smart Materials and Structures ,5(5), 607.

Kim, W.-B., S.-H. Lee, et al. (2004),Surface finishing and evaluation of three-dimensional silicon microchannel using magnetorheological fluid, Journal of manufacturing science and engineering , 126(4), 772-778.

Kordonski, W. and D. Golini (1998) Magnetorheological suspension-based high precision finishing technology (MRF), Journal of Intelligent Material Systems and Structures ,9(8) , 650-654.

Kordonski, W. and D. Golini (1999),Fundamentals of magnetorheological fluid utilization in high precision finishing, Journal of Intelligent Material Systems and Structures, 10(9), 683-689.

Kordonski, W. and D. Golini (1999), Progress update in magnetorheological finishing, International Journal of Modern Physics B,13(14n16), 2205-2212.

Kordonski, W. I. and S. Jacobs (1996), Magnetorheological finishing, International Journal of Modern Physics B,10(23n24), 2837-2848.

Kordonski, W. I., A. B. Shorey, et al. (2005), Magnetorheological Jet (MR JetTM) Finishing Technology, Journal of Fluids Engineering ,128(1), 20-26.

Kumar Singh, A., S. Jha, et al. (2011), Design and development of nanofinishing process for 3D surfaces using ball end MR finishing tool, International Journal of Machine Tools and Manufacture ,51(2), 142-151.

Kumar Singh, A., S. Jha, et al. (2012), Nanofinishing of a typical 3D ferromagnetic workpiece using ball end magnetorheological finishing process, International ,Journal of Machine Tools and Manufacture , 63(0), 21-31.

Lee, S.-N., S.-J. Park, et al. (2005), Application of MRF scheme for low-loss transmission lines on CMOS-grade silicon, Electronic Components and Technology Conference, 2005, Proceedings. 55th, IEEE.

López-López, M., J. de Vicente, et al. (2005), Stability of magnetizable colloidal suspensions by addition of oleic acid and silica nanoparticles, Colloids and Surfaces A: Physicochemical and Engineering Aspects, 264(1):,75-81.

Miao, C., S. N. Shafrir, et al. (2009), Shear stress in magnetorheological finishing for glasses,Applied optics,48(13), 2585-2594.

Park, J. H., B. D. Chin, et al. (2001), Rheological properties and stabilization of magnetorheological fluids in a water-in-oil emulsion, Journal of colloid and interface science 240(1), 349-354.

Phulé, P. (2001), Magnetorheological (MR) fluids: principles and applications, Smart Materials Bulletin,2001(2), 7-10.

Phulé, P. P. and J. M. Ginder (1999),Synthesis and properties of novel magnetorheological fluids having improved stability and redispersibility, International Journal of Modern Physics B,13(14n16), 2019-2027.

Rabinow, J. (1948),The magnetic fluid clutch, Electrical Engineering,67(12), 1167-1167.

Rankin, P. J., A. T. Horvath, et al. (1999), Magnetorheology in viscoplastic media, Rheologica Acta ,38(5),471-477.

Sadiq, A. and M. Shunmugam (2009),Investigation into magnetorheological abrasive honing (MRAH), International Journal of Machine Tools and Manufacture,49(7), 554-560.

Sadiq, A. and M. S. Shunmugam (2009),Magnetic field analysis and roughness prediction in magnetorheological abrasive honing (MRAH), Machining Science and Technology,13(2),246-268.

Schinhaerl, M., G. Smith, et al. (2008), Mathematical modelling of influence functions in computer-controlled polishing: Part I, Applied Mathematical Modelling ,32(12), 2888-2906.

Seok, J., S. O. Lee, et al. (2009), Tribological properties of a magnetorheological (MR) fluid in a finishing process, Tribology Transactions, 52(4), 460-469.

Shorey, A. B., S. D. Jacobs, et al. (2001), Experiments and observations regarding the mechanisms of glass removal in magnetorheological finishing, Applied Optics,40(1), 20-33.

Sidpara, A., M. Das, et al. (2009), Rheological Characterization of Magnetorheological Finishing Fluid, Materials and Manufacturing Processes, 24(12), 1467-1478.

Singh, A. K., S. Jha, et al. (2012), Nanofinishing of Fused Silica Glass Using Ball-End Magnetorheological Finishing Tool, Materials and Manufacturing Processes,27(10), 1139-1144.

Singh, A. K., S. Jha, et al. (2013), Mechanism of material removal in ball end magnetorheological finishing process, Wear, 302(1–2), 1180-1191.

Tricard, M., P. R. Dumas, et al. (2003), Prime silicon and silicon-on-insulator (SOI) wafer polishing with magnetorheological finishing (MRF), ASME.

Tricard, M., P. R. Dumas, et al. (2003), SOI wafer polishing with magnetorheological finishing (MRF), SOI Conference, 2003, IEEE International, IEEE.

Tricard, M., W. Kordonski, et al. (2006), Magnetorheological jet finishing of conformal, freeform and steep concave optics, CIRP Annals-ManufacturingTechnology, 55(1), 309-312.