Effect of Magnetic Field on MR-Fluid in Ball End Magnetorheological Finishing

Harry Garg[1]**,Vipender Singh Negi**[1]**, Ashish Singh Kharola**[1]**, Rohit Sharma**[1]
[1]Optical Devices & Systems
CSIR-CSIO, Chandigarh, 160030, India
*Corresponding author: Optical Devices & Systems, CSIR-CSIO, Chandigarh, 160030 India
harry.garg@gmail.com

Abstract: MRF is one of the precision finishing processes in which magnetic field is used to drive abrading forces for Finishing 2D and complex 3D surfaces. In this paper ball end magnetorheological finishing (BEMRF) has been analyzed for fluid behaviors under the influence of strong magnetic field. Polishing action in MR-fluid depends on magnetization, magnetic intensity, fluid composition and relative motion between fluid and surface to be finished. Here fluid stiffness is key functionality which is determined in terms of magnetorheology effect, In most precision optics this behavior plays a predominant role in obtaining very high precision of the order of 70nm or even less. In this context viscosity of fluid has be analyzed in the presence of magnetic field produced by the electromagnet. As fluid viscosity is a function of magnetization, volume fraction and magnetic intensity, they have been described to generate the magnetorheological effect in fluid.

Keywords: Flux density, Surface finish, Magnetorheology.

1 Introduction

Magnetorheological fluids are mainly dispersion of particles made of a soft magnetic material in a carrier oil. Most often MR-fluid is made up of particles of carbonyl iron in silicone oil. The characteristics of MR-fluid is determined in terms of yield stress which directly depends on the magnetic properties of the fluid and availability of the magnetic field in space. This yield stress represents the maximum of the stress versus strain. since the gel-like structure will break when the stress would have reached this maximum value.

MR-fluid was invented by Rabinow [1] in late 1940s. Interestingly, this work was almost concurrent with Willis Winslow's [2] work on electrorheological (ER) fluids. MR-fluid belong to a class of smart controllable materials whose rheological behavior can be controlled externally by using some energy field. In the absence of magnetic field, an ideal MR-fluid exhibits Newtonian behavior and on the application of the external magnetic field, it exhibits magnetorheological effect. The iron particles in non-magnetic fluid acquire dipole moments proportional to the magnetic field strength and when the dipolar interaction between the particles exceeds their thermal energy, the particles aggregate into chains of dipoles aligned in the field direction. Because energy is required to deform and rupture these chains, this microstructural transition is responsible for the onset of a large controllable finite yield stress. when the external field is removed, the particles return to their random state and fluid exhibits its original Newtonian behavior. of MR-fluid in the presence of magnetic field.

The Field-responsive behavior of MR fluids is often represented as a Bingham plastic having a variable yield strength [3] for stresses τ above the field dependent yield stress $\tau_0(H)$ the flow is governed by Bingham's equation.

$$\tau = \tau_0(H) + \eta\dot{\gamma} \text{ for } \tau \geq \tau_0(H)$$

Below the yield stress (strains of order 10^{-3}), the material behaves visco elastically.

$$\tau = G\gamma\,,\ \tau < \tau_0(H)$$

$$\tau_0(H) = \sqrt{6}\phi\mu_0 M_s^{\frac{1}{2}} H^{\frac{3}{2}}$$

$$\tau_0(H) \propto \phi\mu_0 H^2$$

where τ is the applied shear stress, $\dot{\gamma}$ is the shear rate, G is the complex material modulus, η is dynamic viscosity determined by the base fluid composition, and the field-induced shear stress $\tau_0(H)$ depends on the magnetic field strength H. The strength of the fluid increases as the applied magnetic field increases but this increase is non-linear since the particles are ferromagnetic in nature, and magnetization in different parts of the particles occurs non-uniformly [4]. MR-fluids typically exhibit dynamic yield strength of 50ï 100kPa for applied magnetic field of 150ï 250kA/m [5]. The ultimate strength of MR-fluid is limited by magnetic saturation. The ability to electrically manipulate the rheological properties of MR-fluid attracts attention from a wide range of industries, and numerous applications are explored [6][7]. These applications include shock absorbers, damping devices, clutches, brakes, actuators, and artificial joints[8]-[18].

2 Magnetorehological Finishing(MRF)

Precise Finishing of internal surfaces and complex geometries has always been target for achieving advance technology in various field of science. abrasive with small multiple cutting edges are generally employed to get desired surface finish characteristics and geometrical accuracy by removing unwanted material from the work piece. the traditional finishing processes such as grinding, lapping and honing works on this mechanism of finishing. but due to development of new materials which are difficult to machine due to complex geometrical shapes, available traditional finishing processes are alone not capable of producing required surface finish and other characteristics of the product. Advancement in last few decades in non-conventional machining processes has relaxed the limitation of hardness requirement of the cutting tool. some of these machining processes are EDM, ECM, USM, AJM etc. Cutting of material using predefined motion between cutting edges with respect to cutting surface imposes limit in finishing complex surfaces. to overcome this problem, the multiple cutting edges in some loosely bonded form are directed to follow the intricate geometries to be finished. This process lacks controlled flow of the abrasive over the desired surface. This possess the limitation for finishing complex geometry and sometimes impart surface and subsurface damages.

One such process which address the control and direction of abrasive bound slurry is Magnetorheological finishing (MRF). Magnetorheological finishing is a precision surface finishing technology. Optical surfaces are polished in a computer controlled magnetorheological finishing slurry. Unlike conventional rigid lap polishing, the MR-fluid's shape and stiffness can be magnetically manipulated and controlled in real time. The optic's final surface form and finishing results are predicted through the use of computer algorithms. 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).

3 BEMRF(Ball-End Magnetorehological Finishing)

BEMRF comprises of a central rotating core, stationary electromagnet coil, and copper cooling coils wrapped over the outer surface of the stationary electromagnet coil for continuous cooling. The cooling medium is supplied by a low temperature bath. A magnetically generated ball end finishing spot of MR polishing (MRP) fluid at the tip surface of the rotating core is used as a finishing segment to finish the work piece surfaces. The flow of MRP fluid at the tip of the rotating core is not continuous. It means, whenever MRP fluid is required to be conditioned after a certain period of finishing operation only then was it made to flow to the tip surface of the rotating core through a peristaltic pump. Otherwise, an already formed ball end finishing spot of MRP fluid is used continuously for the finishing operation.

The BEMRF tool has comparatively less limitations on finishing of different work piece surfaces, as compared with regular MRF. The finishing spot of MRP fluid formed at the tip surface of the central rotating core can be easily made reachable for the different 3D surface profiles. The vertical tapered tool tip, with finishing spot of MRP fluid, can be moved and performed finishing with the help of a computer controlled program over different kinds of surfaces in a work piece, such as projections at different angles or in-depth pocket profiles; whereas finishing of these surfaces in the work piece are likely to be inaccessible by a regular MRF process owing to rotating wheel size or mechanical interferences. MR jet finishing was developed to finish the internal surface of a steep concave and spherical dome, where the jet was impinged on the work piece surface from the bottom and the work piece surface was rotated relative to the MR jet. In this process, the relative movement of different 3D complex work piece surfaces, with respect to the MR jet, may have challenged the task. The newly developed finishing process can be found in more industrial applications in the area of MRF processes.

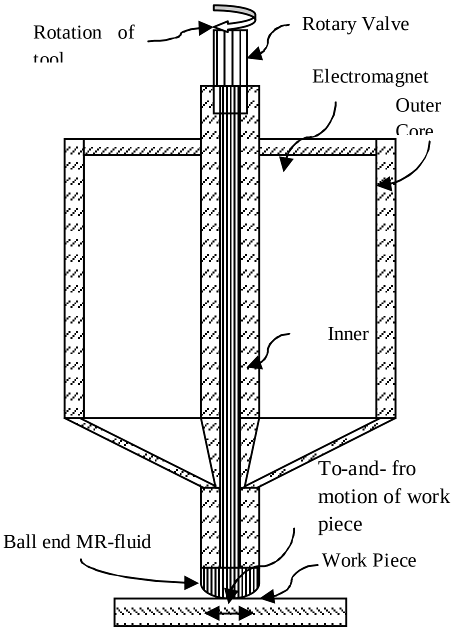

Figure 1 BEMRF Tool.

In mechanism of BEMRF pressurized MRP fluid enters from the top end of the central rotating core. As soon as it reaches the tip surface of the tool the electromagnet is switched ON. A ball end shape of the finishing spot, with semi-solid structure, is formed at the tip surface of the rotating core. When the magnet is switched OFF, the ball end finishing spot of the MRP fluid breaks down and behaves like a paste-type of viscous fluid. The material removed from the work piece surface by silicon carbide abrasives depends on the bonding forces between the carbonyl iron particles in the finishing spot of the MRP fluid.

4 Modeling BEMRF

Considering the schematics described in figure 1. The model is formed and analyzed using Comsol Multiphysics. Due to interaction of fluid and magnetic field i.e. laminar flow and Magnetic field are considered for further analysis. following are the governing equations which are used create mathematical model of BEMRF.

4.1.1 Laminar flow

Momentum Equation

$$\rho(\mathbf{u}.\nabla)\mathbf{u} = \nabla.\left[-p\mathbf{I} + \mu(\nabla\mathbf{u} + (\nabla u)^T - \frac{2}{3}\mu(\nabla.\mathbf{u})\mathbf{I}\right]$$

$$+F$$

$$\nabla.(\rho\mathbf{u}) = 0$$

Reference Temperature 293.15K

Density 2000kg/m^3

Wall

u=0, No slip boundary condition.

Velocity field

u=0, Pressure P=0

Inlet P_0=4bar

Outlet P_0=1bar

Volume Force

Fx=d(U_B)/dx, Fy=d(U_B)/dy

4.1.2 Magnetic Field

Amperes law

$$\nabla \times (\mu_0^{-1}\mu_r^{-1}\mathbf{B}) - \sigma\mathbf{v} \times \mathbf{B} = \mathbf{J}_e$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E}$$

$$\mathbf{B} = \mu_0\mu_r\mathbf{H}$$

Magnetic Insulation

$$\mathbf{n} \times \mathbf{A} = 0$$

Initial Value

A=0

Multi-turn Coil

$$\mathbf{J}_e = \frac{NI_{coil}}{A}e_{coil}$$

$$\nabla \times (\mu_0^{-1}\mu_r^{-1}\mathbf{B}) - \sigma\mathbf{v} \times \mathbf{B} = \mathbf{J}_e$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

Number of turns (N) 2000

Coil Conductivity is 6e7 S/m

d_{coil} is1mm, I_{coil} is 4A

Amperes law

$$\nabla \times (\mu_0^{-1}\mathbf{B} - \mathbf{M}) - \sigma\mathbf{v} \times \mathbf{B} = \mathbf{J}_e$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{B} = \mu(\mathbf{H} + \mathbf{M})$$

Table 1 Magnetic Permeability

Parameter	Material	µ
MR Polishing Fluid	MR-fluid	4
Electromagnet Coil	Copper	1
Inner and Outer Core	Iron	5000

5 Results

Magnetic field in the BEMRF generated by electromagnetic coil having 2000 copper turns, 2A current . The generated magnetic field enters the high permeability region which is the inner and outer iron core of the ball end tool. This can be observed in the figure 2 where the envelop in formed between inner and outer core of the tool. This highly permeable passage allows magnetic field to concentration field at the tip of the tool which is the prerequisite of the experiment. In figure 3 formation of the ball end at the tool tip using streamline plot for magnetic flux density is obtained and approximate hemispherical shape is formed. This is the region where fluid get stiffed because of the concentration of the magnetic flux density and correspondingly this region provides the necessary stiffness for polishing optical component.

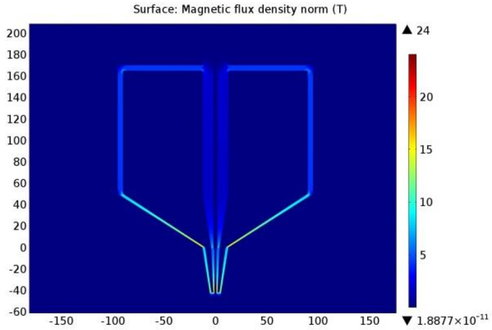

Figure 2 Magnetic flux density.

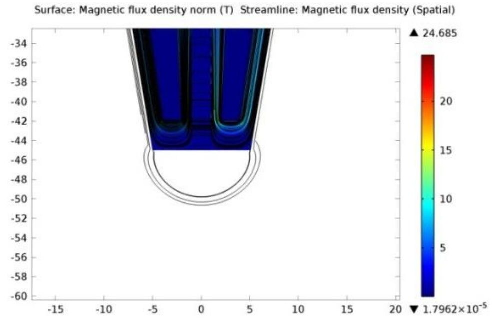

Figure 3 Magnetic field near the tip of the tool forming hemispheric (Ball Shaped).

The rotational motion of the tool tip and transfers motion of the work piece provides the necessary relative motion for polishing action. In this region the magnetic field is very high 24T at the inner corners of the tool tip.

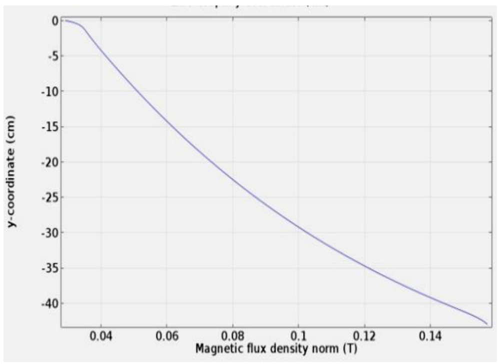

Figure 4 Magnetic flux density in MR-fluid.

Magnetic field in the fluid section inside the tool increases in the lower converging end of the tool and it increases to 0.16T (figure 4) near the exit point of the tool.

6 Conclusions

Ball end MRF technique can be used for polishing Ferrous as well as non-ferrous component. Magnetostatic simulation analysis flux density indicates the formation of the ball end finishing spot. The intensity of the of the magnetic field at the tip will depend on the magnetizing current, number of turns, magnetic permeability of the MR-fluid and iron core. Magnetization of the MR-fluid will be maximum at the tip of ball end tool.

7 References

[1] J. Rabinow, The magnetic fluid clutch, *AIEE Transactions* 67 (1948) 1308.

[2] W.M.Winslow, *J. Appl. Phys.* 20 (1949) 1137.

[3] Philips RW. PhD. Dissertation, University of Calfornia, Berkeley (1969).

[4] J.M.Ginder et al., L.C.Davis, Shear Stresses In Magnetorheological Fuids: role of magnetic saturation, Appl. *Phys. lett.*,65 ,26 (1994)

[5] J.D. Carlson, D.M. Catanzarite, K.A. Clair, Commercial Magnetorheological Fluid Devices, *International Journal of Modern Physics* B 10 (23,24) (1996) 2857ï 2865.

[6] D.J. Klingenberg, Magnetorheology: applications and challenges, *AIChE Journal* 47 (2) (2001) 246ï 249.

[7] J.M.Ginder et al., L.C.Davis, L.D.Elie, Rheology of magnetorheological fluids: model and measurments, *International journal of modern physics* b, 10, 23-34 (1996)

[8] Sunil Jha, V.K.Jain et al. ,Design and development of the magnetorheological abrasive flow finishing (MRAFF) process, *International Journal of Machine Tools & Manufacture*,44 , 1019-1029 (2002)

[9] G.Bossis et al., S.Lacis, A.Meunier, O.Volkova, Magnetorheological fluids, *Journal of Magnetism and Magnetic Materials*,252,224-228, (2002)

[10] Seval Genc et al., Pradeep P Phule, Rheological Properties of magnetorheological fluids, *Institute of physics publication*,11,140-146, (2002)

[11] T. Butz et al., O. Von Stryk, Modelling and simulation of Electro- and Magnetorheological Fluid Dampers, *ZAMM Z. Angew. Math. Mech.*, 82,3-20,(2002)

[12] S.C.Jayswal et al., V.K.Jain, P.M.Dixit, Modeling and simulation of magnetic abrasive finishing process, *Int J Adv Manuf Technol*, 26,477-490(2005).

[13] A.Roszkowski et al., M.Bogdan, W.Skoczynski, B.Marek, Testing viscosity of MR-fluid in Magnetic field, *Measurment Science review*, 8, 3 (2008)

[14] V.K.Jain, Magnetic field assisted abrasive based mircro-/Nano-finishing, *Journal of Material processing Technology*, 209, 6022-6038 (2009)

[15] Anant Kumar Singh et al., Sunil Jha, and Pulak M.Pandey, Magnetorheological ball End Finishing process, *Material and Manufacturing processes*,27, 389-394, (2012).

[16] Ajay Sidapara et al., V.K.Jain, Theoretical analysis of forces in magnetorheological fluid based finishing process, *International Journal of Mechanical Sciences*, 56, 50-59(2012).

[17] Sunil Jha et al., Anant Kumar Singh, Pulak M. Pandey, Mechanism Of Material Removal In Ball End Magnetorheological Finishing Process, *Wear*,(2012)

[18] K. Saraswathamma, Magnetorheological Finishing, *International conference on Advances in Mechanical Sciences* (2014).

8 Appendix

Physical Quantity(Unit)	**Symbol**
Shear Stress(N/m^2)	τ
Yield Stress(N/m^2)	$\tau_0(H)$
Viscosity(Pa-s)	η
Strain Rate	$\dot{\gamma}$
Complex Modulus(N/m^2)	G
Magnetic Field (A/m)	H
Density(Kg/m^3)	ρ
velocity(m/s)	u
Pressure(N/m^2)	p
Force Density (N/m^3)	F
Pressure at inlet outlet(N/m^2)	P_o
Current density(A/m^2)	J_e
Absolute, Relative permeability (Tm/A)	μ_0, μ_r
Absolute, Relative permittivity (C^2/N-m^2)	ε_0, ε_r
Normal Vector	n
Number of Turns	N
Current in a coil(A)	I_{coil}
Induced emf in the coil(V)	e_{coil}
Electrical Conductivity(S/m)	σ
Magnetic vector potential(Wb/m)	A
Magnetization (A/m)	M
Magnetic Energy Density	U_B
Volume fraction	ϕ