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Magnetorheological Fluid Finishing of Soft Materials: A Critical Review

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Abstract: Magnetorheological Finishing (MRF) is one of the precision finishing processes and recently commercialized method for finishing of various materials like optical glasses, metals, non-metals etc. This method utilizes a suspension consisting of a fluid carrier which can be water or oil, both magnetic and non-magnetic particles and stabilizing agents. Rheological behavior of this mixture of magnetorheological (MR) fluid with abrasives changes under the influence of magnetic field which in turn regulates the finishing forces during finishing processes. Present study critically reviews the MRF process used for achieving nano-level finishing of soft materials and the advancements made in this process.

Keywords: Magnetorheological Finishing (MRF), Magnetorheological (MR), Abrasives, Finishing forces

I. INTRODUCTION

High precision finishing methods are of utmost importance, and are the need of present day manufacturing industries where the focus is to increase precision of the products at micro-/nano-scale to perform certain functions. Recent developments in modern technology industries such as electronics, automobile, medical and aviation require highest level of surface finish to increase their life and performance. To meet the demand in the new era of nanotechnology, the traditional finishing processes alone are incapable of producing the required surface characteristics. A large number of products require high level of surface finish to reduce fluid flow resistance, friction, and optical losses some of them are silicon in IC industries, micro-channels in micro-fluidics, optics and free-form surfaces in medical science, and bearings in automobile. Usually, a surface finish improvement operation is required during or after fabrication of a part. Due to the development of three-dimensional (3D) complex-shaped components and very hard material components the traditional abrasive-based finishing processes, such as grinding, honing, and lapping, are not capable of producing ultrafine surfaces due to the abrasives in the bonded form and high specific cutting energy requirement. Therefore, loose abrasive finishing processes, such as chemo-mechanical polishing/planarization, abrasive flow finishing (AFF), and magnetic field-assisted finishing processes, are preferable over the traditional finishing processes. However, many finishing processes, such as lapping, chemo-mechanical polishing, and AFF, are not deterministic in nature because the abrading forces acting on the workpiece are not externally controllable by other means such as magnetic field.

In this article, magnetorheological finishing (MRF), magnetorheological abrasive flow finishing (MRAFF) and ball end magnetorheological finishing (BEMRF) processes have been reviewed. These processes make use of MR fluid whose performance can be controlled in-process by changing the magnetic field intensity. The beauty of all these processes is that they can finish complex-shaped 3D components apart from finishing of inaccessible areas and miniature features.

II. MAGNETORHEOLOGICAL FINISHING (MRF)

MRF is a high precision finishing process that was invented and developed by an international group of collaborators at the Center for Optics Manufacturing (COM) in the mid 90's [1] and commercialized by QED Technologies, Inc. in 1997 [2]. In this process (Fig. 1(a)), MR fluid is supplied to the circumferential edge of a rotating wheel. The rotating wheel is positioned on work surface in such a way that a converging gap takes place. In the absence of a magnetic field, the MR fluid is liquid like and flows easily. When a magnetic field is applied, rheological property of MR fluid changes and the viscosity increases by several orders of magnitude, and the fluid becomes solid like. The magnetic force between iron particles encompassing abrasive grain provides bonding strength to it and its magnitude is a function of iron concentration, applied magnetic field intensity, magnetic permeability of particles and particle size [3]. The stiffened MR fluid on periphery of rotating wheel tool helps to remove peaks from the surface of work material. Figure 1(b) shows a magnified view of mechanics of material removal during MRF process, showing normal and tangential forces responsible for penetration and shearing of peaks during finishing, respectively.

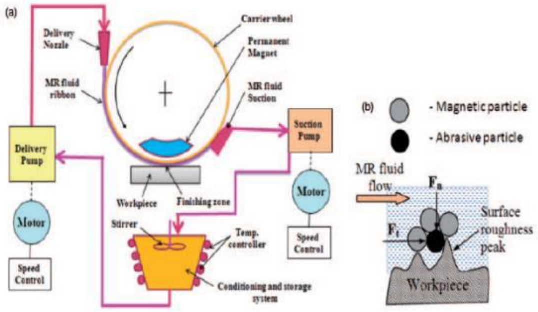

Fig. 1: (a) Schematic of magnetorheological finishing process and (b) magnified view of finishing zone [5]

A.Past Investigations

The past investigations in the domain of MRF process includes the design and development of various types of setups based upon different requirements, theoretical studies as well as experimental works reflecting the effects of various process parameters on the responses such as MRR and surface finish. Shorey et al. [4] performed experiments to study the separate roles of mechanical abrasion and chemical softening during magnetorheological finishing (MRF) of two optical glasses (borosilicate, BK7 and fused silica, FS) and one phosphate laser glass (LHG8). They investigated how variations in particle and glass hardness affected material removal in MRF while keeping wheel speed, height of the MR fluid ribbon, the separation between the wheel and the glass surface, the applied magnetic field constant. It was found that the material removal rate depends on the mechanical properties of both the particles and the glass as well the chemistry of the fluid. A particle softer than the glass surface was shown to be able to slowly abrade material while not able to penetrate the glass surface the way a harder particle can. It was shown that by adding water to turn on chemistry, the way in which the hard particles interacted with the glass surface was changed. Shorey et al. [6] performed material removal experiments and showed that the hydrated layer generated by the chemical effects of water changes the way material is removed by hard CI. It was found that material removal rates increased with the addition of polishing abrasives and concentration as well while magnetorheological finishing of fused silica (FS) surfaces. DeGroote et al. [7] carried out polishing experiments on optical polymers which include polymethylmethacrylate (PMMA), cyclic olefin polymer (COP), polycarbonate (PC), and polystyrene (PS) with standard CeO2-based and nanodiamond-based MR fluids, or with MR fluids containing SnO2, ZrO2, Al2O3, TiO2, or SiO2. The foremost goal was to study the effects of various process parameters on removal rate, surface form error reduction, and surface micro-roughness reduction. Results indicated that ZrO2-based MR fluid successfully smoothed and figured corrected the plane surface of a diamond turned PMMA part to 0.5nm rms and 0.4μm p-v, respectively and also eliminated the diamond turning marks. Of the other abrasive/polymer combinations tested, Al2O3 showed the greatest potential for processing COP, PS, and PC without roughening or introducing surface artifacts. Kim et al. [8] investigated the influences of the process parameters (finishing time, magnet rotational speed and gap between magnet and specimen) on the material removal and compared the surface topographies before and after finishing of three-dimensional silicon microchannel structures using magnetorheological fluid. The results showed that as the polishing time and/or the magnet rotational speed increased and the gap between the magnet and the specimen decreased, the material removal was accelerated and the surface roughness was improved. During MR finishing, they found that the average channel height decreased by 2–3mm, with the formation of slight rounding at the edges (or corners).

Seok et al. [9] thoroughly studied the procedures for the evaluation and analysis of surface characteristics of a work-piece and on the fabrication method of the curved surface on silicon-based micro-structures using magnetorheological finishing. The effect of magnetic field around tool assembly on finished surface profiles is investigated using a finite element method (FEM). The analysis on the magnetic field is performed separately from that of the fluid flow field with the assumption that the field is weakly coupled to the working fluid at steady state with a certain geometric configuration adopted in this work. Response surface methodology (RSM) is utilized to create an efficient analytical model for surface roughness in terms of cutting parameters: feed, cutting speed, axial depth of cut radial depth of cut and machining tolerance. Results showed that the edge effect turned out to be very important as the target work-piece gets smaller, which can be actively used for the fabrication of curved surfaces on millimeter-scale structures. It was observed that the surface roughness of the work-piece decreased gradually and reached to the limiting value. On the other hand, no apparent change is observed in the radius of curvature until about 80 min. However, it can be observed that the radius of curvature dramatically changes after that time and converges to 425.8mm after 130 min.

DeGroote et al. [10] introduced a new MRF material removal rate model for glass. This model contained terms for the near surface mechanical properties of glass, drag force, polishing abrasive size and concentration, chemical durability of the glass, MR fluid pH and the glass composition. It was found that increasing the drag force or shear stress in the modified Preston's equation produced higher material removal rate for each glass type with increasing nano-diamond concentration. The addition of nano-diamonds increases the material removal efficiency, but eventually the nano-diamonds reach a saturation point where removal no longer increases. Smaller nano-diamond particles increase MRF peak removal rate. Results showed that even though the MRF material removal process is dominated by mechanics, chemical durability of glass and hence the pH of the MR fluid play a role in the process.

Vahdati&Shokuhfar [11] experimentally indicated the effects of various finishing parameters viz. rotational speed of magnet holder (pole N), operation time, abrasive type, working gap between magnet holder and work-piece, and lubricant type on material removal rate (MRR) and surface roughness during finishing of aluminium alloy AA–6061. Homogeneous mechanical mixture of abrasive powder (Silicon Carbide) and ferromagnetic iron particles are used as the magnetic abrasive particles MAPs. It was realized that the value of surface roughness improved and material removal per unit time increased with increasing rotating speed and results in a smoother surface. Surface roughness primarily increased with time and then a decrease in roughness improvement is recognized. This is because of creating secondary micro scratches on the finishing surfaces. It was also observed that by increasing the gap between the rotational pole (N) and the work-piece, the surface roughness improved this may be because of stronger magnetic field gradient and high finishing pressure and with the gap of less than 5mm, the surface finish improvement was not continued and the trend was changed.

III. MAGNETORHEOLOGICAL ABRASIVE FLOW FINISHING (MRAFF)

From the above discussion of MRF process, it is concluded that the finishing forces can be controlled externally using magnetic field but the complex geometries and hard-to-machine materials cannot be finished up to high precision due to setup configuration and medium level composition of MR fluid. Keeping in view of the above limitations, AFF and MRF were combined together leading to the development of MRAFF process [12]. In MRAFF process (Fig. 2), a magnetically stiffened slug of MRP fluid is extruded back and forth through or across the passage formed by workpiece and fixture. Abrasion occurs selectively only where the magnetic field is applied across the workpiece surface, keeping the other areas unaffected.

A.Past Investigations

Jha & Jain [12] developed magnetorheological abrasive flow finishing (MRAFF) process for deterministic finishing of internal and external surfaces of Silicon Nitride by extruding magnetically stiffened magnetorheological abrasive polishing fluid. The finishing of silicon nitride work-pieces was done using boron carbide, silicon carbide and diamond. The effectiveness of different abrasives was investigated and surface topography was observed under atomic force microscope. Results showed that MRAFF is effective in super finishing harder materials such as silicon nitride using boron carbide, silicon carbide and diamond abrasives. The initial work-pieces had very deep marks on the surface which were not completely removed even after finishing for 4000 cycles. Silicon carbide was found to be more effective in finishing Si3N4 work-piece in comparison with boron carbide. In case of MRAFF with diamond abrasives, though the measured surface roughness value increased, the quality of surface as observed under atomic force microscope improved and the surface finish improvement rate was faster in first few cycles owing to availability of bigger peaks for shearing, which gradually decreased and reached to a stagnant level.

Jha & Jain [13] conducted finishing experiments on stainless steel workpieces at different magnetic field strength to observe its effect on final surface finish using Magnetorheological (MR) polishing fluid comprising of carbonyl iron powder and silicon carbide abrasives dispersed in the viscoplastic base of grease and mineral oil in presence of external magnetic field. Significant improvement in surface finish was observed at high magnetic field strength. Depths of initial grinding marks were reduced progressively as the experiments were performed at higher magnetic flux density, by reducing asperities.

Hong et al. [14] performed a series of MR polishing experiments for alumina reinforced zirconia ceramics containing 20 vol% of alumina under various polishing conditions including wheel rotational speed, electric current and polishing time using magneto rheological (MR) fluids and diamond abrasives. Conventional sand paper polishing was performed as preliminary steps. MR polished surfaces were observed using a scanning electron microscope (SEM) and surface profiler to investigate the variation of the surface integrity. A very fine surface roughness of Ra= 1.960nm was obtained when the electric current was 0.5 A and the wheel rotational speed was 300 rpm after 60 minutes of MR polishing.

IV.CHEMO-MECHANICAL MAGNETORHEOLOGICAL FINISHING (CMMRF)

In the era of nanotechnology, highly finished surfaces are in great demand in various industries. Keeping in view the finishing of soft materials like optical glasses, silicon wafers etc. it was thought by combining the effect of chemical etching during chemical mechanical polishing (CMP) process and controlling the finishing forces by MRF process to obtain the best MRR and surface finish, leading to the development of a hybrid finishing process, CMMRF [15]. Figure 3 shows the schematic of CMMRF process.

B. Past Investigations

Jain et al. [15] developed a new finishing process, namely, chemo-mechanical magneto-rheological finishing (CMMRF) for polishing silicon blanks that combines the beneficial features of chemical mechanical polishing (CMP) and magnetorheological finishing (MRF) without the detrimental effects of either process involved. It was observed that the CMMRF process has the ability to finish silicon work-piece due to the combined effect of chemical activation as well as mechanical erosion. The best surface finish obtained is 4.8A. Finishing with very fine abrasive results in superior surface finish. Important parameters identified in the process were working gap, finishing time, and magnet rotational speed.

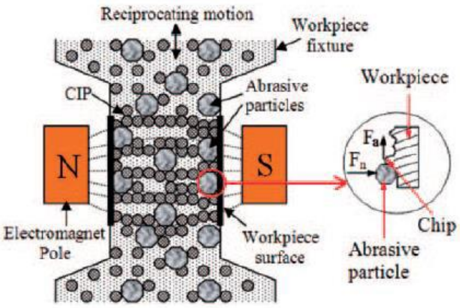

Fig. 2: Mechanism of MRAFF process [5]

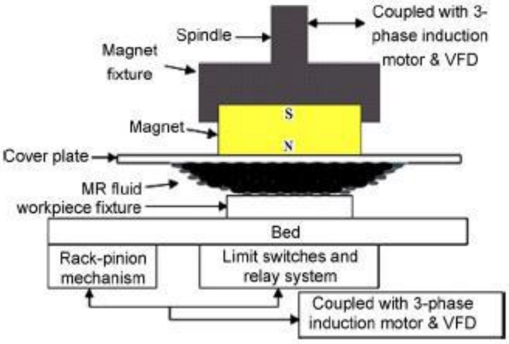

Fig. 3: Schematic of CMMRF process [15]

Jang et al. [16] proposed a new electrochemomechanical polishing process for polishing of glassy carbon molds using a magnetorheological (MR) fluid. Results showed a drastic increase the material removal rate and improved surface roughness by about 14 fold compared to conventional MRP.

Ranjan et al. [17] developed chemo-mechanical magnetorheological finishing (CMMRF) process, one of the advanced nano-finishing process, by combining essential aspects of chemo-mechanical polishing (CMP) process and magnetorheological finishing (MRF) process for surface finishing of engineering materials. The CMMRF process was experimentally analyzed on silicon and copper alloy to generate surface roughness of the order of few angstroms and few nanometers respectively. An attempt has been made for theoretical study of CMMRF process to analyze the effects of MR fluid under various process parameters. A mathematical model has been proposed and simulated to compute material removal as well as surface finish (Ra). This model has been validated experimentally for better understanding, process prediction as well as optimization of the CMMRF process on aluminium alloy as work-piece material.

V. BALL END MAGNETORHEOLOGICAL FINISHING (BEMRF)

Ball end magnetorheological (MR) finishing is a recently developed nano-finishing process which is a variant of magnetorheological finishing process [18-21]. This process utilizes a flexible ball shaped finishing tool made of magnetorheological polishing fluid [22]. The flexible ball adjusts its compliance according to the shape in contact. This makes the process capable of finishing complex surfaces like concave, convex, aspheric or freeform overcoming the shape limitations of magnetic assisted processes [23, 24]. For gentle finishing the stiffness of the MRP fluid ball can be controlled externally applied magnetic field. A schematic elevation view of a magnetorheological (MR) finishing machine is shown in Fig. 4.

A. Past Investigations

Singh et al. [18] designed and developed a computer controlled experimental setup using ball-end magnetorheological (MR) finishing tool to study the process characteristics and performance while finishing flat and 3D surfaces of ferromagnetic as well as non-ferromagnetic materials. The smart behavior of MRP fluid is utilized to precisely control the finishing forces and hence the final surface finish. The magnetostatic simulations of flux density in MRP fluid between tool andworkpiece has been done to visualize the finishing spot shape and size in contact with the workpiece surface. EN-31 magnetic steel and nonmagnetic copper work-pieces were finished using developed machine to validate the process concept. Surface finish of 70nm and 102nm was obtained on EN-31 and copper work-pieces, respectively. The shape and size of the finishing spot in contact with the work-piece surface was found varying with the working gap for the same magnetizing current. Process performance greatly depends on magnetic nature of work-piece material, working gap, and magnetizing current.

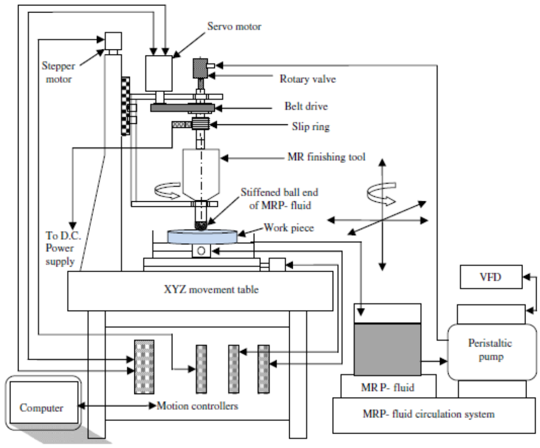

Fig. 4: Schematic of BEMRF process [18]

Singh et al. [24] developed a nano-finishing process using ball end magnetorheological (MR) finishing tool for finishing 3D work-piece surfaces. They focused on surface finishing and performance evaluation of a typical three-dimensional ferromagnetic work-piece using a ball end magnetorheological finishing process. A typical 3D work-piece surfaces were made by milling process at different angles of projection such as flat, 30°, 45° and curve surfaces. The effect of number of finishing passes on final surface roughness was also studied. The experiments were also performed on a flat ground surface to study the process performance as compared with the milled work-piece surfaces. The finite element analysis has been done to study the distribution of magnetic flux density at tip surface of the tool with an inserted typical 3D work-piece surfaces. Results showed that the surface roughness were reduced as low as 16.6nm, 30.4nm, 71nm and 123.7nm respectively on flat, 30°, 45° and curve surfaces for 60 passes of finishing. The roughness of flat ground surface was reduced as low as 19.7nm for 120min of finishing. The experimental results demonstrated that the newly developed ball end magnetorheological finishing process was effective in finishing typical 3D ferromagnetic work-piece surfaces.

Singh et al. [25] studied the effect of finishing time on final surface roughness during magnetorheological finishing of fused silica glass surface. Experimental results showed that surface finish improved with finishing time and low DC supply.

Sidpara& Jain [26] experimentally investigated the forces on the freeform surface. The effects of the process parameters such as angle of curvature of the work-piece, rotational speed of the tool and feed rate on normal, tangential and axial forces, were studied. Theoretical results were compared with experimental results to validate the proposed models. The experimental results concluded that the normal and tangential forces significantly reduced with increase in the angle of curvature of the work-piece surface due to reduction in the contact area of the MR fluid brush with the work-piece surface. Rotational speed of tool and the feed rate of work-piece had an optimum value where the normal force and tangential force were high due to separation and low strength of CIP chains structure. The theoretical normal force as well as the tangential force was less than those of experimental forces in case of angle of curvature of the work-piece surface. That may be due to additional contact area of the MR fluid brush with the work-piece surface apart from the selected area of the finishing spot. The theoretical normal force and tangential force increased with increasing rotational speed of the tool due to rise in Coriolis force.

Niranjan et al. [27] conducted experiments for finishing of mild steel for 30 min with bidisperse magnetorheological polishing fluid (MRPF) by ball end magnetorheological finishing (BEMRF) tool under given experimental conditions. Percentage reduction in surface roughness (%ΔRa) was calculated and compared with %ΔRa obtained by finishing the work-piece with existing monodispersed MRPF. Machining parameters were tool rotational speed, working gap, DC supply, total finishing time, abrasives and carbonyl iron powder. The magnetorheometery results showed that the maximum yield shear stress and viscosity were observed for bidisperse MRPF (Carbonyl iron powder 16 vol.% CS grade, 4 vol.% HS grade, 25 vol.% SiC abrasive and 55 vol.% base fluid) as compared to monodisperse (Carbonyl iron powder 20 vol.% CS grade, 25 vol.% SiC abrasive and 55 vol.% base fluid) MRPF. Percentage reduction in surface roughness was found better by finishing the work-piece surface using bidisperse MRPF with maximum yield shear stress and viscosity than monodisperse MRPF.

Niranjan & Jha [28] prepared bidisperse MR polishing fluid samples with varying percentage of small sized magnetic contents of carbonyl iron powder (CIPs) HS grade within same vol% of total magnetic contents. Magnetorheological behaviours of bidisperse MR polishing fluid for comparison with monodisperse MR polishing fluid using physica MCR-301 rheometer had been studied. Evaluation of the flow behaviour of MRP fluid has been done by steady state rheograms at different magnetic field strength. The yield shear stress and viscosity of bidisperse MRP fluid for all experiments were found maximum at 16 vol% CIPs CS grade, 4 vol% CIPs HS grade, 25 vol% abrasives and 55 vol% base fluid. The results indicate that the yield shear stress and viscosity of bidisperse MRP fluid has been found improved as compare to monodisperse MRP fluid for all magnetic field strength. After characterization, the experiment was performed with bidisperse MRP fluid on mild steel work-piece using ball end MR finishing tool for 30 minutes with a set of given machining parameters. Percentage reduction in surface roughness (%ΔRa) was calculated and found superior results while using bidisperse MRP fluid (16 vol% CIPs CS grade, 4 vol% CIPs HS grade, 25 vol% SiC abrasives and 55 vol% base fluid).

Garg et al. [29] "Effect of Magnetic Field on MR-Fluid in Ball End Magnetorheological Finishing" analyzed the ball end magnetorheological finishing (BEMRF) process for fluid behaviors under the influence of strong magnetic field. It was observed that the intensity 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.

Niranjan & Jha [30] made an attempt to improve the percentage reduction in surface roughness of mild steel work-piece for 30 min with sintered magnetic abrasives based MRP fluid on BEMRF tool. Sintered magnetic abrasives were developed by mixing of 20 vol% carbonyl iron powder (CIP) CS grade and 25 vol% SiC in ball mill then pellets of 5 g each have been made at 8-ton pressure. These pellets were allowed to sinter in tubular furnace at 1200 °C in the controlled atmosphere of argon. The sintered pellets were crushed in a ball mill to obtain sintered magnetic abrasives. MRP fluid was synthesized with 45 vol% sintered magnetic abrasives and 55 vol% base fluid. It was observed that %ΔRa increases with increase of tool rotational speed, then reaches a maximum at 600 RPM, and decreases thereafter due to tool aging effect. Hence, optimum tool rotational speed was found as 600 RPM. Tool aging effect has been minimized with the use of sintered magnetic abrasives based MR polishing fluid.

Niranjan & Jha [31] carried out a comparative study based on percent reduction in surface roughness (%ΔRa) on mild steel surface with synthesized and unbounded magnetic abrasives based MRP fluid. It has been observed that the working gap is the most significant machining parameter affecting %ΔRa. Additionally magnetizing current and tool rotational speed also provides secondary contribution to %ΔRa. The response %ΔRa decreases continuously with the increase of working gap and the response increases with increase of magnetizing current. The response %ΔRa first increases by increasing the tool rotational speed and reach at its maximum value, thereafter decreases. Therefore, an optimum tool rotational speed was found as 500 rpm. Predicted response %ΔRa was calculated and found as 54.69 by regression model at an optimum machining conditions of magnetizing current = 5.7 A, tool rotational speed = 500 rpm and working gap = 0.66 mm.

Saraswathamma et al. [32] experimentally studied through statistical design of experiments the effect of process parameters such as core rotational speed, working gap, and magnetizing current on a percentage reduction in surface roughness of silicon wafer in BEMRF process. Individual effect on surface roughness values in terms of arithmetical mean roughness (Ra) was studied by applying ANOVA. The final observations indicated that the working gap was the critical process parameter for finishing silicon work-piece by ball end magnetorheological finishing. The increase in working gap decreases the percent reduction in surface roughness of the silicon work-piece. Increase in magnetizing current was found to increase the percentage reduction in Ra values. Less significant improvement in percentage reduction in Ra values for different core rotational speeds was observed at lower working gaps. However, at higher working gaps, percentage reduction in Ra decreases with increase in core rotational speed.

Khan et al. [33] carried out a magnetic simulation over both copper and ferromagnetic material and subsequently copper work-piece is finished using permanent magnet as base. Magnetic simulation performed on copper work-piece in BEMRF process shows that the magnetic flux density is very less and uneven at the copper surface. Slight improvement in magnetic flux density over copper work-piece was observed with mild steel base but significant improvement is only obtained by permanent magnet below the copper work-piece. The improvement in magnetic flux density by placing permanent magnet below copper work-piece was experimentally verified by using gauss meter. Using permanent magnet base, copper work-piece was finished and the surface roughness reduced from Ra = 35.7nm to Ra = 7.3nm in 30 minutes.

Khurana et al. [34] developed a ball nose magnetorheological nano-finishing process based on solid rotating core tool instead of a rotating core with central hole for flow of polishing fluid at the tool end surface in existing ball end magnetorheological finishing (BEMRF) process to generate a uniform magnetic field at the end of a magnetizable rotating core tool for providing a uniform surface roughness on a spot finishing of precision components. Results showed that uniform magnetic flux density at the end surface of a solid rotating core tool is found as compared to the rotating core tool with central hole. Uniform magnetic field at the entire end surface of a solid rotating core tool facilitated the uniform strength of MR polishing fluid at its entire uniformly magnetized end surface. This confirmed that the magnetic normal force has been applied uniformly during the spot nano-finishing on the work-piece surface. Ball nose magnetorheological finishing with a solid rotating core tool produced uniform nano-level surface roughness on a spot area of work-piece surface due to uniform magnetic flux density at the end surface of a solid rotating core tool. Uniform decrease in surface roughness values (Ra) throughout the spot finishing surface from 290 to 20nm in 90 min revealed that the present finishing process based on a solid rotating core tool is effective for a spot nano-finishing of precision components.

Khan & Jha [35] explored problems associated with ball end MR finishing of copper and a fluid composition suitable for finishing of copper has been developed. A novel approach using two opposite magnetic pole has been used to enhance the magnetic flux density distribution between tool tip and copper work-piece surface. The effect of fluid composition parameters has been analyzed by the statistical model developed by response surface. Results showed that copper reacts with the oxygen and the surface turns black and brownish in color due to oxide formation irrespective of type of base fluid.

VI. CONCLUSION

Critical review of MRF, MRAFF, CMMRF and BEMRF high precision finishing techniques is presented in this article. Following conclusions can be drawn from the above discussion.

The MRF is an effective finishing process for finishing micro as well as macro components. Surface roughness up to nanometer level is achieved without subsurface damage. Shear stress that is due to the hydrodynamic flow of the MR fluid between the rotating wheel and the workpiece surface controls the removal rate on the size scale of the spot. Further, the stability of MRP fluid is a major concern in MRF and MRAFF processes, which needs intensive research. It can be improved by inclusion of different types of surfactants.

The present study state that BEMRF and magnetic fluid are used to obtain very high level surface finish on variety of work-piece materials. It is observed that magnetic field has the highest contribution on the yield stress and viscosity of the MR fluid.

MR fluids can be used for high precision finishing of variety of components including optical glasses, fluid clutches, aerospace, sealing, automotive and civil damping application. These fluids can also be used for material removal process for variety of brittle materials like hard crystals.

The bimodal MRP fluid can also be used for finishing of composite materials. With the addition of nano magnetic particles which have high magnetic saturation the shear strength of bimodal MRP fluid can be further be improved.

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