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# CONTEMPORARY APPLICATIONS OF MAGNETOREOLOGICAL FLUIDS FOR FINISHING PROCESS

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**Abstract:** The article presents the current state of knowledge on the use of magnetorheological fluids for finishing processes. The paper descsribes the type of the materials and surfaces to be machined and the composition of the magnetorheological fluids used in this area. The most interesting applications were described in more detail, paying particular attention to the schematic diagram of the test stands, obtained results of experimental tests and the results of roughness measurements of the surfaces exposed to magnetically controlled fluids. The article also describes the directions of the newest experimental and simulation research on the application of magnetorheological fluids in the field.

**Keywords:** magnetorheological fluid, magnetorheological finishing, surface roughness

## 1. INTRODUCTION

*Magnetorheological* (MR) *fluids* are classified as an intelligent and controllable materials. These liquids are a non-colloidal mixture of ferromagnetic particles, non-magnetic abrasive particles and additives in the form of surfactants to prevent oxidation and aggregation of particles, randomly dispersed in the supporting substance.

The main active component of MR fluids is usually very high purity carbonyl iron particles (CIP) with diameters from 0.1 μm to 10 μm (Fig. 1a). This component of the magnetorheological fluid may also constitute cobalt particles (Co), nickel particles (Ni) and other ferromagnetic [1]. In a typical MR fluid, the percentage of particles with ferromagnetic properties is between 20% and 80% [2]. In some cases, non-magnetic abrasive particles are also used to produce MR fluids, e.g. diamond powder, alumina or cerium oxide ($Ce_2O_3$) (Fig. 1b) [3].

Depending on the intended use of the MR fluid, an indifferent magnetic carrier fluid may be oil, glycol, deionized water or liquid hydrocarbon.

The quality of MR fluids is determined primarily by the percentage of ferromagnetic particles in the carrier medium, their size and magnetic properties. The magnetic properties of particles have a direct influence on the upper limit of their magnetization, which is important in the process of controlling the properties of MR fluids.

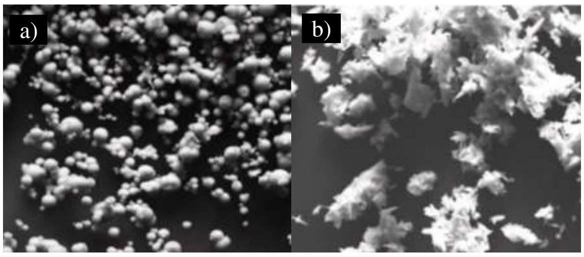


Fig. 1. SEM photo of: a) carbonyl iron particles, b) cerium oxide particles; mag. 5000×

MR fluids, or indeed the properties of these substances, are controlled by changes in magnetic field strength. When magnetorheological fluids are not exposed to the magnetic field, their properties and behaviour are similar to the Newton fluid model, in which the tangential stresses are proportional to the deformation velocity. Below a certain limit of shear stress, MR fluids behave like elastic solids, and above that limit as Newtonian fluid [4]. Under the influence of magnetic field, particles with ferromagnetic properties (floating freely in liquid) move and redesign their arrangement, creating chains of magnetic dipoles arranged parallel to the magnetic field.

These microscopic chains have a macroscopic effect to change the apparent viscosity of the fluid. To break such a structure requires additional forces. The tangential stress changes and the apparent yield strength appears [5].

The MR fluid behaves following a so called Bingham law, which means that it exhibits a non-zero shear stress value for a zero shear rate [6], behaving more like a solid than like a liquid. The value of the shear stress at no shear rate is called yield stress of the MR fluid and is controlled by the applied magnetic field. The larger the field, the higher the yield stress. The higher the yield stress the higher the force the material can withstand without flowing [7].

Due to the way in which the fluid moves in relation to the magnetic field vector and the possible way in which the resulting stresses can be converted into external force, there are three basic modes of MR fluid action: *flow* mode, *shear* mode and *squeeze* mode [8]. In all the mentioned cases the working principle is the same: the applied magnetic field regulates the yield stress of the fluid and changes its apparent viscosity.

In the *flow mode*, also called *valve mode*, fluid flows through the gaps between parallel fixed walls. The magnetic field is normal to the fluid flow direction and choke the flow rate. In *shear mode* the fluid is constrained between two walls which are in relative motion with the magnetic field, normal to the wall direction. In the *squeeze mode* MR fluid fills the space between two parallel walls, which, due to the load, can come close together and cause the fluid to extrusion. The magnetic field is normal to the walls directions and prevents the walls from approaching.

The rheological properties of the MR fluid depend on the composition and concentration of individual components in the MR fluid [9].

MR fluids, depending on the size of ferromagnetic particles, are divided into two subgroups [1]: micro-magnetorheological fluids in which ferromagnetic particles have a particle size of several micrometres, ferromagnetic (aka: nano-magnetorheological) fluids, in which the ferromagnetic particles have a size from several to several dozen nanometres.

MR fluid was discovered by Rabinow in 1948. The change in rheological property of MR fluid after applying magnetic field reported by same researcher [10]. Currently, there are several companies on the market which produce their own MR fluids. A major producer and global leader in the production and use of magnetorheological fluids are: Lord Corporation (USA), BASF SE (Germany), Bayer AG (Germany) and Nippon Shokubai Co. Ltd. (Japan). The new MR fluids' formulas are also created in scientific and research institutions, e.g. Warsaw University of Technology (Poland) [1], Silesian University of Technology (Poland) [11].

In addition to technical solutions such as car dampers [2], clutches [12] and brakes [13], magnetorheological fluid is also used in magnetic field supported finishing processes.

Different types of magnetic field assisted finishing processes are available, e.g. Magnetic Abrasive Finishing (MAF) [14], Magnetorheological Finishing process (MRF) [15], Magnetorheological Jet Finishing (MRJF) process [16], Magnetorheological Abrasive Flow Finishing (MRAFF) [17], Rotational Magnetorheological Abrasive Flow Finishing (RMRAFF) [18] and Ball-end Magnetorheological Finishing (Ball-end MRF) [19]. They are an alternative to the developed abrasive processes that require an impregnation [20, 21] or regeneration process [22] of tools, or special solution for coolant feed to the machining area [23], or monitoring [24] to achieve high surface quality.

## 2. APPLICATION OF THE MR FLUID IN THE FIELD

Magnetorheological finishing (MRF) is a smart finishing processes applied to a variety of applications. The overview of applications of MR fluids in the years 2015-2016 and the composition of the used fluids are presented in the Table 1 and Table 2.

Tab. 1. The use of MR fluids in the years 2015–2016

| Authors | Machined surface | Material | Surface roughness |
|---|---|---|---|
| Wang et al. [25] | interior surf.,<br>the plane position,<br>the corner position | tool-steel, Cr12 | $Ra$=0.132 nm<br>$Ra$=0.287 nm |
| Niranjan and Jha [26] | external surf., the plane position | mild steel | $Ra$=0.0914 μm |
| Chen et al. [27] | external surf., the plane position | KDP crystal | $Ra$=0.624 nm |
| Pan and Yan [28] | external surf., plane surface | monocrystalline Si wafer | maximum material removal 1.5 μm |
|  | external surf., plane surface | monocrystalline 6H-SiC wafer | maximum material removal 13.3 μm |
| Das et al. [29] | external surf., flat surface | stainless steel | $Ra$=0.13 μm |
| Ji et al. [30] | external surf. | KDP crystal | $St$=305 nm |

Tab. 1. *continue*

| | | | |
|---|---|---|---|
| Ji et al. [30] | external surf. | KDP crystal | $St=305$ nm |
| Wang et al. [31] | external surf. | fused silica | $Ra=0.460$ nm |
| Liu et al. [32] | backside of the external surface | glass | $Ra=0.018$ µm |
| Kim et al. [33] | external surf., the deepest removal point | glass BK7 | $Ra=1.15$ nm |
| Chen et al. [34] | external surf., plane surface | fused silica | $Ra=0.517$ nm |
| | interior surf., curved surface | stainless steel | $Ra=0.005$ µm |

Tab. 2. General characteristics of grinding conditions

| Authors | Composition of the magnetorheological fluid |
|---|---|
| Wang et al. [25] | Reduced iron powder, SiC, water, PEG. |
| Niranjan and Jha [26] | Sintered magnetic abrasives 45 vol% and 55 vol% base fluid. |
| Chen et al. [27] | Nonvolatile hydrocarbon, deionized water (4.5 wt.%), carbonyl iron powder. |
| Pan and Yan [28] | Carbonyl iron powder 4%, deionised water 88%, abrasives (the abrasive for 6H-SiC is diamond powder 4%, the abrasive for Si is alumina) and 4% stabiliser. |
| Das et al. [29] | Carbonyl iron 30 % (particles of CL grade (25 µm) from BASF Germany), 10% SiC abrasive with 600 mesh size (25.33 µm), 12% grease, and 48% paraffin oil. |
| Ji et al. [30] | Fluid containing cubic $Fe_3O_4$ nanoparticles. |
| Wang et al. [31] | Deionized water, carbonyl iron powder, stabilizer, cerium oxide, additives. |
| Liu et al. [32] | Carbonyl iron particles, polishing abrasive particles, water and stabilizers. |
| Kim et al. [33] | Spherical carbonyl iron particles 38.2 vol%, deionized water58.4 vol%, glycerol 2.6 vol% and 0.8 vol% sodium carbonate+ cerium oxide particles were mixed with the MR fluid at a volume ratio of 5:95. |
| Chen et al. [34] | Carbonyl iron particles 36 vol%, water-based fluid medium 57 vol%, cerium oxide abrasive particles 6 vol%, stabilizing agent 1 vol%. |

Wang et al. [25] used a magnetorheological fluid to polish the internal surfaces of matrices obtained during the EDM cutting process. This process is a form of subtractive machining used to produce complex geometry components and is based on the removal of material by melting and evaporation caused by electrical discharges between electrodes — the shape of the workpiece is formed by wire electrode.

Internal surfaces obtained in the WEDM process are characterized by high difficulty in their effective polishing. In the manufacture of the matrix, a core is formed that is ideally suited to the internal surface. In the proposed method, the core is used as a polishing tool by supplying the magnetic field and immersion of the workpiece in the magnetorheological fluid. Under the influence of magnetic field, ferromagnetic particles of fluid formed rigid chains adhering to the core. Under the influence of reciprocating movement of the core along the internal surfaces of the matrix, material was removed by contact of abrasive particles with the workpiece (Fig. 2).

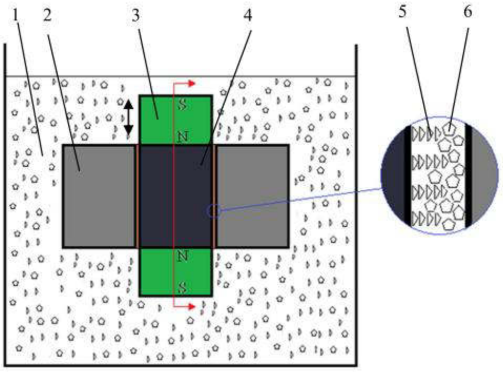


Fig. 2. Schematic diagram of core MRF for pierced die cavity. Notes: 1 — MR fluid, 2 — pierced die cavity workpiece, 3 — permanent magnets, 4 — core, 5 — magnetic particles, 6 — non-magnetic polishing particles [25]

The proposed processing method does not require the production of special polishing tools for different internal matrix surfaces. The results of the experiments have shown that the polishing effect depends on the surface area to be machined. Flat surfaces are characterized by high quality in contrast to corners. On the other hand, an analysis of the impact of eaves radius has shown an increase in surface quality as the radius of the corners increases. This is due to a linear increase in the density of the magnetic flux as the radius of the polished curvature of the surface increases — Fig. 3.

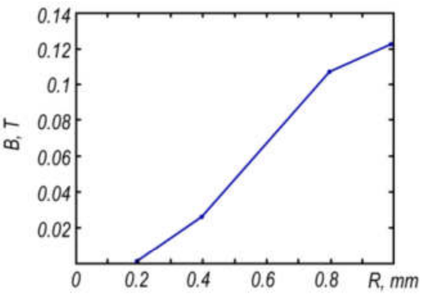


Fig. 3. Relationship between the arc radius and the magnetic flux density [25]

Niranjan and Jha [26] used a magnetorheological fluid in the precise milling process. For this purpose, a special design of the polishing head was used (Fig. 4a). It was designed for machining flat and three-dimensional ferromagnetic and diamagnetic materials. The process of magnetorheological finishing with a ball-end milling cutter — known as *ball-end magnetorheological finishing*, BEMRF.

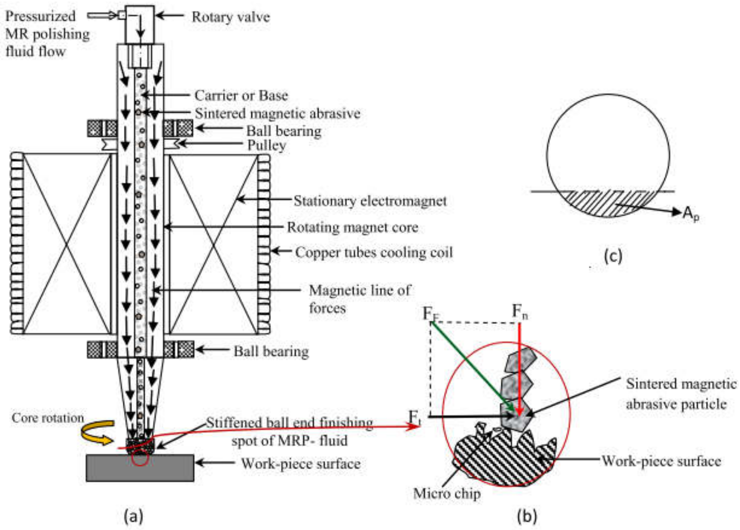


Fig. 4. Schematic diagram of (a) designed polishing head, forces (b) acting on sintered magnetic abrasive particle and area of penetration (c) considered for the calculation of resistance offered by the work-piece surface during material removal [26]

In the presented study the authors have developed sintered magnetic abrasive magnetic particles consisting of 20% volumetric carbonylic iron powder and 25% volumetric SiC. As a result of the crushing of both components in the ball mill, 5 g lozenges were made, which were sintered at 1200 °C in the argon atmosphere. The sinter was crushed again in a ball mill to produce magnetic abrasive particles.

The use of an innovative tool reduced the surface roughness of the steel samples compared to the polishing process with a magnetorheological fluid free of magnetic abrasive particles with the same machining parameters. The introduction of magnetic abrasive fluid reduced the roughness of polished surfaces by 32.5% (measured with the *Ra* parameter), while the same process carried out with a magneto-rheological fluid without magnetic abrasive particles resulted in a 19% reduction in roughness. The morphology of magnetic abrasive particles is depicted in Fig. 5 in confrontation with unsintered particles.

In the developed tool, the polishing fluid is fed under pressure through an internal channel, which results in abrasive particles reaching the outlet of the polishing head in the environment of other MR fluid components. As a result of the external magnetic field, the magnetic abrasive particles form a strong column structure along the field lines. Therefore, the polishing fluid stiffens and forms a hemispherical shape as shown in Fig. 4b.

During machining process, the magnetic force between the abrasive grains binds them together, and a drop of magnetorheological fluid at the end of the polishing head is introduced into the relative motion to the workpiece — by rotating the tool and cutting the tops of the micropolished surface. The authors have indicated that the amount of material removed from the surface of the workpiece depends on the binding force of the magnetic abrasive particles ($F_n$) generated by the magnetic field and the cutting force ($F_t$) resulting from the rotational movement of the tool. Normal force is related to the depth of material penetration, while the cutting force is responsible for material removal.

Chen et al. [27] used a MR fluid to polish KDP type of crystals (Potassium Dihydrogen Phosphate; molecular formula: $KH_2PO_4$). The KDP crystals are characterized by low hardness, high brittleness, temperature change sensitivity and water solubility. The above mentioned features resulted in the development of a new method of magneto-rheological polishing in which no abrasive particles are used and the water content has been reduced to the minimum necessary (approx. 4.5% vol. of the solution).

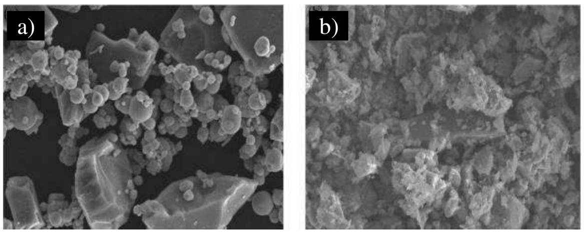


Fig. 5. Scanning electron microscopy of unbonded (a) and sintered (b) magnetic abrasives; mag. 5000× [26]

Deionized water is the abrasive molecules in the solution of the magnetorheological liquid. 1 g of water is capable of dissolving 0.33 g of KDP crystal, which corresponds to 141 mm$^3$ of the volume of this material (at 25°C) — Fig. 6.

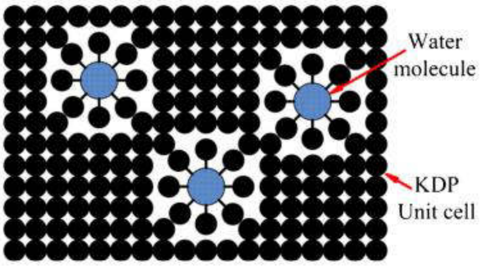
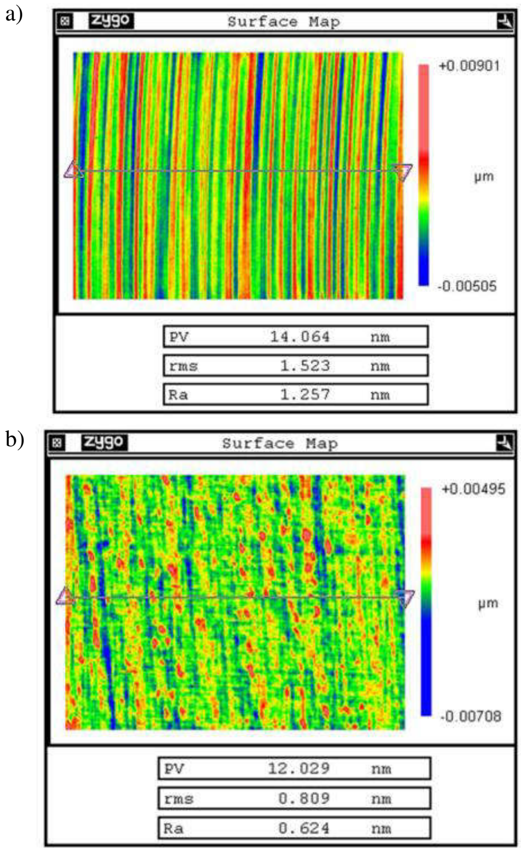


Fig. 6. Material removal of non-aqueous MRF [27]

As a result of the magnetic field action, carbonylic iron powder particles adhere to the polishing disc causing the water molecules to move to the outer layer of the magnetoreological fluid. In contrast to traditional MRF polishing, the proposed solution allows to remove the crystal material from the workpiece with much lower individual tool pressure. During processing, only a small amount of water molecules remain in contact with the crystal surface, which are quickly removed from the processing zone in order to avoid matting of the KDP crystal surface.

The surface roughness (*Ra* parameter) of the crystals after machining with the developed method falls from an initial value of 1.257 nm to 0.624 nm. The surface is smooth and free from defects (Fig. 7).



a)

PV 14.064 nm
rms 1.523 nm
Ra 1.257 nm

b)

PV 12.029 nm
rms 0.809 nm
Ra 0.624 nm

Fig. 7. Surface roughness (a) before and (b) after MRF [27]

Ji et al. [30] have developed a different magneto-rheological fluid for the finishing of KDP crystals. They replaced the sensitive magnetic particles (carbonyl iron) and abrasive particles ($CeO_2$/diamond) with cubic nanoparticles $Fe_3O_4$. The distribution of the size of $Fe_3O_4$ nanoparticles with sharp edges and corners is between 100 nm and 200 nm.

The differences between conventional finishing with carbonyl iron particles containing micro-scaled spherical CIPs and abrasive particles to produce a smooth surface of KDP crystals and the designed new fluid, in which carbonyl iron and abrasive particles were replaced by nano-scaled cubic $Fe_3O_4$, are shown in Fig. 8.

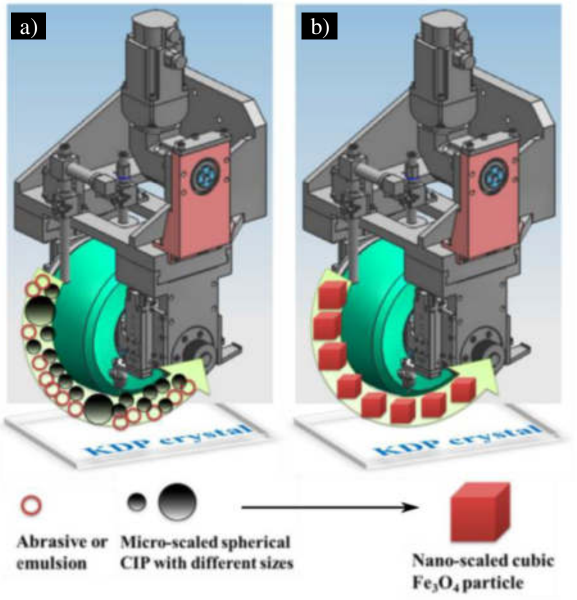
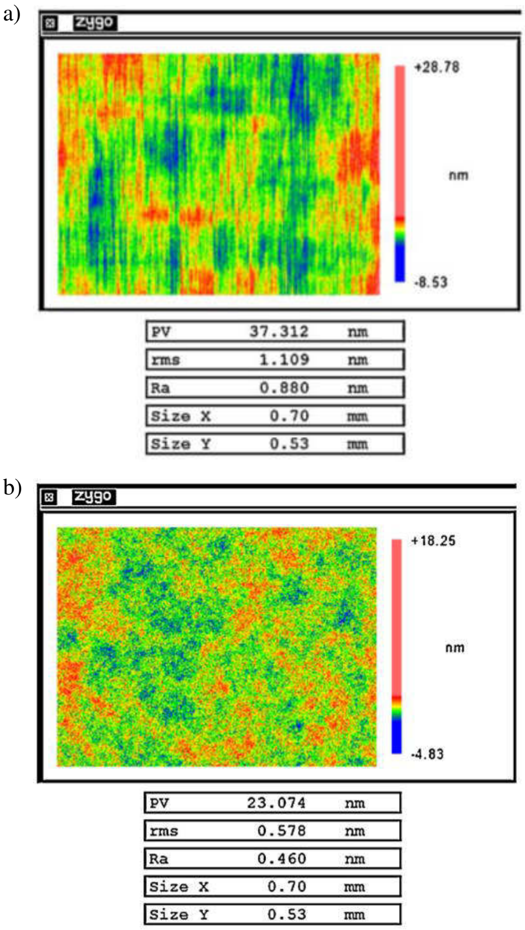


Fig. 8. The conventional CIP with abrasive are substituted by $Fe_3O_4$ nanoparticles simultaneously: a) standard MRF mechanism, b) MRF with nanoparticles [30]

For surfaces obtained by the use of conventional magnetorheological fluid clearly exhibits a great deal of *falling star* like pits and scratches. Authors deduced that these flaws are arising from the strike of carbonyl iron particles because the widths are micrometer sized and just located in the carbonyl iron particles range. The results obtained by the authors showed that the geometric structure of the surface is significantly improved when using MR fluid with $Fe_3O_4$ addition. In the surface texture of the finished KDP with the fluid containing $Fe_3O_4$ few pits and scratches can be found, and there are only fine grooves which may be produced by the rolling and shaving actions between nanoparticles and KDP during finishing.

The surface area obtained by the magnetorheological finishing process is characterised by directional surface texture due to the constant flow direction of the MR polishing fluid. Wang et al. [31] studied the mechanism of surface texture formation by texture modelling. They have used a dual-rotation magnetorheological finishing (DRMRF) to suppress directional surface texture after analysing the results of the texture model for common MRF. The results of the surface texture model for DRMRF and the proposed quantitative method based on mathematical statistics indicate the effective suppression of directional surface texture.

Experimental research results obtained by authors show that DRMRF successfully suppresses the directional texture. As a result, the surface roughness is lowered (the root-mean-square value of surface roughness of DRMRF is 0.578 nm, which is lower than 1.109 nm in common MRF) (Fig. 9).



a)

| | | |
|---|---|---|
| PV | 37.312 | nm |
| rms | 1.109 | nm |
| Ra | 0.880 | nm |
| Size X | 0.70 | mm |
| Size Y | 0.53 | mm |

b)

| | | |
|---|---|---|
| PV | 23.074 | nm |
| rms | 0.578 | nm |
| Ra | 0.460 | nm |
| Size X | 0.70 | mm |
| Size Y | 0.53 | mm |

Fig. 9. The measured surface topography in common MRF (a) and DRMRF (b) [31]

Liu et al. [32] developed a new four-axis MRF machine tool using the magnetic tip of the spherical polishing head, which can be used to precisely finish the concave surfaces of complex parts with a low radius of curvature (Fig. 10).

The authors performed a static deformation analysis of the designed MRF machine tool using the FEM method, which showed that the static displacement of polishing head can be less than 0.67 µm by optimizing structural parameters of gantry part.

The authors also conducted spot polishing experiments, which showed that the proposed MRF process can achieve stable polishing area which meets the requirement of deterministic polishing. The developed MRF machine tool is capable of processing small-bore complex parts. Test results have shown that a four-axis MRF machine tool can be used to achieve fine surface quality with sphericity 1.3 µm and surface roughness *Ra* less than 0.018 µm. The surface roughness after final polishing is shown in Table 3 and Fig. 11.

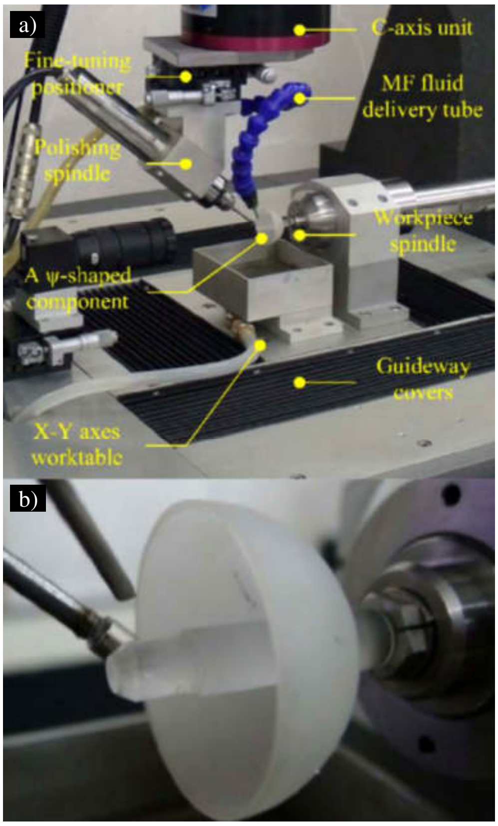


Fig. 10. The MRF machine tool with ball-end permanent-magnet polishing head: a) general overview, b) ψ-shaped small bore component [32]

Tab. 3. Surface quality from different parts of the polished components [32]

| | C axis angle (°) | Polishing gap (mm) | Spindle speed (rpm) | Surface roughness *Ra* (µm) |
|---|---|---|---|---|
| Inside of the internal surface | -15 | 0.08 | 5000 | 0.007 |
| Outside of the internal surface | -30 | 0.1 | 5000 | 0.015 |
| Forepart of the external surface | 55 | 0.1 | 8000 | 0.011 |
| Backside of the external surface | 115 | 0.14 | 8000 | 0.018 |

Kim et al. [33] used as many as three different magnetorheological fluids of various compositions for MR fluid jet polishing of BK7 glass disks. MR fluid 1: soft-grade MR fluid + cerium oxide, MR fluid 2: hard-grade MR fluid + cerium oxide, MR fluid 3: pure hard-grade MR fluid. A schematic of the MR jet polishing system is shown in Fig. 12.

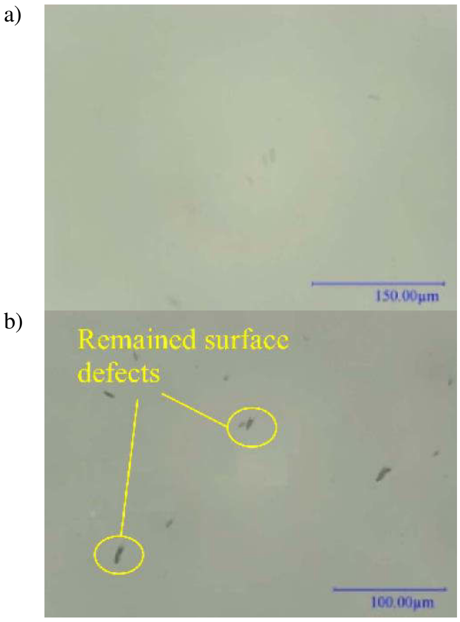


Fig. 11. Surface morphology after polishing for: a) inside of internal surface, b) backside of external surface [32]

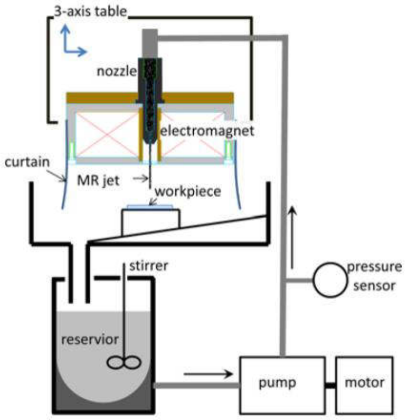


Fig. 12. Experimental setup [33]

Obtained results showed that absolute material removal depths change depending on the type of MR fluid (hardness of carbonyl iron particles and the presence of abrasives), the duration of process and impinging jet velocity.

Fig. 13 shows the surface textures of a 70 mm × 50 mm area at the centre (1), the deepest removal point (2), and the edge (3) of a removal spot, obtained by applying MR fluid 2 with jet velocities of 10 and 30 m/s.

## 3. THE MOST RECENT STUDIES

Alam and Jha [35] have developed a mathematical model for the components of normal and tangential cutting forces during machining of steel in magnetorheological milling process known as *ball end magnetorheological finishing* (BEMRF). This process has been developed for ultra-precise finishing of components with complex curvilinear shapes and surfaces [36, 37]. The milling process uses a dedicated tool with a cutter tip on which a magnetic fluid MRF is applied (Fig. 14).

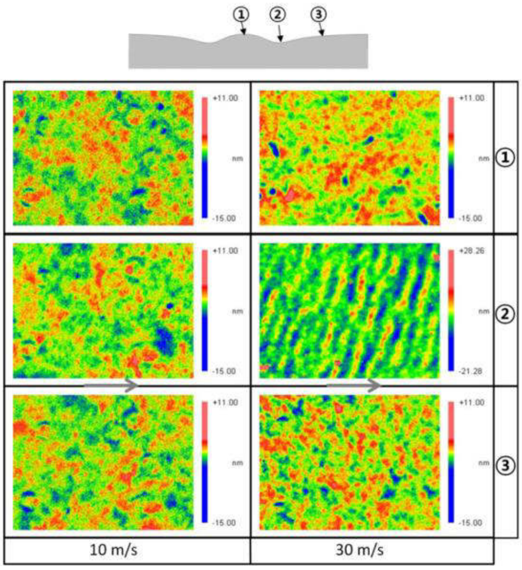


Fig. 13. Surface roughness at the centre, area of deepest erosion, and edge of the axisymmetric spot [33]

The authors explained the depth action of the abrasive particles and the material removal mechanism by theoretical analysis of the cutting force. The normal force component is mainly responsible for the depth action of abrasive particles (penetration) on the surface of the material. The tangential force component model, however, helps to understand the microcutting mechanism that occurs as a result of the shear of the surface microdegradation vertices.

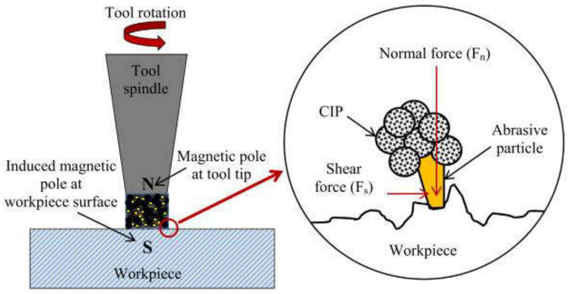


Fig. 14. Mechanism of ball end magnetorheological finishing process [35]

It is worth noting that this process occurs only under favourable conditions, when the value of the tangential force component exceeds the value of the resistance it places on the abrasive particles of the material ($F_s > R_s$). In this case, the *two-body wear process* takes place and the grain, after cutting off the tip of the roughness of the workpiece, moves forward according to the tool movement. If the tangential component of the cutting force is less than the resistance of the material, the chain of CIP particles holding the abrasive particles is broken. As a consequence, active abrasive particles can rotate freely and slide on the workpiece surface. This contributes to *the three-body abrasive wear* of the workpiece surface (Fig. 15).

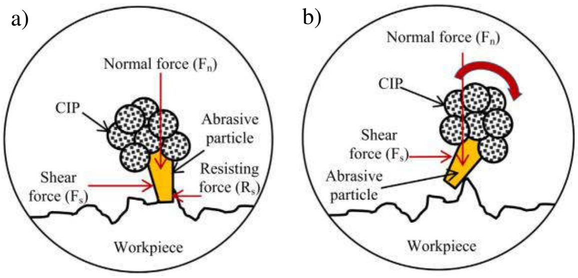


Fig. 15. Abrasive wear mechanism: a) Two-body abrasion, b) Three-body abrasion [35]

The analyses allowed the authors to develop a mathematical model of surface roughness for the BEMRF process. For this purpose, the Brinell model was used and the following values were determined: volume of material removed by the abrasive ($V_{abr}$) per rotation of the tool depending on the amount of abrasive material, the contact area of a single abrasive grain and the roughness of the surface of the material to be treated (initial and after processing) expressed by the *Ra* parameter.

After the transformations, a mathematical model was obtained which determines the *Ra* value of the surface roughness of the workpiece in the BEMRF process with an error between 7% and 31%.

Peng et al. [38] have developed effective methods for locating an aspherical lens in an MRF. They examine the workpiece localization of aspheric surface in MRF by compensating the probe radius and developing a localization algorithm. The photos of measuring and figuring process are shown in Fig. 16a–b, respectively.

The probe radius in measurement data is compensated by fitting the equidistant surface with a polynomial equation. For aspheric surface localization, an SIL algorithm is proposed in order to improve the computational efficiency which is verified by the simulation results.

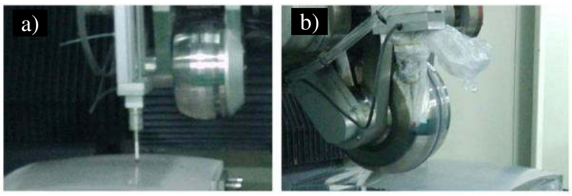
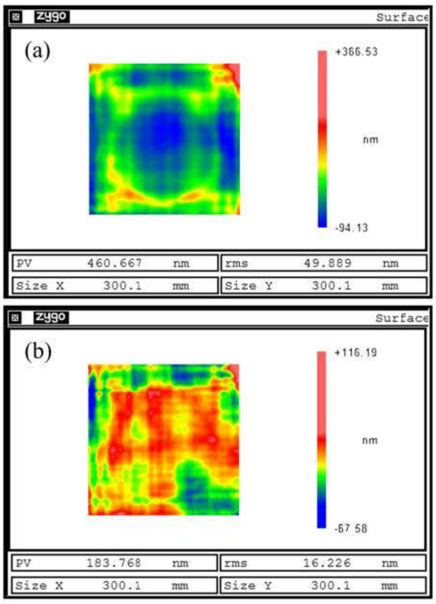


Fig. 16. Photos in the figuring experiment: a) measuring process photo, b) figuring process photo [38]

The authors have succeeded in limiting surface errors of the aspheric lens: the surface error PV is decreased from 460.7 nm to 183.8 nm, RMS is decreased from 49.9 nm to 16.2 nm (Fig. 17). The time taken by the workpiece localization procedure was 20 minutes (while it takes about 120 minutes for manual alignment of the same workpiece).



PV 460.667 nm rms 49.889 nm
Size X 300.1 mm Size Y 300.1 mm

PV 183.768 nm rms 16.226 nm
Size X 300.1 mm Size Y 300.1 mm

Fig. 17. Surface measurement results: a) surface error distribution before figuring, b) surface error distribution after figuring [38]

The accurate and efficient workpiece localization has been achieved in a MRF removal function experiment and an aspheric lens figuring experiment, which confirms the validity and practicability of the workpiece localization system invented by the authors.

The process of finishing with the use of magnetorheological fluid is also recognized for the analysis of the phenomenon using computer simulation.

Grover and Singh [39] have used magnetorheological fluid for finishing process designed for internal finishing of ferromagnetic cylindrical workpieces. Schematic of carbonyl iron particles chains gripping the active abrasives in MR polishing fluid when current excitation given to the electromagnet coil of magnetorheological honing tool is shown in Fig. 18.

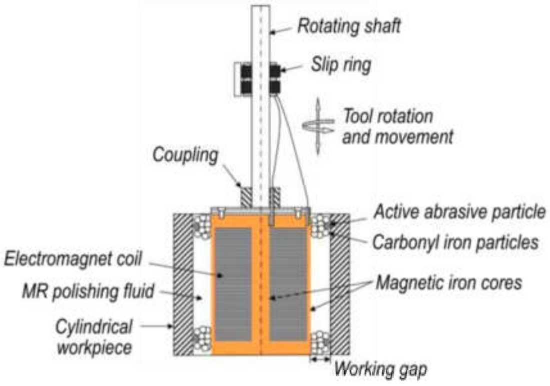


Fig. 18. Schematic of carbonyl iron particles chains locked the active abrasives in MR polishing fluid [39]

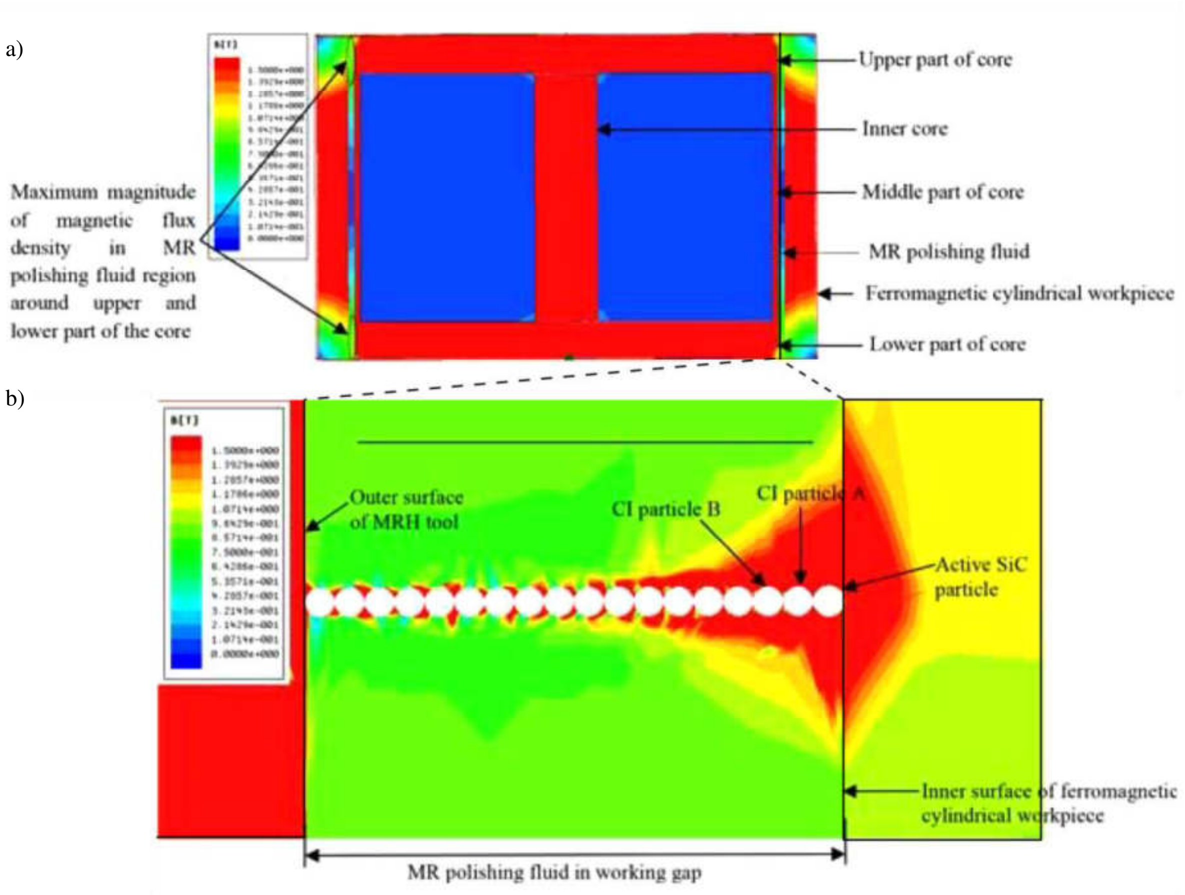


Fig. 19. Magnetic flux density distribution obtained from finite element analysis for: a) MR polishing tool and cylindrical workpiece, b) MR polishing fluid in working gap [39]

Using the finite element method, the authors analysed the distribution of magnetic flux density and magnitude of magnetic force acting on carbonyl iron particles (Fig. 19). The conducted simulation tests showed that higher magnitude of magnetic flux density in working gap is located near the region of upper and lower parts of the present magneto-rheological honing tool.

Therefore, in presented magnetorheological honing process, the finishing is mainly performed by the lower and upper parts of the tool as strong chains of carbonyl iron particles are formed in these regions.

From the magnitude of magnetic force acting on carbonyl iron particles obtained from magnetic finite element analysis justified that the carbonyl iron particle which is just adjacent to the active silicon carbide abrasive particle is major contributed to make the active SiC particles indent to workpiece surface.

Arman and Das [40] analysed the *magnetic field assisted finishing process* (MFAF). The presented results help to understand the MR fluid behaviour and the mechanism of finishing process, as well as achieving better process performance in the future.

The authors made simulation models for: the distribution of magnetic *flux* density on the workpiece surface and the preservation of the MR fluid during machining. The material removal and surface roughness model of the finishing process and the indentation force by a single active abrasive particle on the workpiece surface were also presented. For this purpose, the commercial ANSYS Maxwell (ANSYS Inc., USA) and COMSOL Multiphysics (COMSOL Inc., USA) software was used. Both applications are the great software for the design and analysis of any electromagnetic devices.

The magnetic flux density distribution on the workpiece surface is presented in Fig. 20. The authors have proved that the distribution of the magnetic field density on the surface of the machining tool is symmetrical with respect to the Cartesian axis, but is non-homogeneous. The maximum magnetic flux density (0.4 Testla in Fig. 20) is available in the corner regions due to the edge effect of the magnetic pole and hence higher magnetic field concentration.

The flow of MR fluid between permanent magnet and brass workpiece has been analysed in [40]. The simulation of the flow velocity of the MR fluid exposed to magnetic field (Fig. 21) showed the presence of two separate zones, i.e. the core area and the perimeter output zone. In the core area there are no changes in the speed gradient, whereas in the output area there is a change of speed gradient, which resembles the non-Newtonian behaviour of the fluid.

Chemo-mechanical magnetorheological finishing (CMMRF) process, one of the advanced nanofinishing process, was developed by combining essential aspects of chemo-mechanical polishing (CMP) process and magnetorheological finishing (MRF) process for surface finishing of engineering materials.

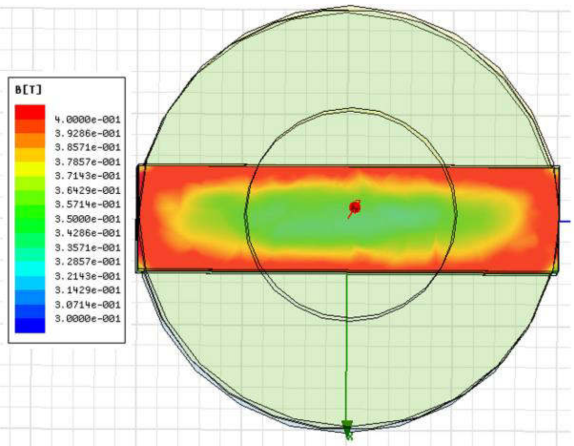


Fig. 20. The distribution of magnetic flux density on the workpiece with rectangular cross-section [40]

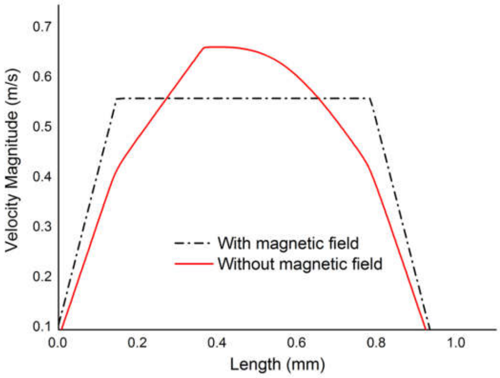


Fig. 21. The flow velocity of the magnetorheological fluid exposed to magnetic field [40]

Ranjan et al. [41] carried out the FEA based simulation, for modelling and analysis of CMMRF polishing pad as well as process towards theoretical investigation. They have developed a mathematical model to predict material removal as well as surface roughness during the CMMRF process. This model has been validated experimentally for better understanding, process prediction as well as optimization of the CMMRF process on aluminium alloy as workpiece material. Authors presented simulation results where magnetic force inducted in MR fluid deforms the shape of fluid itself (Fig. 22).

In general magnetic field needs some time (sometimes few seconds) to form a stiffened pad after applying magnetic field.

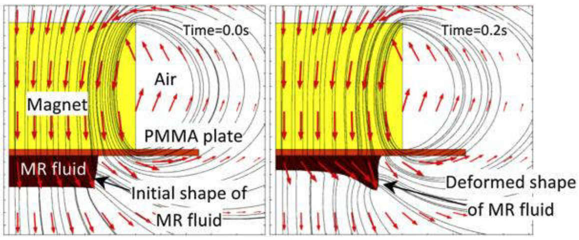


Fig. 22. Magnetic flux with direction indicated by arrows after applying magnetic field for time = 0 s (left) and after 0.2 s (right) [41]

All the examples presented above indicate that, finite element method can be successfully used to modelling of finishing processes using magneto-rheological fluids.

## 4. CONCLUSIONS

The following conclusions can be drawn from the analysis of literature concerning the use of magnetorheological liquid for finishing:

1. The magnetorheological fluids are widely used not only for processing flat surfaces, but also for finishing complex concave elements with a low radius of curvature and aspheric surface.
2. The design and construction of special MRF machines, the development of new methods for positioning the workpiece during magneto-rheological fluid processing, and the use of finite element methods to simulate phenomena occurring during machining, allow the continuous development of the method and achieve even better machining results, which is directly linked to the high quality of the resulting surfaces and an ever-growing range of applications.
3. The development of mathematical model for normal and shear forces for finishing processing material and hence model the surface roughness for a given machining parameters, increases understanding of the physics of process and mechanism of finishing action.
4. The development of surface texture model for DRMRF and the proposed quantitative method based on mathematical statistics indicate the effective suppression of directional surface texture and reduces surface roughness.

In recent years, new trends in the development of magnetorheological fluids of various compositions have emerged. In addition to the carbonylic active magnetic iron, other magnetic particles in the form of cobalt and nickel particles are also used to produce MR fluids, cubic $Fe_3O_4$ nanoparticles or sintered magnetic abrasives. The most common non-magnetic abrasive components of MR fluids, depending on the intended use of the fluid are: cerium oxide, SiC, diamond powder and alumina. Deionized water is the most common supporting medium for MR fluid.

The need for the development of new MR in fluids is mainly due to the different physical and mechanical properties of materials exposed to such fluids (metals, glasses, KDP crystals, monocrystalline 6H-SiC, monocrystalline Si, etc.) and the used type of magnetic field assisted at finishing processes.

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