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Magnetorheological finishing on metal surface: A review

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Abstract: Magnetorheological finishing (MRF) process is capable to fabricate an ultra-fine surface from flat to three-dimensional profile structures using Magnetorheological polishing fluid MRPF). MRPF is a smart fluid that can change from liquid to near solid state under the influences of magnetic field. Abrasive particle is essential material in MRPF. Three main methods in MRF process are reviewed including composition of the MRPF, rheological properties and polished surface quality.

1. Introduction

Finishing process of a metal using different methods come out with different outcome in terms of cost, time, final surface roughness and many more depending on facilities availability. MRF technique has been reported by many researchers to finished wide materials until the range of nano meters. MRPF is a smart controllable material that can change in viscosity under the application of magnetic field. General composition of MRPF are magnetizable particle, carrier liquid and non-magnetic polishing abrasive particle. In finishing process, among the widely used materials are carbonyl iron particle (CIP) as a magnetic particle, abrasive particle such as alumina [1], diamond [2], ceria [3], and deionized water as a medium carrier.

MRF has successfully polished optical glasses, hard crystals, silicon wafer and knee joint implant to sub-nanometre surface-roughness level [4]. The process is performed by interaction of magnetically stiffen MRPF-particle-structure with the metal surface under the effect of a magnetic field. This behaviour assists the material removal mechanism during the polishing process [5]. In previous study, selection of the abrasive particle determine the quality of the surface finish [6, 7].

Different type of metal such as copper [3], brass [2] and aluminium [8] has successfully polished by MRF process. This finishing process give a high impact in manufacturing industry nowadays. The significant rheological properties of MRPF such as yield stress and viscosity that can be change under the influence of a magnetic field [9] play major contribution in the polishing area. Other metal surface polishing technique such as manual polishing, chemical mechanical polishing, magnetic polishing, electrolytic polishing and ultrasonic polishing unable to effectively polished complex surface features such as micro grooves [10]. With MRF, the polishing media able to fill the void and polished the surfaces. This article provides a better understanding on MRPF that used in MRF and three main methods in MRF were briefly addressed.

2. Magnetorheological polishing fluid (MRPF)

The MRPF components and volume fraction play important roles ensure the quality of finishing process. Ajay et al. [11] reported that the different concentration of the CIP and abrasive particle play significant role in material removing mechanism. Changes of one fluid concentration will lead to rheological changes of the MRPF properties and performance. As for magnetizable particle, carbonyl iron particle (CIP) is preferable due to high permeability and low magnetic remnant [12]. For carrier liquid, few options have been reported, such as silicone oil, water and mineral oil. Among them, water based carrier liquid is the best option for polishing metal based surfaces [13].

Deionized water is commonly used as a based fluid because of the forming of soft hydrated layer on the workpiece surface compared to an oil layer surface if oil as a based fluid which restricted the interaction between abrasive and workpiece surface, thus, lower the material removal rate (MRR) effect. However, the water base carrier fluid induced more friction which lead to higher surface roughness due to lack of lubrication compared with oil-based MRPF [13].

Abrasive particle is the main contribution in MRR. This is because the spherical shape and softness of CIP has least MRR [14] compared to MRPF with abrasive particle. There were various type of abrasives particle used in MRPF namely alumina, silicon carbide, and cerium oxide and diamond particle [15]. All of them are the ceramic particles with to high hardness properties. Ajay et al [11] used alumina and ceria to polish silicon and study the effect of this two-abrasive particle. In another study, diamond particle was used as an abrasive to deburr a brass surface from Ra of 192 nm to 34 nm [2]. Surface roughness produced form ceria based MPRF on silicon surface was at wider range between 1300nm to 8 nm [16].

The hardness and the shapes of the abrasive particle with irregular and sharp edges, provide enough yield strength to remove materials on the metal surfaces [17]. Smaller size of abrasive particle shows the most irregular and sharp edges. Nagdeve et.al [18] reported that different size of abrasive particles, influence both strength and toughness of the MRPF. This is because the when MRPF were influence by magnetic field, the nonmagnetic abrasive were trap between CIP which align like a chain like structures. Bigger the size of abrasive particle that trap into the CIP chain, resulted in low magnetic force interaction. When the size of CIP and abrasive particle less different, the force interaction higher and highest changes in percentage of surface roughness.
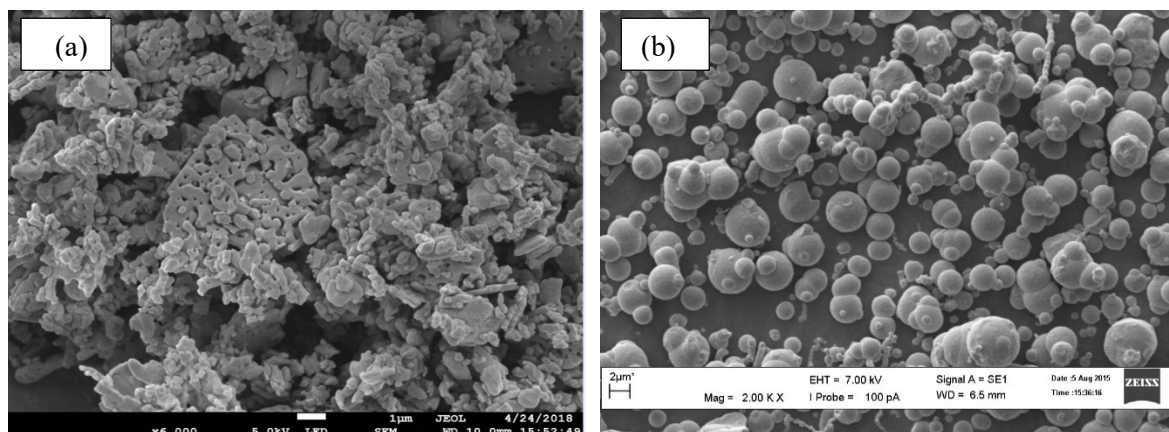

Figure 1. SEM images of a) abrasive particle b) carbonyl iron particle.

Figure 1 are the example of Scanning electron microscope (SEM) of abrasive and carbonyl iron particle. As shown in the picture, the shape of abrasive is irregulars and the shape of CIP are round. Therefore, abrasive is essential in polishing mechanism in MRF process. Additive were added to MRPF in order to suspend and as an anti-corrosion component [19]. Anti-corrosion agent was important

because water was used as the carrier fluid in most MRPF suspension. Additive such as grease, surfactant and glycerin glycol were included to improve the stability of MRPF suspension. Khan and Jha [20] added benzotriazole to MRPF to avoid oxidation of the copper workpiece in MRF process.

2.1. Effect of different composition in MRPF

In MRPF, the alignment of the CIP is the main force effect to the workpiece surface [21] and the abrasive particle play major role in material removal process. Different researchers used different composition of MRPF and regarding to the type of polished metal. The composition of each material is always different from any researcher. For example, Table 1 show different composition of the MRPF used in the MRF process. The volume fraction of CIP was ranged between 25 % and 40 %. Meanwhile the volume fraction of water- based carrier fluid was between 47% and 66.75%. Most of the MRPF is added with Glycerol as a stabilizer of the suspension with volume fraction between 1% to 8% [3], [5], and [1]. Kim et al [22] reported that adding 2% of glycerol will enhance the cohesion of the MRPF.

Lou et al [23] state that the concentration of abrasive particle contributes a large effect on surface finish. However, at certain amount of abrasive particle, the surface finished remaining constant. This is due to the excessive amount of abrasive particle that is grip by the CIP chain make the grip of abrasive particle by the CIP less strong. Nagdeve et al [18] studied the effect CIP and abrasive size and the volume concentration of this composition of should be constant in order finishing process to perform well.

Maan and Singh [24] reported that the percentage change in roughness will decrease if the abrasive particle is too high in the fluid because the CIP chain cannot grip all of the abrasive. They also state that 20% concentration of CIP particle, the optimum abrasive particle is around 15 % to 20%. This report was based on their investigation on finishing a harden AISI 52100 steel and silicon carbide as an abrasive particle in the MRPF. Beside of the concentration of CIP and abrasive particle in the MRPF, other polishing parameters should be considered during polishing process.

Kim et al [25] reported that, an MRPF with 5% volume fraction of 0.05μm alumina, showed good quality of polishing of micro parts compared to the other composition with the same size of abrasive particle. Zhang et al [26] also study the effect of particle size on MRPF and it is found that Carbonyl Iron particle of 20% volume fraction, sized 1.5 – 2.7 μm in average diameter show good in zero-field viscosity and sedimentation ratio less than 20%.

2.2. Rheological Properties of MRPF

Rheological behavior of MRPF were significantly influence by the intensity of the magnetic field applied and the concentration of the fluid composition [4] . Vein and Ajay reported that increasing of the CIP and abrasive concentration will decrease in surface roughness and increase in material removal rate in finishing process.

Yield stress of MRF is the minimum stress value required for the onset of flow and is of special interest in torque transfer applications [27]. The yield stress also depends on the composition of the MRF, the strength of the magnetic field, particle size, particle distribution [28] and the content of the fluid. The shear stress is the mechanical energy that is applied perpendicular to the direction of the chain formation of the MRF, when exposed to the magnetic field [29]. This intensity of this stress that capable to remove material from polishing process. Low shear stress of the MRPF can be overcome by changing the parameters of the polishing process such as increase polishing time and increase the intensity of the magnetic field applied.

Table 1 Various composition of MRPF for metal polishing [3], [20], [1], [5], [30].

Component of MRPF					
Abrasive (%)*	Carrier Fluid (%)*	Stabilizer (%)*	Magnetic Particle (%)*	Percentage change in Ra	Polished material
5.00 CeO_2	47.00	8.00	40.00	71.51	Copper
14.00 Al_2O_3	63.00	-	23.00	42.34	Copper
6.00 Al_2O_3	57.00	1.00	36.00	97.83	Stainless steel
3.50 Dia.	48.50	8.00	40.00	-	Stainless steel
14.00 Al_2O_3	61.00	-	25.00	75.66	Copper

* Percentage of volume fraction.

3. Magnetorheological Finishing Methodology

There are three main methods discussed in most of the article that related to the MRF process. To determine the polishing machine used to polish some considerable were taken such as the specimen that will be polished, size and shape of specimen, sample position, position of the magnet. In the polishing parameters, the first method that had been identified is rotating carrier wheel [4], second is rotating tool [20] and the third is trough [31] where MRPF were filled in a container. Each method polished different type and shape of material and different polishing parameters. Researcher have a different system on the MRPF suspension. Some of them replace the used MRPF with new MRPF at every interval time and others just use is at a minimum amount of time.

3.1 Rotating wheel method

In this method, a carrier wheel which is made up from a magnetic material or being fix with magnetic material, were rotated. The MRPF were attached to this wheel through a small gap to the workpiece. In the present of magnetic field, the MRPF ribbon were stiffened. The gradient of the magnetic field moved the CIP nearer to the wheel while the abrasive particle will move towards the workpiece. Thus, when the carrier wheel rotates, MRPF drags to the converging gap between the workpiece and the carrier wheel, and material removal took place.

This type of finishing method were first used to finished an aspheric optical workpiece [32]. Wang et al [33] established a dual rotating mechanism where there is another rotating were added in the wheel to solve directional texture problem in Figure 2. The dual rotation mechanism is to suppress directional surface texture on the workpiece. From flat, aspherical and 3D shape were able to finish by this method and had a lowest surface roughness which is 0.58 nm.
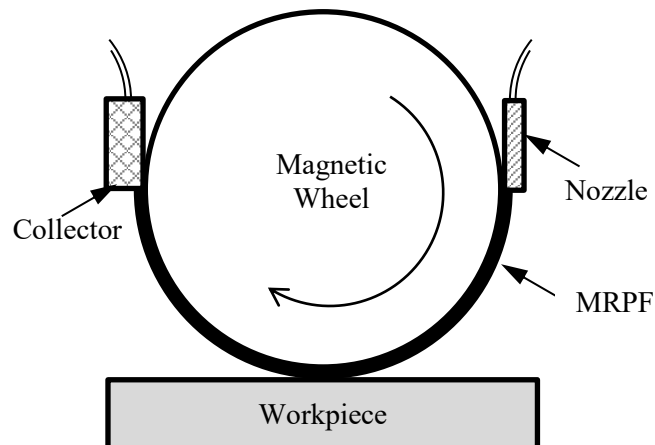
Figure 2. Principle of Wheel Rotating.

3.2 Rotating tool method

MRPF were stick at the end of the finishing tool that are made from magnetic material and produce a flexible end shape finishing tool [20] as shown in Figure 3. The flexible shape can be control by controlling the magnetic field induced to the finishing tool. When the rotating finishing were exposed by the magnetic field, the MRPF which located at the end of the tool tip surface get stiffened where the abrasive particle found closer to the workpiece surface. Thus, when the tool tip rotates on the workpiece, material removal take place.

The rotating finishing tool also known as ball end MRF are capable to polished complex of shape such concave, convex, aspheric and freeform because of the flexibility of the end tool to contact with the workpiece surface [34]. According to Singh [34] there are some advantages with this method such as the ball end can move in 3 axis in the CNC machine thus can polish variety shape of workpiece, heat, debris and wear of cutting tool can be avoided because the MRPF were continuously replenished.
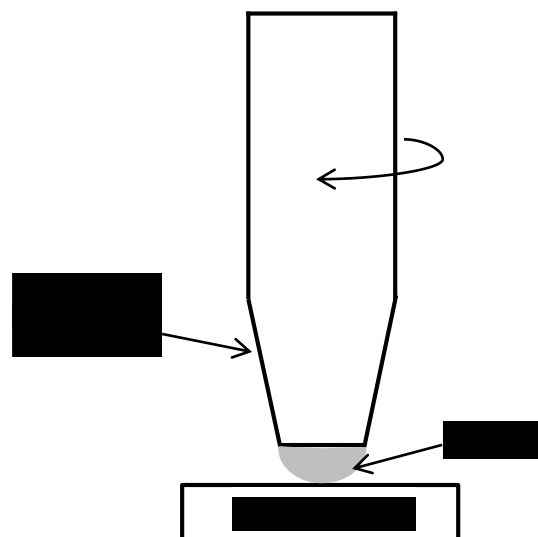
Figure 3. Principle of rotating tool method.

3.3 Rotating disk method

A disk or a through, filled with MRPF, also been used in MRF process where the workpiece submerged in the container[8] as shown in Figure 4. This method were the first used in MRF application in 1990 [35] where the north and south pole of the electromagnet straddle the trough and the workpiece were

hold by the rotating spindle. In this process, the trough rotates at 60 rpm while the rotating spindle rotate at 700 rpm. MR fluid in the rotating trough stiffens by a factor of 100 when it enters the ~4 kilogauss magnetic field near the workpiece.

In this method, the workpiece was either rotate or static is depending on the polishing machine itself. Wang et al [31] rotate both the polishing disk and the workpiece together. The surface finish of the workpiece was dependent on the polishing parameters. Luo et al [23], replace manual lapping and dimpling by using MRPF. They combine method of rotating tool and submerge the polishing tool in a through filled with MRPF. When magnetic field applied, the rotating tool which stiffened by MRPF will perfume a material removal mechanism. This result was free from dimpling related defect.
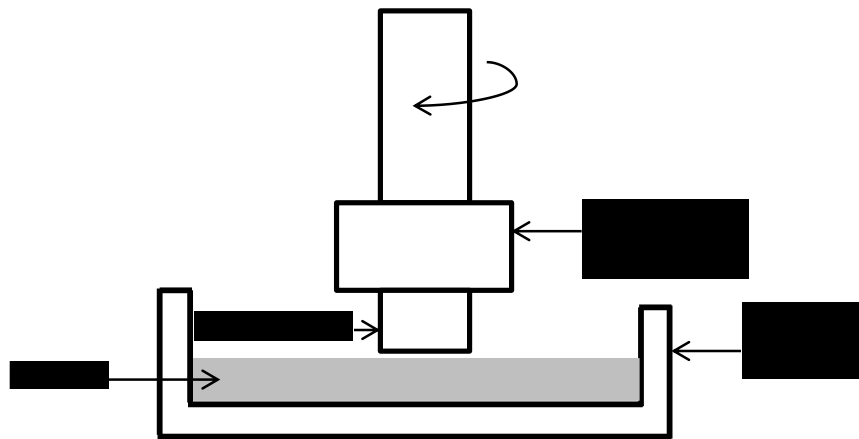

Figure 4. Principle of rotating disk method.

There are wide range of magnetic flux density uses in MRF process. Song et al. [8] only use maximum of 0.5mT with the surface speed of 80110 mm/min. Seok et. al [36] uses 200mT of magnetic field and 18850 mm/min of surface speed. From this value, the smaller magnetic field used, the higher surface speed needed. This is because lower magnetic field produce lower surface roughness and increasing the polishing time must be increase to achieve desirable surface roughness [8]. To avoid the problems, increasing the surface speed can increase the surface roughness a shorten the polishing process. To avoid the problems, increasing the surface speed can increase the surface roughness a shorten the polishing process.

From table 2, many researchers were open to the idea of using vertical carrier wheel as their polishing method. This is because the polishing machine are more simple and the MRPF are constantly delivered to the finishing zone, heat and debris are continuously removed [37]. This is important to avoid wear abrasive particle to be used many times. All the polishing machine applied different finishing conditions and finished different type and surface of material. From the polishing parameters, it is found out that most of the finest surface roughness obtain is in 0.58 nm.

The different in final surface roughness is because the polishing process are dependable on the type of the workpiece to be polished, type of abrasive material and the polishing parameters. For example, one research succeed to polished until 0.58nm but the time of polishing process did not mention in the article, while Kim et al [25] consume 20 second to produce surface roughness of 3.8nm. It is concluded that polishing parameters play a major role in surface roughness value.

Table 2. Polishing parameters of MRF methods.

Methods	Surface Speed (mm/min)	Gap (mm)	Shapes	Surface roughness
Rotating wheel	18850 to 26389	0.8 – 8	Aspherical, curve, flat surface and 3D (groove)	0.58 nm to 49 nm
Rotating tool	63617	0.08 – 2.34	Rectangular, flat, concave, irregular and curve	Less than 3 nm to 30 μm
Rotating disk	23939 to 80110	0.8 – 2.5	Flat and cylindrical surface	0.74 nm to 600 nm

4. Polished Surface Quality

There are many factors contributed to surface finished quality in MRF methods. Kathri et al [38] study the influences of working gap, magnetizing current and wheel speed as their parameters in determined the surface finish in silicone. Jang et al [2] removing burr of a different type of machined specimen with same type of abrasive particle. Nagdeve et al [18] concluded that when an abrasive particle has a less different size with CIP or in the same size, the changes in surface roughness were at the optimum condition. The effect of different composition of MRPF in MRF process also been studied by Khan and Jha [30] and they found that 14% of volume fraction of an abrasive particle were the optimum parameters in changing the surface roughness of the copper specimen.

There are also another factors influence the surface quality in MRF process such as type of abrasive particle [6], [5] , concentration of CIP and abrasive particle [4], [23], particle size [39] and strength of magnetic field and the polishing time [8]. Selection of an abrasive particle plays important roles in MRF. This is because of the interaction between abrasive particle and the workpiece increases the material removal rate in glass polishing [4]. From table 2, all methods are capable to polished workpiece until nanoscale. The significant different in MRF methods is the ability of the machine to polished complex shape of the specimen. All the methods can polish flat surface, but only rotating wheel methods are capable to polished 3D specimen.

Jha and Jain [40] developed a new method in MRF application which they combine MRF and Abrasive Flow Machining (AFM) and named it as MRAFF. This method capable in finishing a complex internal geometry shape up to nanoscale by controlling the behavioral of the rheological properties of the MRPF. On the other study, smaller size of abrasive particle shows more reduces in surface roughness compared to the bigger size of abrasive particles [39].

Khan and Jha [20] reported that when abrasive concentration reaches 14 % to 16 % of volume fraction, the surface roughness decrease. This is may be because when the abrasive reaches the limit, it may decrease the magnetic permeability of the MRPF due to increasing of nonmagnetic particle in the chain like structure.

There are several factors should be taken in polishing parameters such as intensity of magnetic field, size of particle and concentration of the particle. Some researchers study the concentration of abrasive particle and they conclude that 14% are the optimum concentration of the abrasive in the MRPF suspension. Polishing a complex shape still facing a problem with the restricted capability of the MRF machine. From this MRF process, researchers are capable to polished until 0.59 nm.

5. Conclusion

From the published article on MRF, an attempt has been made in this article to review on recent development MRPF and methods to polish metal surfaces. In other to determine the abrasive particle of MRPF, one should recognize what materials to be polished. Selection of suitable composition in MRPF improved the surface roughness of the polished materials. Rheological properties also play important

rule in MRF. There are three main methods that have been recognized in MRF process. Polishing parameters can be optimized depending on the composition of the MRPF. MRF proved successful finishing in nano level.

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