Journal of Basic and Applied Engineering Research
p-ISSN: 2350-0077; e-ISSN: 2350-0255; Volume 4, Issue 7; October-December, 2017, pp. 542-544
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Smart Cutting Fluids: A Review

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Abstract—*This paper will present the information about properties, applications and composition of smart cutting also known as Magnetorheological fluids. MR fluids are being used in many advance machining processes. The smart properties of these MR fluids can be manipulated and controlled by means of externally applied magnetic field. This paper will help us to understand the composition and use of these smart cutting fluids in detail. By using these cutting fluids nano level surface finish of work-piece can be achieved.*

Keywords*: M.R. fluids, Magnetic properties, Carbonyl Iron powder, Polishing Abrasives, Magnetorheological finishing.*

1. INTRODUCTION

Technologically advanced industries such as aeronautics, nuclear reactor, automobiles etc. are demanding materials such as high strength temperature resistant (HSTR) alloys having strength to weight ratio. Researchers in the field of materials science are developing the materials having high strength, hardness, toughness and other diverse properties. This also needs the development of improved cutting tools so that productivity is not hampered. In conventional machining processes, increase in hardness of work materials results in decrease of economic cutting speed. It is no longer possible to find tool materials like titanium, stainless steel, ceramics and similar other high strength temperature alloys and difficult to machine alloys. Production of complex shapes in such materials by the traditional methods is still more difficult. Other high level requirements are better surface finish, low values of tolerances, high production rate, complex shapes etc. making of holes in difficult to machine materials is another area where appropriate processes are very much in demand. To meet such demand, different classes of machining processes (advanced machining processes) are to be developed.

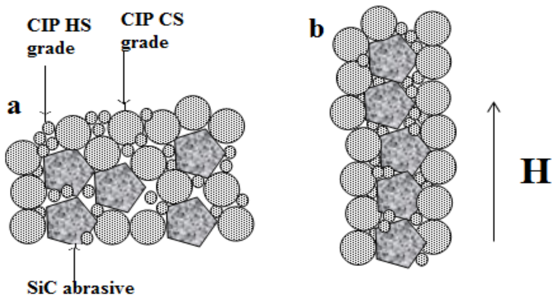
Advanced finishing processes like abrasive flow finishing (AFF) process which provides high level surface finish and close tolerances with an economically acceptable rate of surface generation for a wide range of industrial applications. The limitation of AFF process is that the rheological property of abrasive medium is not controlled by external means during the finishing. Secondly, it is very difficult to mix the abrasive particles in the polymeric medium uniformly.

The Magnetorheological finishing (MRF) is another finishing process in which the rheological properties of smart MR fluid is manipulated and controlled by means of externally applied magnetic field. Hence, controlled way finishing of work-piece materials takes place and nano level surface finish of work-piece can be achieved.

2. COMPOSITION OF SMART MR FLUIDS

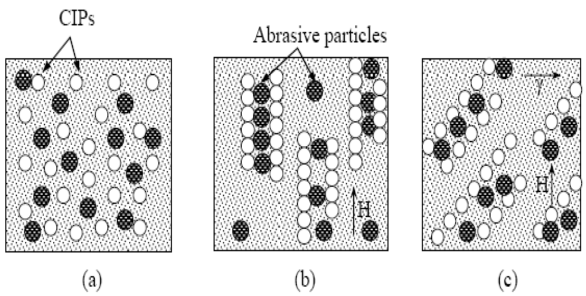
Magnetorheology deals with the study of flow and deformation of materials under applied magnetic field. Discovery of MR fluid is credited to Jacob Rabinow in 1949, whose rheological behavior can be manipulated by external magnetic field. MR fluids are suspension of carbonyl iron powder (CIP), polishing abrasives, carrier fluid, and stabilizers which act as key element in MR finishing. MR fluids represent a class of smart materials whose rheological properties such as apparent viscosity and shear stress change with magnetic field. Apparent viscosity changes significantly (10^5 - 10^6 times) within few milliseconds when magnetic field is applied and found completely reversible on its removal. Fig. 1 shows the schematic diagram of particles in absence and in presence of magnetic field.

CIPs and abrasive particles are randomly distributed in absence of magnetic field as shown in fig. 2(a). These particles form a stable chain like columnar structure with abrasives embedded in between in external magnetic field as shown in fig.2 (b). The magnetic force between iron particles encompassing abrasives provide bonding strength to it and its magnitude is a function of iron concentration, magnetic field intensity, magnetic permeability of particles and particle size. Particles acquire dipole moments proportional to magnetic field strength and when dipolar interaction between particles exceeds their Brownian kinetic energy, particles aggregate into chains of dipoles aligned in magnetic field direction [6]. Fig. 1(c) shows an increasing resistance to an applied shear strain (γ) due to MRP fluid yield stress.



Schematic diagram of particles (a) in absence of magnetic field (b) Chain formation in magnetic field H

Figure 1



(a) MRP-fluid at no magnetic field (b) at magnetic field strength H (c) At magnetic field H & applied shear strain
Figure 2

3. MAGNETORHEOLOGICAL FINISHING

Magnetorheological (MR) finishing is an advanced finishing method to finish work-piece surface without damage of surface/subsurface layers. In this process, finishing forces can be precisely controlled by external magnetic field and selective material removal takes place which is an important consideration for nano level finishing of work-piece with close tolerances. The normal force acting on abrasive particle is relatively very small as compared to traditional polishing methods and material removal is governed by shear stress rather than hydrodynamic pressure. It was observed that the normal force acting on abrasive particle within MR fluid ribbon is approximately 1×10^{-7} N which is very small as compared to traditional polishing, $5–200 \times 10^{-3}$ N [10]. The process is used for finishing variety of surfaces such as flat, concave, convex and spherical optical components and its working principle is shown in fig.3. MRP fluid creates temporary finishing surface, whose stiffness can be manipulated and controlled in real time by changing applied magnetic field. The work-piece is attached at fixed distance from moving wheel and electromagnet located below the wheel surface generates magnetic field in the working gap. When MRP fluid is delivered to the wheel, it is pulled against the wheel surface by magnetic field and becomes a subaperture polishing tool. Computer program determines schedule for varying position of work-piece as it sweeps through polishing zone.

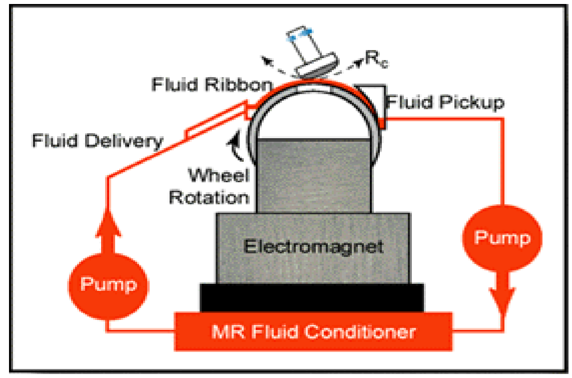


Fig. 3: Magnetorheological finishing apparatus

Mechanism of MR finishing process where CIPs chain structure holds polishing abrasives firmly as shown in Fig.4. Wear occurs on the surface by MR particle chains under relative motion with work-piece. Tips of surface asperities are abraded due to plastic deformation caused by stress concentration.

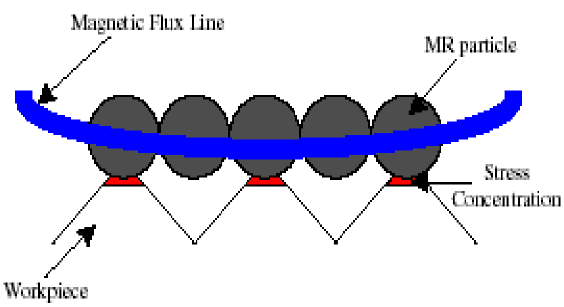


Fig. 4: Possible wears mechanism in MR finishing process

4. PROPERTIES AND SELECTION OF MR FLUID COMPOSITION

The performance of all magnetorheological finishing processes relies on magnetorheological effect exhibited by carbonyl iron particles along with abrasive particles in non-magnetic carrier medium. Hence, magnetorheological fluid and its composition are crucial in MRF processes. MR fluids respond to an applied magnetic field in their rheological behavior (Rabinow 1948). MR fluids are suspensions of micron sized magnetic particles in a visco-elastic base medium such as silicone oil, water, glycerol, paraffin oil with some additives.

In the absence of magnetic field, these fluids exhibit non Newtonian behavior i.e. weak Bingham behavior. On the application of magnetic field, these fluids become stiffer and large shear force is required to make the fluid flow. The ultimate strength of MR fluid is limited by magnetic saturation.

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

The remnant magnetization of the particles causes undesired particle aggregation arises in concentrated MR fluids. As a result, the formation of stiff sediments, which are very difficult to redisperse, is facilitated. In order to reduce particle aggregation and settling, different procedures have been proposed:

- Adding thyrotrophic agents (ex. Carbon fibers, silica nanoparticles) (Bossis, Volkova et al. 2003; De Vicente, López-López et al. 2003).
- Adding surfactants (ex Oleic or stearic acid) (Phulé and Ginder 1999).
- Adding magnetic nano-particles (Chin, Park et al. 2001; López-López, de Vicente et al. 2005).
- The use of visco-plastic media as a continuous phase (Rankin, Horvath et al. 1999).
- Water-in-oil emulsions as carrier liquids (Park, Chin et al. 2001). Glycerol and surfactants are used in water based fluid as stabilizers. Alkaline also helps to improve the stability and resistance to rust (Kordonski and Golini 1998).

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

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

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

5. CONCLUSIONS

The following conclusions can be drawn from the above presented views. That with the help of MR Fluids we can use effectively super finishing process for optical materials with variety shapes such as flat, spherical. Concave and convex surface finish up to nanometer level and it can be achieved without sub surface damage. That because of smart properties of M R fluids new machining processes has been developed as a new deterministic finishing process. These processes also possess the ability to correct roundness error of hard cylindrical stainless tubes. . Further, 3D CFD simulation of MRP fluid in the finishing zone and simulation of surface roughness will help to automate R-MRAFF process for better finishing performance.

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