Effect of Various Factors on Forces Acting in Magneto Rheological Fluid Finishing: A Review

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ABSTRACT
Micro/Nano machining has been classified in to two categories traditional and advanced. In advanced surface finishing , free abrasive is mixed with fluid and allow to flow to perform machining . The main benefit of these methods are surface finishing of complex shapes can be easily achieved and forces acting on free surface by action of abrasive flow can be controlled as well. The magnetorheological(MR) fluid based finishing is an appropriate process for finishing of flat ,3D and freeform surfaces . In case of finishing, the knowledge of forces acting during finishing operations helps to understand the process more because by controlling the forces , surface roughness can be controlled . An investigation has been carried out to study the effect of various factors such as curvature of workpiece , rotational speed of tool and effect of feed rate of workpiece . The normal force seems to dominate over all the forces . A theoretical model has been developed which tells about the normal and tangential forces acting on workpiece , which helps in understanding the interaction of abrasive and workpiece particle in MR fluid based finishing . A comparison has been carried out between theoretical and experimental model which shows that both are in good agreement.

Keywords
Magneto Rheological Fluid

1. INTRODUCTION
Magnetorheological fluid based finishing is used for variety of materials such as optical,crystals & few metals also. In this process abrasive is combined with CIP's & fluid which under the effect of magnetic field become stiff & remove material from work material. Finishing of curved free form 3D surface is very difficult due to difficulty in defining the mathematical equation of surface , researchers have developed many techniques such as honing[1], grinding[2], ball burnishing[3] , flexible abrasive tool [4] but still the requirement for nanometer surface finish is still an issue. However , in MR finishing nanometer level finishing can be achieved which is only possible due to the control of forces arises due to the interaction of abrasive - workpiece material . Kim and Noh [5] developed a magnetic polishing of dies and mould . The initial surface roughness is reduced by abrasive wheel which is followed by surface roughness to further reduce the roughness of material up to 90 nm from 640 nm . Singh et al.[6] developed a ball end MR finishing 3D workpiece surface made by milling processes at different angles is reduced to16.6nm , 30.4nm ,71nm and 123.7nm on flat , curve surfaces respectively in 60 passes of finishing . Experiment is based on prosthesis knee joint implant made of titanium . Different MR fluids such as oil based , water based and chemical added water based are used to study the effect on the joint .

Schinhaerl et al. [10] found that normal force vary between 2 and 20N ,and observed that it is mainly dependent on working gap between tool and workpiece .

Miao et al.[7] suggested that normal force and tangential force increases with diamond concentration up to some level and beyond that it destabilizes. It has been found that normal and tangential forces are effected by these parameters such as working gap , rotational speed of tool , feed to the tool .

2. EXPERIMENTATION
Fig. 1(a) shows that MRFF tool is mounted on a CNC milling machine.MR fluid is allowed to flow from lower end of tool where a permanent magnet is attached. [11] A sintered Nd-Fe-B permanent magnet(N50 grade) is used for the magnetization of MRfluid , which has maximum energy product (BH_{max}) of 48-51 mega Gauss Oersted (MGOe). The MR fluid get stiffened and create a flexible brush as shown in Fig. 1(a) . The tool moves downward up to a particular gap and to cover more area feed is given in X axis as well as Y axis .

To measure the components of forces a dynamometer is placed on the table. Initially when there is no contact between the tool and workpiece it shows the value of normal force due to the weight of workpiece . Tangential force value is obtained when the tool start machining the workpiece and axial force is obtained when the feed is given to tool. The workpiece is a replica of joint implant having atleast two radii of curvature . The material of workpiece is a stainless steel. The curvature is only along the y-direction and the surface non variant flat along x-direction as shown in Fig. 1(c). The finishing tool is attached at the 3-axes CNC milling , no inclination is given to tool . In order to study about the effect of effect of curvature on forces it become necessary to measure the curvature on the workpiece .

Table 1. Constant parameter during experiment [8]

Parameters	Values
Working gaps (mm)	1
Average size of CIP's (µm)	6
Average size of diamond particles (µm)	6
Concentration of CIP's (%vol)	40
Concentration of diamond particles (%vol)	3.5
Concentration of water (%vol)	48.5
Concentration of glycerol (%vol)	8

Table 2. Selected process parameters [8]

PARAMETERS	L1	L2	L3	L4	L5
-Angle (deg)	5	10	15	20	25
-Tool rotation speed (RPM)	700	800	900	1000	1100
-Feed rate(mm/min)	1	2	3	4	5

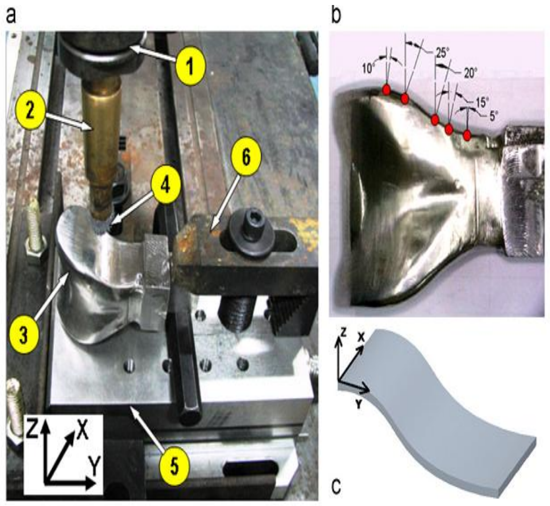

Fig.1. (a) Photograph of freeform surface (1-tool holder , 2-MRFF tool ,3-workpiece,4-MR fluid brush , 5-three axes dynamometer and 6- workpiece fixture) , (b) Location of force measurement at different angles , (c) Schematic profile of surface . [11]

On measuring the curvature, it is found that radius of curvature lies between (5 degree to 25 degree) as shown in Fig. 1(b) . In this study the effect of angle of curvature of workpiece , rotational speed of tool and feed rate of workpiece has been proposed . Based on earlier reported work [8] parameters are kept constant as shown in (table 1) . the process parameters and levels are given in (table 2).

The full factorial design of experiments [12] were performed and total 125 experiments were conducted to collect force measurement data . A lab view software is used to simultaneously record the normal force (F_n) , axial force (F_a) and tangential force (F_t) . Different variation of forces during preloading and loading condition is show in Fig.2.

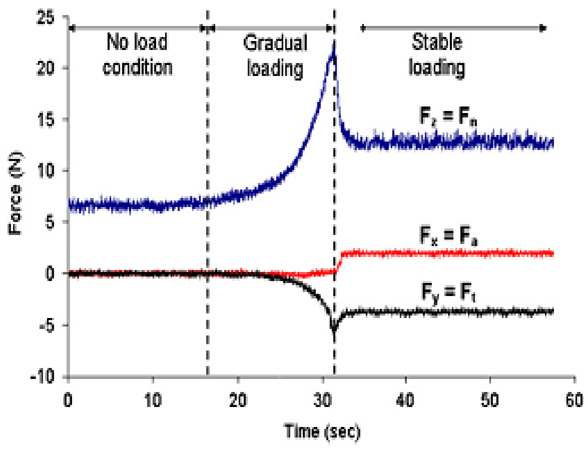

Fig.2. Sample for force measurement of data [11]

The measured force values are fitted with quadratic equations (1-3) . It has also been observed from ANOVA that interaction term have less than 1% of contribution to the force

- F_a(N)= $-4.372 - 0.0810\theta + 0.012S + 0.247F - 0.000040\theta S - 0.00210\theta A + 0.00009SF + 0.002\theta^2 - 0.000006S^2 - 0.044F^2$ (1) [11]
- F_t(N)= $-7.257 - 0.191\theta + 0.021S + 0.526F - 0.000080\theta S - 0.00800\theta F + 0.0001SF + 0.006\theta^2 - 0.00001S^2 - 0.077F^2$ (2) [11]
- F_n(N)= $-15.027 - 0.266\theta + 0.042S + 0.757F - 0.00020\theta S - 0.00560\theta F + 0.0001SF + 0.0085\theta^2 - 0.00002S^2 - 0.115F^2$ (3) [11]

3. RESULTS AND DISCUSSIONS

The effect of rotational speed of tool , feed of workpiece and curvature on workpiece on normal force , axial force and tangential force .

3.1.Angle of curvature of the workpiece surface

The angle of curvature of workpiece is defined as angle between the rotational axis of tool and normal to the workpiece . It is observed that with increase in curvature of workpiece forces decreases due to decrease in area of contact as shown in Fig.3. Furthermore working gap also varies with angle of curvature as shown in Fig.4 . As the gap increases , magnetic flux density decreases as magnetic flux density is inversely proportional to working gap . As a result strong interaction of tool with workpiece do not take place which results in decrease in normal force . A model has been set up in software . A magnetometer is used to measure magnetic properties such as (saturization magnetization , magnetic field and magneticflux).

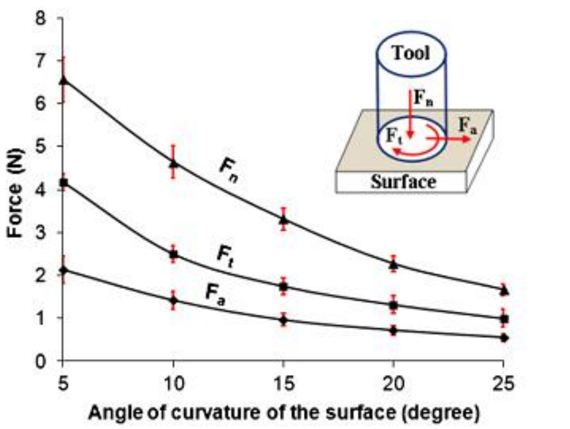

Fig.3. Effect of angle of curvature on forces at s=1000RPM and f=4mm/min [11]

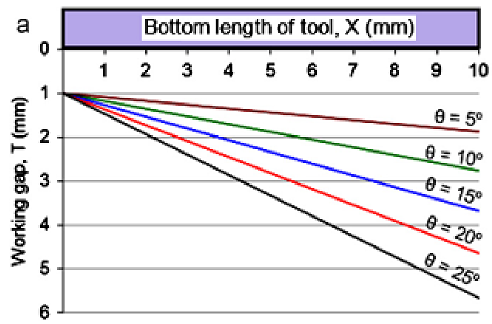

Fig.4. Working gap with angle of curvature [11]

A non linear B-H curve is obtained from simulation .All the inputs (properties of MR fluid , work piece and magnet) are supplied to the FEA solver and simulation is carried out. The relation between magnetic flux and working gap is obtained as shown in Fig.5 .

3.2. Rotational speed of the tool

Increase in rotational speed of the tool results in increase in magnitude of all the forces up to optimum value . On reaching the optimum value , increase in rotational speed of tool results in decrease on forces which results in decrease of MRR as shown in Fig.6. The main reason behind the reduction of force is decrease in yield stress of material due to yielding . It has been reported that yield stress of MR fluid decreases with increase of velocity [9] .

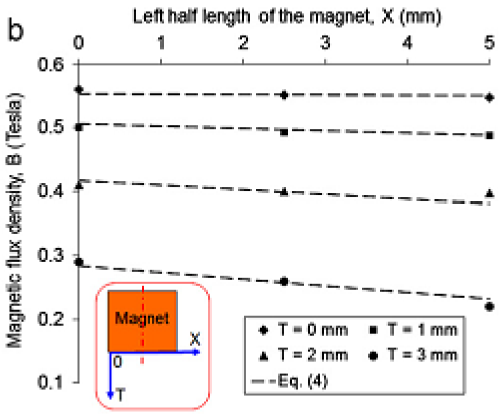

Fig.5. Magnetic flux density in working gap

[11]

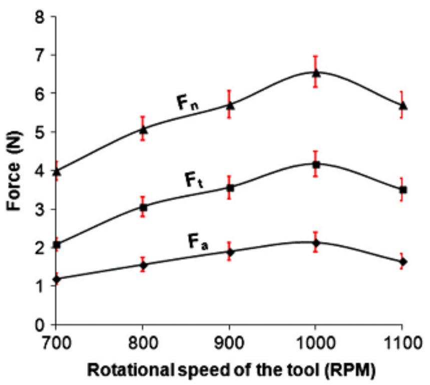

Fig.6. Effect of rotational speed of tool on the forces at f=4mm/min and $\theta = 5^{\circ}$ [11]

The destruction of CIP's chains become so prominent that it results in decrease in stiffness of MR fluid brush . As can be seen from Fig.7, due to decrease in stiffness , spikes start generating in MR fluid brush which is not able to exert enough force on workpiece.

Fig.7. Condition of MR fluid brush at different rotational speed of tool 900 RPM and 1100 RPM respectively [11]

3.3. Feed rate of workpiece

The main motive behind providing feed to the workpiece to increase the surface area covered by tool . As from Fig.8. we can see that it follows the same pattern as that of rotational speed of tool . But on reaching optimum value it decreases at lower rate as compared to rotational speed . The reason for decreasing of value of forces is shearing of MR brush due to breakage of CIP's chain at high feed rate .

4. MODELING OF FORCES

After performing the experiment , efforts has been applied to develope model of normal force and tangential force to understand the mechanism of MRR.

Assumptions has been made for modeling of forces . [11]

- All abrasive particles of same size and spherical in shape .
- Only abrasive particles which are in contact with workpiece are active abrasive.
- Due to low MRR, the material removed mixed with MR fluid do not alter its properties.

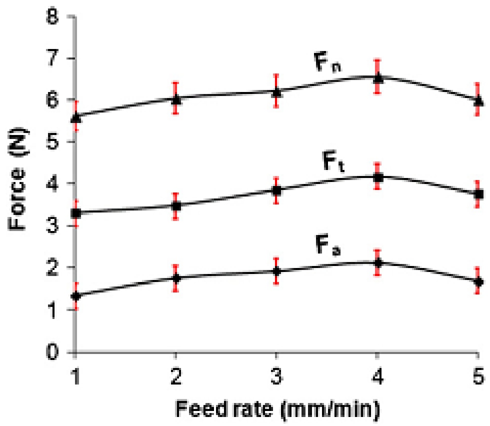

Fig.8. Effect on feed rate on force at s=5000RPM and $\theta = 5^{\circ}$ [11]

4.1. Forces acting on abrasive

In MRFF , normal force is responsible for indentation in workpiece and tangential force is responsible for shearing of workpiece . So that's why it had became important to create a model of forces .

4.1.1. Normal force and tangential force

The number of active abrasive particles in contact with workpiece is calculated by

$N_{act,abr} = S_a \div d^2$ [11]

where ,

$S_a = 37.584 + 13.06\theta - 1.7147\theta^2 + 0.0667\theta^3 - 0.0008\theta^4$ [11]

θ= angle of curvature of workpiece

d= distance between centres of active abrasive as shown in Fig.9.

The volume of active abrasive can be calculated by

$V_{act,abr} = N_{act,abr} \times V_{abr}$ [11]

NORMAL FORCE ($F_{n\ total}$)

$F_{n\_total} = F_{n\_abr} \times N_{act,abr}$ [11]

$F_{n\_abr} = F_{mn} + F_{cfn}$ [11]

$F_{mn} = -V_{act,abr}(-0.5474 + 454.42B - 551.51B^2 + 300.04B^3 - 60.78B^4)\nabla B \times \cos\theta$ [11]

where,

$\mathbf{B} = 0.552 - 3\theta 10^{-2} - 6X10^{-4} - 0.03T + 3\theta 10^{-10} + \theta T10^{-11} - 0.003XT - \theta^2 10^{-13} + 6X^2 10^{-5} - 0.02T^2$ [11]

θ=angle of curvature

T=working gap(mm)

X=bottom length of tool

$F_{cfn} = m_a \omega^2 \sin\theta \,|\sum_{i=0}^{n} 5 - id\cos\theta|$ [11]

where,

m_a=mass of abrasive

ω=angular velocity of tool

n=number of tracks of abrasive particles

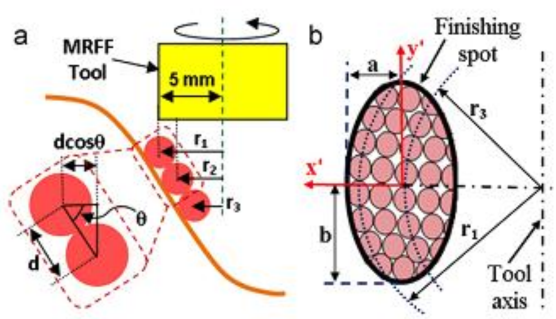

Fig.9.(a)Front view (b)top view of variation in r with respect to location of abrasive[11]

TANGENTIAL FORCE (F_t)

$F_t = F_s + F_{cor}$ [11]

$F_s = A_p \times \tau_y$ [11]

where,

$\boldsymbol{\tau_y} = -163243.51 + 4447.55A + 39378.94B + 8241.52C - 0.03S + 223.23AC + 0.001BC + 0.001CS + 3955.64AB - 0.002AS + 0.05BS + 365.27A^2 - 25097.02B^2 - 92.02C^2 + 0.0000002S^2$ [11]

A_p = projected under tool(assumed elliptical)

$F_{cor} = m_a \omega^2 |\sum_{i=0}^{n} 5 - id\cos\theta|$ [11]

where,

m_a=mass of abrasive

ω=angular velocity of tool

n=number of tracks of abrasive particles

5. CONCLUSION

- Normal and tangential force decreases with increase in radius of curvature of 3D workpiece due to decrease in area of contact .
- Forces increases with increase in rotational speed of tool and feed rate of workpiece up to optimum value and start decreasing. The main reason behind the reduction of force is decrease in yield stress of material due to yielding .
- Theoretical values of forces is less than that of experimental values due to increase in contact area of tool.
- Theoretical value of normal and tangential forces increases due to increase in coriolis force.
- Magnetic flux density decreases with increase in working gap between tool and workpiece .
- Forces can be controlled by varying parameters which make it possible to control the surface roughness.

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