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Modeling and simulation of surface roughness in magnetorheological fluid based honing process

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ABSTRACT

A newly magnetorheological fluid based honing process is developed for internal surface finishing of ferromagnetic cylindrical workpiece as existing magnetorheological fluid based finishing processes are not found suitable to finish the ferromagnetic internal surfaces. The performance of the present developed finishing process in terms of reduce wear and improve the functional application of cylindrical components, mainly depends on the normal force acting on abrasive particles due to magnetic behavior of carbonyl iron particles in magnetorheological polishing fluid. Also, it depends on shear force acting on surface by abrasive particles due to translational and rotational motion of tool as similar to the honing operation. For the newly developed finishing process, the modeling of surface roughness with the effect of induced magnetic field and magnetic normal force for different finishing cycles have been proposed. To validate the model and understand the wear mechanism during finishing, the experiments have been performed on the internal surface of cylindrical ferromagnetic workpiece with the three different sets of finishing cycles. The surface roughness of cylindrical workpiece has experimentally measured with Mitutoyo SJ-400 surftest. Also, to understand wear mechanism during finishing, the scanning electron microscopy has been performed. The theoretical calculated values of surface roughness with number of finishing cycles are validated with experimentally obtained surface roughness values for the same number of finishing cycles and conditions. Both were found in close agreement within 5.88%. Thus, the present developed finishing process is found suitable to reduce wear on internal surface of cylindrical components which leads to saving in service, energy consumption, maintenance costs, and improves its functional applications as compared to traditional finishing techniques.

1. Introduction

The surface finishing mainly depends upon the material removal by wear mechanism. In case of abrasion wear, the chip removal takes place due to micro-cutting which mainly influence the finishing performance. The different required components must be made to satisfy the functional necessity of surface roughness as per its standardization in today's industry [1]. Also, industries are facing challenges to get required functional necessities of product having complicated shapes, geometry and large variation in sizes [2,3]. The traditional finishing processes are incapable to produce high qualitative surface finish due to lack of precise control over forces on workpiece surface through abrasive particles during the finishing. The traditional processes uses a rigid type of tool for removing material from the workpiece surface and induces substantial normal stress which causes micro-cracks, reduces strength and reliability of the product [4]. Therefore, the precise control of cutting forces produce during finishing operation is an important aspect for achieving closer tolerances design and better surface quality without damaging the surface textures.

These expectations led to the development of magnetorheological (MR) fluid based finishing processes in which finishing forces can be precisely controlled through the externally applied magnetic field [5]. Therefore, the surface can be finished more effectively to get required surface characteristics. The MR polishing fluid used during finishing is commonly a suspension of magnetic iron powder and abrasive powder mixed in base medium of silicon oil and grease or water etc. [6,7]. The removal of unwanted material during MR fluid based finishing processes is mainly due to shear force [8]. The depth of indentation of abrasive particle onto the workpiece surface is due to magnetic normal force [9,10]. The

Abbreviations: MR, Magnetorheological; MRAFF, Magnetorheological abrasive flow finishing; R-MRAFF, Rotational-magnetorheological abrasive flow finishing; PLC, Programmable logic controller; DC, Direct current; HMI, Human machine interface; CIPs, Carbonyl iron particles; SiC, Silicon carbide; SWG, Standard wire gauge.

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Nomenclature

F_{normal}	Magnetic normal force (N)
F_{Ls}	Longitudinal shear force (N)
F_{Ts}	Tangential shear force (N)
R_{normal}	Normal reaction (N)
F_{shear}	Shear force (N)
R_{shear}	Shear reaction (N)
θ	Angle made by the arc which is formed with finishing surface of tool core with the central vertical axis of tool (°)
R_1	Radius, from the centre of tool to the internal surface of cylindrical ferromagnetic workpiece (mm)
R_2	Radius, from the centre of tool to the finishing surface of tool core (mm)
D	Working gap (mm)
w	Width of tool core (mm)
A	Area of MR polishing fluid layer (mm^2)
V_{MRPF}	Volume of MR polishing fluid (mm^3)
h	Height of tool core (mm)
V_{CIPs}	Volume of carbonyl iron particles (mm^3)
V_{single_CIP}	Volume of single CIP (mm^3)
d_c	Diameter of CIP (mm)
m	Mass of single CIP (kg)
n	Number of electromagnetic coil turns
I	Current passing through the line segment of electromagnet (A)
H	Magnetic field intensity (A/m)
B	Magnetic flux density (T)
μ_0	Magnetic permeability of space (N/A^2)
μ_r	Magnetic relative permeability (N/A^2)
μ	Magnetic permeability (N/A^2)
F_m	Magnetic force due to magnetic field (N)
χ_m	Mass of magnetic susceptibility (m^3/ kg)
M	Magnetization of CIP (A-m^2/Kg)
F_i	Indentation force (N)
D_g	Diameter of abrasive grain (mm)
D_i	Diameter of indentation (mm)
d	Depth of indentation (mm)
H_{BHN}	Brinell hardness number (BHN)
V_{single_SiC}	Volume of single SiC (mm^3)
N_g	Number of active abrasives particles during single stroke of finishing action
Y_i	Roughness profile at i^{th} location
R_a	Centreline average roughness value (μm)

magnetic field strength is an imperative characteristic for improving MR polishing fluid rheological properties [11]. An apparent viscosity of MR polishing fluid changes with the application of magnetic field [12]. The different types of MR fluid based finishing processes [13–18] have been developed for finishing of several shapes of objects such as flat, concave, internal intricate, dome type, 3D complex surfaces etc. These processes provide the external control over the finishing forces that acted on the surface of workpiece [19]. None of these MR fluid based finishing processes are suitable for finishing internal cylindrical surface made up of ferromagnetic materials.

The existing finishing processes, MRAFF [14] and R-MRAFF [15] are used for internal surface finishing of cylindrical non-ferromagnetic workpiece and not found suitable for ferromagnetic workpiece. During the internal surface finishing of ferromagnetic workpiece, the stiffened MR polishing fluid gets stuck to the ferromagnetic workpiece surface. This is because of the electromagnet was kept outside the ferromagnetic cylindrical workpiece surface and MR polishing fluid moved inside the workpiece surface. The MR polishing fluid gets stuck to the internal surface of ferromagnetic workpiece during its finishing and no abrasion wear taken place. Owing to this, the peaks of roughness from internal ferromagnetic cylindrical surface could not be worn out during the finishing operation. The main reason for the aforesaid MR fluid based finishing processes as these are not found suitable to finish the internal surface of ferromagnetic workpiece due to the higher magnetic flux density on the ferromagnetic workpiece surface than the MR polishing fluid. This is further because of electromagnet position was kept outside the internal surface of cylindrical workpiece. Thus, to overcome this challenge, a new magnetorheological fluid based honing process has been developed to finish the internal surface of ferromagnetic cylindrical workpiece. In the present developed process, the position of the electromagnet along with the finishing tool core surface has been kept inside the internal surface of cylindrical workpiece to reciprocate and rotate during finishing as likely similar to the movement of honing tool in traditional honing process. The present newly developed magnetorheological fluid based honing process can ensure higher magnetic flux density always on the finishing tool core surface and comparatively low on the internal surface of ferromagnetic cylindrical workpiece. The higher magnetic flux density on the finishing tool core surface and low on the internal surface of ferromagnetic cylindrical workpiece evidenced that the MR polishing fluid retain always on finishing tool core surface and does not stick on the internal surface of ferromagnetic cylindrical workpiece (low magnetic flux density) during finishing. As a result, the peaks of roughness from the internal surface of ferromagnetic cylindrical workpiece can be worn out due to abrasion wear when finishing action performed. The application of cylindrical ferromagnetic components in today's industry are useful in cylindrical barrel for injection molding machine, cylindrical molds and dies, wave guides, machine tool components etc. The internal finishing of these components can be made possible by the present specially designed finishing tool which results in improving the functional and technological usefulness of the cylindrical components.

2. Magnetorheological (MR) fluid based honing process and the mechanism of surface finish

A new computer controlled PLC (programmable logic controller) program based magnetorheological (MR) honing process has been made for internal surface finishing of cylindrical objects (both ferromagnetic and non-ferromagnetic) as shown in Fig. 1. The tool developed in this study is used to finish the internal surface as similar to the tool movement in case of traditional honing operation. Therefore, this process is named as magnetorheological fluid based honing process. The specially designed MR honing tool along with the C-shaped aluminum bracket is attached to vertical surface of Z-axis slide and is driven with the help of servo motor through timing belt and pulley arrangement. The DC power is supplied to the electromagnet of MR fluid based honing tool through slip ring along with the carbon brushes. The cylindrical workpiece is fixed to grinding vice with the help of a supporting fixture. The grinding vice is further mounted on X-Y axis linear slides. The proper centering of the cylindrical workpiece with respect to the MR fluid based honing tool along the