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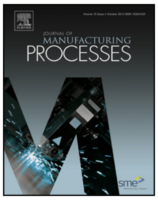

Technical Paper

Determining work-brush interface temperature in magnetic abrasive finishing process

Vivek Mishra[a], Harsha Goel[a], Rahul S. Mulik[b,*], P.M. Pandey[a]

[a] *Department of Mechanical Engineering, Indian Institute of Technology Delhi, New Delhi, India*
[b] *Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Roorkee, India*

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ABSTRACT

Magnetic abrasive finishing (MAF) is a process in which the work surface is finished by removing the material in the form of micro chips by magnetic abrasive particles (MAPs) in the presence of magnetic field in the finishing zone. During the MAF process, the frictional heat is generated at the workpiece surface due to the rubbing action of magnetic abrasive particles with the work surface. The order of temperature rise is important to study, as finishing mechanism and surface integrity of work materials depend upon it. The measurement of temperature distribution during MAF operation at the interface of work piece and flexible magnetic abrasive brush (FMAB) interface is difficult. In the present analysis, finite element based ANSYS software has been used to model and simulate magnetic field distribution, magnetic pressure and temperature distribution at work-brush interface during the process. In this work the maximum magnetic flux density has been simulated of the order of 0.223 T at 0.91 A of current in electromagnet coil. Magnetic pressure on MAPs due to magnetic field of electromagnetic coil has been calculated to evaluate the frictional heat flux generated at the work-brush interface. Transient thermal analysis of workpiece domain has been performed to predict the temperature rise due to frictional heat flux. The predicted temperature on work-brush interface was found in the range of 34–51 °C. The developed simulation results based on FEA have been validated with experimental findings.

1. Introduction

The Magnetic Abrasive Finishing (MAF) process consists of two pairs of magnetic poles (S and N) and the workpiece. The gap between the magnetic poles and the workpiece is filled with the mixture of iron and abrasive particles known as magnetic abrasive particles (MAPs). After the application of magnetic field, the magnetic abrasive particles (MAPs) get aligned along the magnetic field lines between the magnetic poles, forming the flexible magnetic abrasive brush. This brush behaves like multi point cutting tool for finishing operation [1]. Shinmura et al. [1,2] studied the basic principle of the MAF process and confirmed experimentally in a model test that magnetic abrasive particles are subjected to the pressure, which is enough to finish the work surface. The pressure acting on the workpiece surface is the function of magnetic flux density, amount of abrasive particles and the permeability of abrasive medium. It was found that magnetic pressure on the abrasive particles causes penetration of the abrasive particles on the workpiece surface. Due to micro cutting operation, temperature on the surface of the workpiece increases. Very high increase in temperature may deteriorate the surface quality of the workpiece. Therefore, there is a need to evaluate the distribution of temperature on the workpiece surface during finishing operation.

One recent attempt [3] is available to predict the temperature distribution at work piece-brush interface during MAF process. Kim and Choi [4] have developed a mathematical model to evaluate the magnetic field gradient that produces the attractive force between the abrasives as well as the machining pressure in the air-gap. Hou and Komanduri [5] assumed a moving disk heat source model with a parabolic distribution of heat intensity to determine theoretically the flash temperatures and flash times during magnetic abrasive finishing of Si_3N_4 workpiece and the abrasive considered was Cr_2O_3 (unbonded). The flash temperatures were determined as a function of the polishing pressure, sliding speed, and the scratch length of the abrasives on the work surface during polishing. They predicted that at sliding speed of 5.24 m/s, the temperature was raised up to 980 °C. Magnetic flux density in the range of 0.5–1.2 T was considered for the analysis. Kumar and Yadav [6] developed a finite element model to predict the temperature rise in Si_3N_4 workpiece and the abrasive considered was Cr_2O_3 (unbonded). They calculated the temperature rise in the range of 150–800 °C depending upon the magnetic flux density and rpm of the tool. The magnetic flux density considered was in the range of 0.8–1.0 T and rotation of electromagnet was in the range of 5305–6366 rpm. Mulik and

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* Corresponding author. Tel.: +91 1332285761.
E-mail address: rsm@iitr.ac.in (R.S. Mulik).

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Nomenclature

v	linear velocity of electromagnet at radius r (m/s)
μ_f	friction coefficient
K_w	thermal conductivity of work piece material (W/mK)
ρ_w	density of work piece material (kg/m^3)
C_w	specific heat capacity of work material (J/(kg K))
K_a	thermal conductivity of magnetic abrasive material (W/mK)
ρ_a	density of magnetic abrasive material (kg/m^3)
C_a	specific heat capacity of magnetic abrasive material (J/(kg K))
ε	permittivity of the medium (F/m)
ε_0	permittivity of the vacuum (F/m)
ρ	charge density (A/m^2)
E	electric field intensity (V/m)
H	magnetic field strength in the working zone (A/m)
H_s	source magnetic field intensity (T)
J	electric current density (A/m^2)
β	magnetic flux density (T)
β_a	magnetic flux density in air gap (T)
β_w	magnetic flux density in work piece (T)
P	magnetic pressure (Pa)
β_{avg}	average magnetic field density (T)
α	thermal diffusivity (J/(m^3 K)
ϕ	magnetic scalar potential (A)
μ_0	relative magnetic permeability in vacuum (Wb/(A-m))
μ_{Fe}	relative magnetic permeability of iron (Wb/(A-m))
w	volume ratio of iron in magnetic and abrasive mixture
Q_g	heat flux generated due to frictional heating on the work piece-FMAB interface (J/m^2)
Q_w	heat flux going inside the work piece (J/m^2)
T	temperature (°C)
T_∞	ambient temperature (°C)
n	number of turns in coil

Pandey [7,8] designed and fabricated an experimental set up to conduct experiments and to determine the effect of process variables on the surface finish obtained during the MAF process using unbonded Fe and SiC magnetic abrasive particles. A different design of electromagnet was used in their work, which gave better surface finish at lower values of magnetic forces. They evaluated the surface finish considering the electromagnet rotation in the range of 180–450 rpm and magnetic flux density in the range of 0.02–0.2 T. Mulik and Pandey [3] experimentally measured the temperature on the work piece–brush interface in MAF process, where maximum magnetic field was 0.2 T and rotation of magnet was in the range of 180–450 rpm. They found the temperature was in the range of 31–42 °C but they have not developed any process physics based model to predict the temperature. Shinmura et al. [2] used flux density in the range of 1.2 T with circumferential speed of the workpiece at 65 min/m. They have not reported any micro-cracks on the workpiece surface.

Therefore there is a need to develop a process physics based model to predict and simulate temperature distribution in MAF process. In the present Finite Element (FE) based analysis, the set up designed by Mulik and Pandey [8] has been modeled and used for analysis of temperature distribution and experiments have also been performed on the same experimental set up to validate the predicted temperature distribution. To analyze the temperature distribution finite element method based ANSYS 11.0 software has been used to model and simulate the magnetic field in the work piece and FMAB region. This magnetic field applies normal magnetic pressure on magnetic abrasive particles, which get penetrated inside the workpiece and when rotation is provided on the magnet, frictional force causes cutting of work material and generates heat at the work-brush interface. As the finishing operation has been performed for 120–300 s, there was a transient heating of workpiece through transient thermal conduction mode. The heat generated on the work piece and FMAB interface is divided into two parts, one part of heat is taken away by the magnetic abrasive particles and rest amount of heat is conducted in the work piece. The heat absorbed by the workpiece is mathematically calculated and temperature distribution has been obtained at workpiece-FMAB interface. Experiments were performed to validate the obtained temperature distribution.

2. Theoretical background

The generalized equations to solve the magnetic effect of currents, charges and time varying electrical fields are given by Maxwell's equations [9] described as under:

$$\begin{aligned}
&\vec{\nabla}.\vec{E} = \frac{\rho}{\varepsilon_0}\\
&\vec{\nabla}.\vec{B} = 0\\
&\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}\\
&\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}
\end{aligned} \tag{1}$$

where ε_0 is permittivity of vacuum (F/m), ρ is charge density (A/m^2), E is electric field intensity (V/m), $\vec{B}$ is magnetic flux density (T), $\vec{J}$ is electric current density (A/m^2) and μ_0 is relative magnetic permeability in vacuum (Wb/(A-m)). Time independent magnetic field problems (magnetostatic problems) are preferably solved based on magnetic scalar potential formulation. This reduces Maxwell's equations for magnetostatic problems to:

$$\begin{aligned}
&\vec{\nabla}.\vec{B} = 0\\
&\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}
\end{aligned} \tag{2}$$

The above field equations are supplemented by the constitutive relation that describes the behavior of electromagnetic materials. For problems considering magnetic saturation of materials without permanent magnets, the constitutive relation for the magnetic fields is given by [9].

$$B = \mu H \tag{3}$$

where μ is the magnetic permeability of the medium and H is magnetic field strength. The ferromagnetic materials have the property to get magnetized, when placed in external magnetic field. When the gap between the magnet poles and work piece is filled with magnetic abrasive particles (mixture of Fe particles and SiC abrasives), the Fe particles present in the mixture get magnetized and get aligned along the magnetic field lines forming flexible magnetic abrasive brush (FMAB). Magnetic energy gets stored in the magnetic field between magnet poles and work piece gap filled with magnetic particles. The stored energy creates magnetic pressure on magnetic abrasive particles. The magnetic pressure P on magnetic abrasive particles is given by the following equation [4].

$$P = \frac{B^2}{2\mu_0} \frac{3\pi(\mu_{Fe} - 1)w}{6(2 + \mu_{Fe}) + 2\pi(\mu_{Fe} - 1)w} \tag{4}$$

where B is magnetic flux density (T), μ_{Fe} is relative magnetic permeability of iron (Fe), μ_0 is relative magnetic permeability in vacuum (Wb/(A-m)) and w is volume ratio of iron in magnetic and abrasive mixture. The magnetic pressure acting on Fe particles causes