Analysis of forces during spot finishing of titanium alloy using novel tool in magnetic field assisted finishing process

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Abstract

Magnetic field assisted finishing process is a nanofinishing process which uses magnetic field for precise control of finishing forces. Magnetorheological fluid mixed with diamond abrasive particles in base medium of glycerol, hydrofluoric acid, nitric acid, and deionized water is used as the polishing medium. The novel tool is a magnet fixture made of mu-metal which is used to hold the magnet during finishing. In the present experimental study, finishing at a spot on flat titanium alloy is carried out to analyze the forces involved in the finishing. Normal force is the main force responsible for the indentation by the abrasive particle on the workpiece surface. Tangential force helps in removing indented material. The measured normal force and tangential force during the spot finishing are 3.285 N and 0.43 N, respectively. The final surface roughness achieved after spot finishing is 10 nm from initial surface roughness of 200 nm. The percentage improvement in surface roughness is 95%.

Keywords: Nanofinishing process, MR fluid, magnetic field assisted finishing, finishing force.

1. INTRODUCTION

Magnetic field assisted finishing (MFAF) process is an advanced finishing process. It uses magnetic field to precisely control the finishing process [1]. A smart material, magnetorheological (MR) fluid mixed with abrasive particles is used as a polishing medium in MFAF process. Rabinow discovered Magnetorheological fluid as a smart fluid in 1948. Viscosity and yield stress of MR fluid changes with the externally applied magnetic field [2]. Under the magnetic field, MR fluid acts as non-Newtonian fluid [3]. William Kordonski [4] first used MR fluid mixed with abrasive particles as a polishing medium for optics polishing in 1990. Later, different materials having various shapes are finished using MR fluid. MR fluid comprises of magnetic particles, abrasive particles in a water or oil based medium for finishing [5]. Magnetorheological finishing (MRF) is primarily used to precisely finish optics in nanometric level without sub-surface damage [6]. Silicon and polymers are also polished using MRF process at nanometer level [7,8]. Precision nanofinishing of different metals are also carried out using magnetorheological fluid based finishing processes [9,10]. Hence, magnetorheological fluid based finishing process can be used to efficiently finish metal and non-metals. Now, to make the process precise and efficient it is necessary to control the finishing forces involve in the process. Finishing forces acting during finishing is broadly categorized as normal force and tangential force [11]. Normal force is the main force responsible for the indentation of the abrasive particles on the workpiece surface. Tangential force helps in removing indented material. Analysis of finishing force is necessary for better understanding of the process. Finishing forces acting on the workpiece surface provides the insight of process mechanism during finishing process. The results obtained from the finishing process can be controlled accurately by precise control of the finishing forces.

In the present study, experiments are carried out to analyze the forces acting on the workpiece (titanium alloy) surface during spot finishing. A simulation study is carried out in finite element (FE) analysis based software Ansoft Maxwell® to find out the magnetic flux distribution on the workpiece surface during finishing. A dynamometer is used to measure the forces during the spot finishing. Analysis of the measured forces is carried out. Optical profilometer is used to analyze the surface topography and surface roughness before and after finishing.

2. EXPERIMENTAL METHODOLOGY

A spot finishing experiment is carried out to measure the main forces involved in MFAF process when novel MFAF tool [12] is used. To measure forces, a 3-axis dynamometer is used during finishing. Figure 1(a) shows the dynamometer used during spot finishing. Dynoware software is used to process and analyze the acquired signal from the dynamometer. Force measurement is started before the MFAF tool came in complete contact with the workpiece surface. During spot finishing, the MFAF tool is rotating along the Z axis. Hence, the main force components acting on the abrasive particles are normal force along Z axis ($\boldsymbol{F_z}$) and tangential force along Y axis ($\boldsymbol{F_y}$).

The MFAF tool is attached to the 4-axis vertical milling machine as shown in Fig. 1(b). The enlarged view of MFAF tool end is presented in Fig. 1(c). The MFAF tool is made of mu-metal which is a very high permeability material. The composition of the mu-metal is given in Table 1. The MFAF tool encompasses a permanent magnet (Nd-Fe-B of grade N48). Titanium alloy is considered as the workpiece in the present study. A workpiece fixture is developed to hold the workpiece on the dynamometer during finishing. The MR fluid is indigenously prepared by mixing CIP (8 µm), diamond abrasive powder (6 µm), glycerol, hydrofluoric acid, nitric acid, and deionized water. The concentration of MR fluid is decided based on the previous studies. The concentration of MR fluid constituents are 40 vol% CIP, 7.1 vol% diamond abrasive powder in 48 vol% acidic base medium. The base medium is

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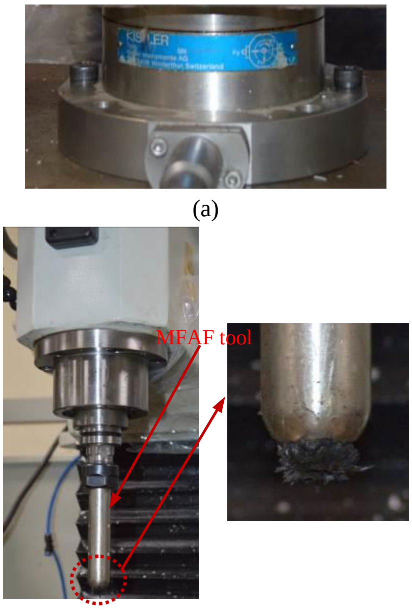
water based which is a mixture of glycerol (8 vol%), hydrofluoric acid (1.17 vol%), nitric acid (2.33 vol%), and deionized water (41.1 vol%). The experimental conditions based on previous experimental study are given in Table 2.



(a)

(b) (c)

Fig. 1. (a) Dynamometer, (b) MFAF tool used to carry out the spot finishing, (c) enlarged view of MFAF tool end

Table 1
Mu-metal composition

Constituents	Chemical composition in wt%
Nickel (Ni)	80-81%
Molybdenum (Mo)	4.5-6%
Silicon (Si)	0.05-0.4%
Manganese (Mn)	0-0.5%
Carbon (C)	0.01%
Iron (Fe)	Balance

Table 2
Selected process parameters

Sr. No.	Parameter	Values
1	Rotational speed of the tool (N)	1200 rpm
2	Working gap (G)	0.8 mm

3. RESULTS AND DISCUSSION

A simulation study is carried out using Ansoft Maxwell® for better understanding of the magnetic field distribution during finishing process. The simulation set-up is shown in Fig. 2. The gap between MFAF tool and the workpiece is fixed as 1.5 mm during simulation. The gap between MFAF tool and titanium workpiece is filled with MR fluid. After simulation, the magnetic flux distribution on the workpiece surface is plotted. The distribution of magnetic flux density on the workpiece surface during spot finishing is shown in Fig. 3. The available magnetic flux density on the workpiece surface is 0.2 T.

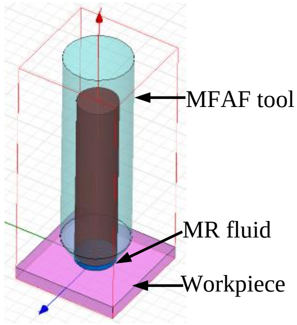


Fig. 2. Simulation set-up considered in Maxwell®

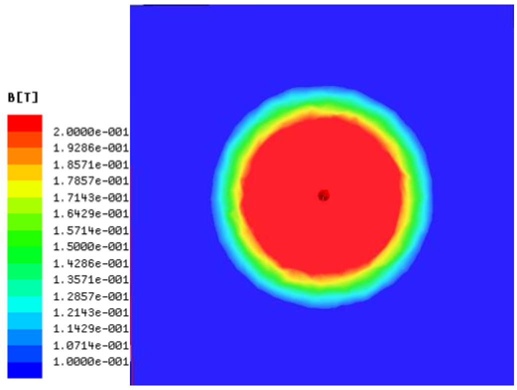


Fig. 3. Distribution of magnetic flux density on workpiece surface

The measured normal force and tangential force during spot finishing of bio-titanium alloy using dynamometer is shown in Figs. 4 & 5, respectively. The mean normal force and tangential force obtained during the spot finishing are 3.285 N and 0.43 N, respectively. The mean forces are measured from the data obtained from the experimental study.

The force measurement starts when the MR polishing fluid first come in contact with the workpiece surface which is between 0 to 18 s as shown in Fig. 4. After 20 s, the MR fluid brush of MFAF tool comes in full contact with the workpiece surface which results in a sudden peak in force measurement (Fig. 4). After 25 s MR fluid brush of MFAF tool retracts from the workpiece resulting in a reduction in measured normal force (Fig. 4). After some time, the measured normal force reaches a steady state value.

As shown in Fig. 5, tangential force follows the similar trend as normal force. After MR fluid brush of MFAF tool comes in complete contact with the workpiece surface, a peak in measured tangential force is observed (Fig. 5). However, the value of tangential force is much lower than the normal force. Magnetic forces acting on the abrasive particles are considered as the main component of normal force. Tangential force mainly depends on the centrifugal force and shear force. In the present case, the MFAF tool is only rotating along its axis, there is no feed force. Hence, the value of tangential force is very low. The abrasive particles indent on the workpiece surface due to the normal force. The removal of indented material from the finishing area occurs due to the tangential force. Indenting the workpiece surface requires more force than the removal of indented material. Hence, normal force requirement is higher than the tangential force. The present experimental study supports the theoretical approach.

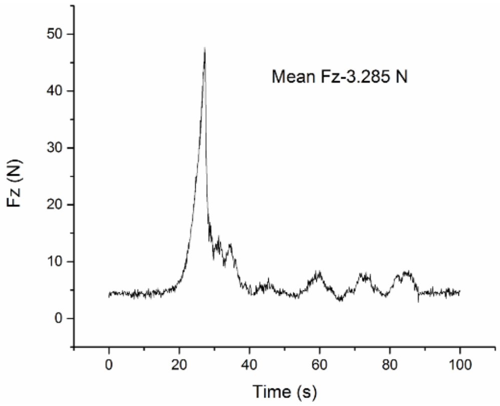


Fig. 4. Measured normal force (F_z) on the workpiece surface during spot finishing

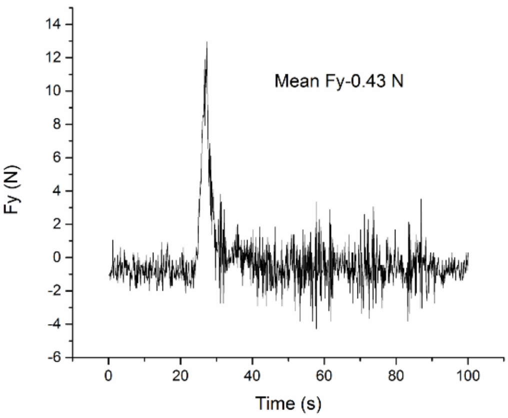


Fig. 5. Measured tangential force (F_y) on the workpiece surface during spot finishing

The workpiece surface is analyzed using optical profilometer before and after the spot finishing. The 3D surface topography and surface roughness profile are measured before and after finishing process as shown in Figs. 6 and 7, respectively. As shown in Fig. 6(a), the initial 3D surface topography shows deep scratch marks with high peaks with a surface roughness (Sa) of 230 nm. The surface roughness profile of the workpiece surface before finishing shows deep valleys due to the deep scratch marks with Ra value of 200 nm as shown in Fig. 6(b). After finishing, the resulted surface topography (Fig. 7(a)) shows very good surface topography with no deep scratch marks (Sa = 12.74 nm). The final surface roughness profile (Fig. 7(b)) shows that the deep valleys are removed in the final surface. The final surface roughness (Ra) obtained is 10 nm.

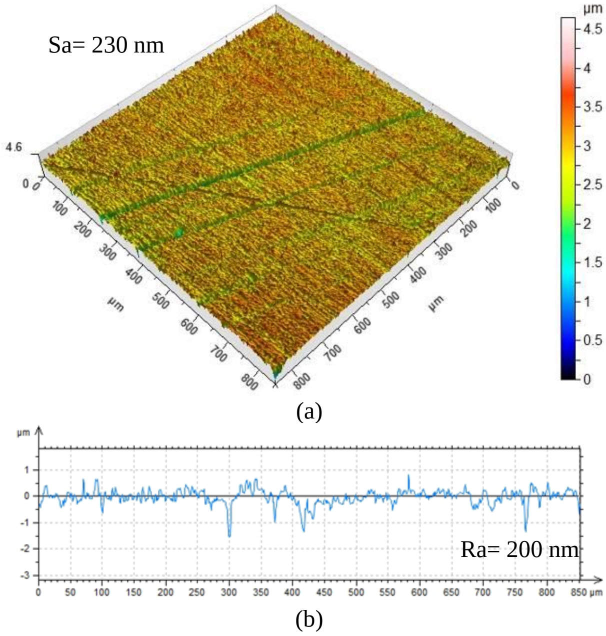


Fig. 6. (a) 3D surface topography and (b) surface roughness profile of titanium alloy before spot finishing

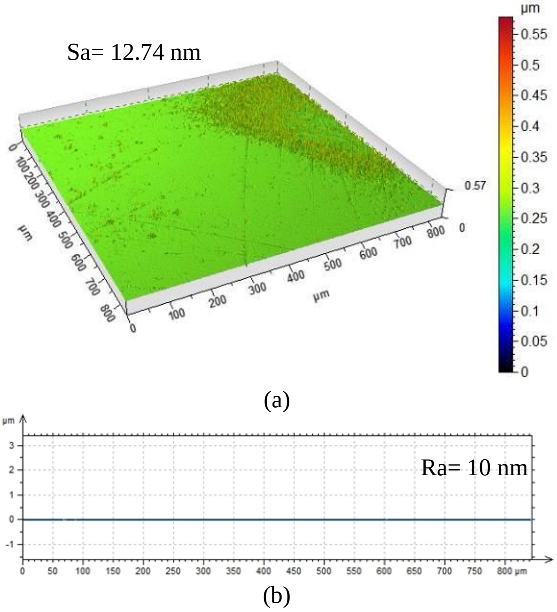


Fig. 7. (a) 3D surface topography and (b) surface roughness profile of titanium alloy after spot finishing

4. CONCLUSIONS

In the present study, spot finishing on titanium alloy using MFAF tool is carried out. The experimental study is carried out to find out the main forces acting on workpiece surface. Also, a simulation study using finite element analysis based software is carried out to find out the magnetic flux distribution on the workpiece surface during spot finishing. The main conclusions drawn from the present study are as follows:

- The simulation study shows that available magnetic flux density on the workpiece surface is 0.2 T which is sufficient to carry out the finishing process.

- The measured mean normal force and tangential force acting on the workpiece surface are 3.285 N and 0.43 N, respectively.

- From the initial surface roughness (Ra) of 200 nm, the final surface roughness (Ra) of 10 nm is achieved. Hence, nano-meter level finishing on hard metal (titanium alloy) is easily achieved using MFAF process.

- The percentage improvement in surface roughness is 95%.

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