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Effect of abrasive particle morphology along with other influencing parameters in magnetic abrasive finishing process

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Abstract. Surface characteristics play a very important role in medical implants and among surface features, surface roughness is very effective in some medical applications. Among the various methods used to improve surface roughness, magnetic abrasive finishing (MAF) process has been widely used in medical engineering. In this study, the effect of abrasive particle morphology along with four other process parameters, including type of work metal, finishing time, speed of finishing operation, and the type of abrasive powder were experimentally evaluated. Full factorial technique was used for design of experiment. Three commonly used metals in orthopedic implants i.e., Ti-6Al-4V alloy, AZ31 alloy and austenitic stainless-steel 316LVM, were selected for this study. Also, two types of magnetic abrasive particles with different shapes (spherical and rod-shaped) were considered in the experiments. The results of the experiments indicated that the morphology of the abrasive particles and the finishing time had the greatest effect on surface roughness and using rod-shaped abrasive particles resulted in better surface quality comparing to the spherical particles. Besides, the surface quality of steel 316LVM after MAF was the best among the other examined metals. Interaction plots of ANOVA also showed that interactions of material with morphology of abrasive particles, and material with machining time were found to be reasonably significant.

Keywords: Magnetic abrasive finishing / surface roughness / abrasive particle morphology / ANOVA

1 Introduction

Magnetic abrasive finishing (MAF), as one of the dedicated process of super finishing has recently received the attention of many researchers. It was invented in 1930s and has been used so far for both internal and external surfaces of cylindrical work-pieces and flat surfaces made of magnetic or non-magnetic materials [1]. In this method, the work-piece is maintained between the two magnets. Abrasive particles, including ferromagnetic particles and fine abrasive powders (Al_2O_3, SiC, CBN or diamond), fill the working clearance between the work piece and the magnet as shown in Figure 1 [2].

As shown in the figure, magnetic field in the working clearance causes to form a brush named magnetic abrasive flexible brush (MAFB). The function of this brush is like a multi-point cutter for finishing operation. In plane magnetic abrasive finishing process (Fig. 1a) the work-piece is fixed and the magnet is rotated. When the magnet starts to rotate, the brush (MAFB) also rotates like a grinding wheel, which simultaneously applies force to the abrasive particles and material is removed from the surface. However, for cylindrical surfaces (Fig. 1b) the work-piece is rotated and the magnet is usually fixed [3].

Smolikin [4] and Vijay Kumar [5] presented equations for calculating forces acting on a paramagnetic particle in MAF. They showed that the vertical force is the result of a magnetic force that pushes the abrasive particles to the surface of the work-piece, and the horizontal force is also the result of the velocity of the abrasive particles. Kala studied the relationship between the velocity of abrasive particles and vertical and horizontal forces [6]. Kala showed that, as the rotational speed increases, vertical and tangential forces will decrease, which will reduce the force acted on the work-piece.

The final surface quality of the MAF process depends on several parameters. There have been many works in which those parameters were investigated. Basera et al. utilized this method to improve the surface quality of taper roller bearings [7]. They used a composition of different types of abrasivepowder (Ferromagnetic iron powder, diamond,

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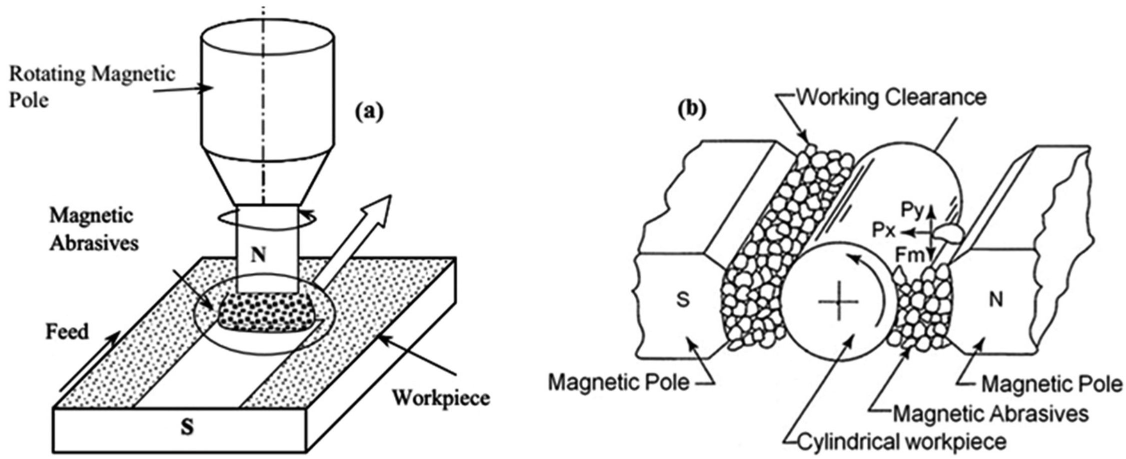

Fig. 1. (a) Plane magnetic abrasive finishing, (b) External magnetic abrasive finishing of cylindrical work-piece [2,3].

boron carbide, aluminum oxide) as abrasive particles, as well as glycerinand de-ionized water as a liquid to prevent from formation of lump. Their results showed that mixing of diamond abrasives to the MAP improved the surface finishing process and the rate of finishing was enhanced as well.

One of the other influencing parameters in MAF process is the velocity of abrasive particles, which was considered by researchers to be equivalent to moving the magnetic field or moving the head of the tool. Basera also found that with increasing the velocity of abrasive particles, the amount of change in surface finish initially increases up to a certain value and afterwards decreases [7].

Samuels et al. [8] explored the effect and type of diamond abrasives on MRR in polishing of annealed brass. They showed that the greatest MRR is achieved if the abrasive grains are 2–4 μm in size.

Shinmura et al. [9] studied the basic principle of the MAF process and showed that the increase in the magnetic abrasive particle size resulted in increasing the material removal and surface finish value (R_a). It means to produce a higher quality surface, abrasive particles with smaller sizes should be used.

Jain et al. [10] investigated the effect of working gap and circumferential speed in surface finish of a cylindrical work-piece. They showed that the mentioned parameters significantly influenced the efficiency of the process. In general, they concluded that increasing working gap or decreasing circumferential speed of the work-piece would lead to material removal enhancement and also increase in circumferential speed of the work-piece would increase the change in surface finish.

Finishing time is also another important parameter affecting surface roughness. Yadava and Khatri [11] developed a theoretical model for the prediction of surface roughness in MAF and showed that with increasing finishing time, surface roughness would decrease exponentially. The model was assessed by experimental tests.

Yin and Shinmura [12] investigated the surface finishing and deburring of magnesium alloy by the use of vertical vibration-assisted magnetic abrasive finishing process. The frequency and amplitude of vibrations were 6 Hz and 1 mm respectively. They showed that using vertical vibrations could reduce the finishing time by 40 percent in comparison with the conventional MAF.

Mulik and Pandey [13] in 2011 introduced a new process namely ultrasonic-assisted magnetic abrasive finishing (UAMAF). Similar to Yin's work they integrated the use of vibrations and MAF to finish surface. However, the frequency of vibrations in this work was 20 kHz. They showed that the UAMAF was able to finish the surface of hardened AISI 52100 steel work-piece with initial average R_a of the order of 100–22 nm (78%) within a short time span (80 s). They also showed the same results for copper alloy and stainless steel [14].

Misera et al. [15,16] presented a mathematical model of finishing force and the surface roughness during UAMAF. Their model shows that the relationship between change in surface roughness and finishing time is exponential. Similar to these works, some researchers have studied on the enhancement of the efficiency of MAF by using a special electrolyte in the machining zone [17–19].

Mun et al. [20] investigated the effect of temperature on the surface quality of the cylindrical work-pieces of magnesium alloy during MAF process. They conducted MAF at three different temperatures i.e., a cryogenic temperature (−120 °C), room temperature (24 °C), and high temperature (112 °C). They showed that the room and cryogenic temperatures could result in excellent performance in terms of the surface roughness.

Achieving a high-quality surface finish in medical applications is very important and required. There are a variety of ways to improve the quality of the surface onbiomaterials, including electropolishing (ECP) and ion implantation process. Despite the successes achieved in these processes, there are still some drawbacks and limitations. For example, Smick et al. [21] showed that using extremely toxic gas sources such as arsine and phosphine in ion implantation process, have considerable effects on human health. Lee et al. [22] showed that electropolishing process cannot smear over or otherwise conceal defects such as seams and non-metallic inclusions in metals. Moreover, rough scratches, mold-surface texture and heavy orange peel texture are not removed by a

Table 1. Chemical composition of Ti-6Al-4V, 316 LVM and AZ31 (wt%).

Element	Al	V	C	O	N	H	Fe	Ti	
Ti6Al4V	6	4	0.03	0.1	0.01	<0.003	0.1	Balance	
Element	**C**	**Si**	**Mn**	**S**	**P**	**Cr**	**Mo**	**Ni**	**Fe**
316LVM	≤0.03	≤0.75	≤2.0	≤0.030	≤0.045	16.0–18.0	2.0–3.0	10.0–14.0	Balance
Element	**Al**	**Mn**	**Zn**	**Si**	**Fe**	**Ca**		**Mg**	
Az31	3.3	0.28	0.9	0.02	0.006	0.0017		Balance	

practical amount of electropolishing, and thus require an initial "cutdown" with abrasives. Also, the chemicals used can have long-term effects on surface quality. Besides, in multi-phase alloys, there may be a possibility of surface quality deterioration due to selective dissolution of different phases.

The ability of the MAF Process has also made it to be widely used in medical applications specially in improving surface quality of medical implants. For instance, Yamaguchi and Graziano in different works used MAF for modification of surface roughness of femoral component of knee prosthetic [23,24].

Since among the influential parameters on MAF performance, the effect of morphology of magnetic abrasive particles has not been studied so far, this paper aims to investigate the effect of this parameter on the surface quality obtained by MAF along with other parameters, including the type of metal, the time of polishing, the speed of polishing and the type of abrasive powder (Al_2O_3, TiO_2). Considering the importance of using MAF process in medical engineering, three commonly used metals in orthopedic implants, i.e., titanium alloy Ti-6Al-4V, magnesium alloy AZ31 and stainless-steel alloy 316LVM, are selected for the work metals.

2 Experimental setup and procedure

2.1 Materials

In this research, three types of metals, including titanium alloy Ti-6Al-4V (Ti grade 5), magnesium alloy AZ31, and austenitic stainless-steel alloy 316LVM, prepared in cylindrical shape were considered for the experiments. These metals are widely used in orthopedic implants. The chemical composition of these alloys obtained by X-ray fluorescence (XRF) apparatus is presented in Table 1.

Titanium and its alloys were considered the most biocompatible metal and its feature arises from the protective oxide layer that forms naturally in the presence of oxygen. This oxide is a strong and stable layer that grows spontaneously in contact with air and prevents reactions between the metal and the surrounding environment. The mechanical properties of the material and the loading conditions in the host have, conventionally, influenced material selection for different clinical applications. Ti-6Al-4V is mostly used in orthopedics while commercially pure titanium frequently used in dentistry [25]. As mentioned, the naturally formed titania (TiO_2) layer on the surface of such titanium implants is thought to protect an implant exposed to the physiological environment from corrosion [26,27]. However, Ti–6Al–4V alloy has poor wear resistance that confines its applications mainly in areas involving friction and wear [28,29].

2.2 Magnetic abrasive particles

In order to investigate the effect of morphology of the magnetic abrasive particles, two types of magnetic abrasive particles with different shapes were considered in the experiments. The most common abrasive particle shapes are spherical and rod-shaped which were studied in this research. These particles have a strong paramagnetic property and respond very well to the magnetic field. These particles are made of hardened carbon steel that have a high potential for surface abrasion.

Oscari is one of the manufacturers and suppliers of stainless-steel magnetic tumbler finishing pins (rod-shaped particles). These particles are in the form of cylinders with a length of 2.1 mm and a diameter of 0.2 mm, creating sharp edges which enhance abrasion ability of these particles. Stainless-steel balls for magnetic tumblers, supplied by FDJ tool, were used as the spherical particles. These particles are in the shape of spheres with a diameter of 1.5 mm, which have no sharp edges due to their special shape.

2.3 Non-magnetic abrasive particle (Abrasive powders)

As mentioned in the introduction, abrasive particles include ferromagnetic particles and fine abrasive powders. There are different types of abrasive powders used for finishing process including silicon carbide (SiC), aluminum oxide (Al_2O_3), Cubic boron nitride(CBN), Diamond powder, Boron carbide (B_4C) and titanium dioxide (TiO_2) etc. In the presented work, titanium dioxide (TiO_2 99.6%) and alumina (Al_2O_3 99.99%) abrasive powders with the same mesh size (#600) were used in the experiments. The term "Mesh" is used to describe the size of an abrasive particle. Since mesh size affects surface quality, the same mesh size was used for the two abrasive powder particles in the experiments. The particle size is about 25 μm for mesh number of 600. The hardness of these

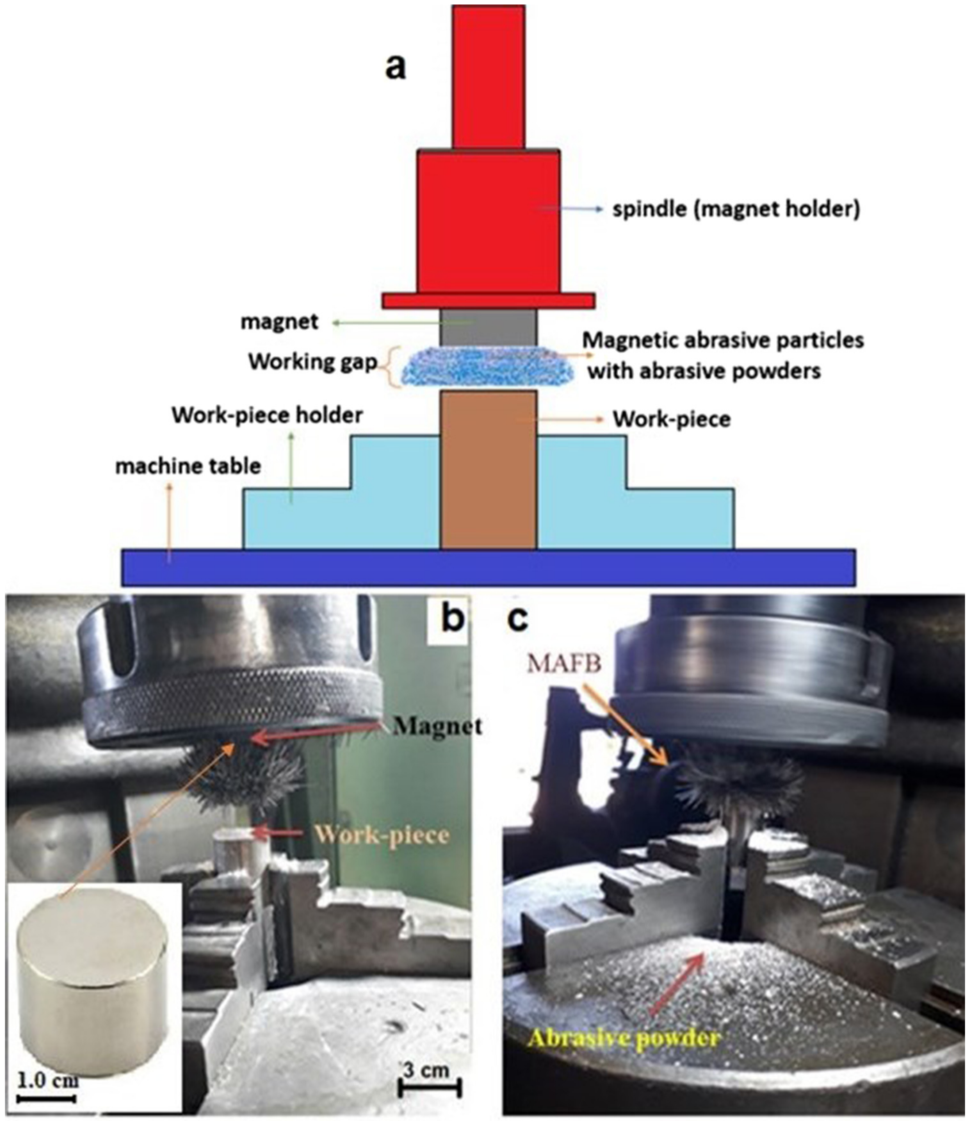

Fig. 2. Experimental setup of MAF process (a) Schematic, (b) Initial state, (c) During the process.

abrasive particles varies with each other. One of the scales for measuring hardness of mineral is the Mohs' hardness scale. The Mohs' hardness scale measures the resistance of a mineral to scratching. The Mohs' hardness values for alumina and titanium dioxide are 9 and 6.5, respectively [30].

2.4 Magnetic field

In this study, a permanent magnet (neodymium magnet) was used to create a magnetic field. The permanent magnets have a high ability to create a strong magnetic field. This magnet is cylindrical and 2.5 cm in diameter. AHGS10A Digital Magnetic gauss meter was used to measure the magnetic field. The resolution and accuracy of this magnetic gauss meter is 0.1 mT and 1% respectively. The strength of the magnetic field produced by the neodymium magnet was 0.461 T.

2.5 Setup

Generally, a lathe machine is used for MAF process, in which case the work-piece is hollow and is fitted in the spindle of the lathe machine and the magnet is placed in the tool holder. In some studies, the magnet fits in the spindle of milling or vertical drilling machine. In this case, the work-piece is fixed on the work table and the magnet rotates. In the present work, a vertical milling machine was also used for MAF process. Thus, the magnet was placed in the spindle and the work-piece was fixed on the work table. MAF setup mounted on vertical milling machine is shown in Figure 2.

The rotational speeds considered for the magnet on vertical milling machine were 90 and 180 rpm. The working gap is 2.5 mm which is the same for all the experiments. The surface roughness of the work-piece after machining was measured by using the surface roughness tester TR110. It has a measuring range of 0.05–10.0 μm.

Table 2. Experiment factors and their levels.

Factor	Level 1	Level 2	Level 3
Machining time (min)	30	60	
Rotational speed (rpm)	90	180	
Material	AZ31	Steel 316lLVM	Ti-4Al-6V
Shape of magnetic particles	Spherical	Rod-shaped	
Abrasive powder	Al_2O_3	TiO_2	

3 Design of experiments

In the present work, a full factorial design was employed for experimentation. Such an experiment allows the researcher to study the effect of each factor on the response variable, as well as the effects of interactions between factors on the response variable [31]. Five factors were selected for the experiments, including rotational speed, shape of the magnetic abrasive particles, machining time, material and type of abrasive powder. Each factor has only two levels except for the material factor which has three levels. Thus, the total number of experiments comes out to be 48. Also, some parameters were constant for all the experiments, such as the strength of magnetic field (0.461 T), working gap (2.5 mm) and the ratio of the abrasive powders and magnetic particles. The ratio between abrasive powders and magnetic particles was 1–3 by weight. Table 2 shows the levels of the process factors.

4 Experimental data

Although all the work-pieces were prepared at the same conditions, the initial surface roughness of them was in the range between 0.75 and 0.9 μm. Therefore, to consider this variety in initial conditions, a ratio of change in the surface roughness to the initial roughness (ΔR_a) was studied as the response.

$$\Delta R_a = \frac{ISR - FSR}{ISR}$$

where ISR is the initial surface roughness and FSR is the final surface roughness.

The experimental results are shown in Table 3.

As a qualitative assessment, the surface quality of stainless-steel 316LVM sample (the best quality obtained) before and after the MAF process is shown in Figure 3.

5 Results and discussion

To investigate the effect of individual parameters as well as interaction effects, analysis of variance (multi-factor ANOVA) was carried out in MINITAB 2017 software. The ANOVA result is presented in Table 4.

It can be seen from Table 3 that the morphology of magnetic abrasive particles (μ) and the machining time (T) are the most dominating parameters, making the contribution to the total variability of as much as 30.65% and 11.08%, respectively. Also, P-values of these parameters are 0 and correspondingly their F-values are high, showing the significance of these two factors. Furthermore, the interactions of material with morphology of abrasive particles ($M^*\mu$), and material with machining time (M^*T) were found to be reasonably significant.

Examining the accuracy of experimental data is of particular importance, which can be measured by various tests. In Figures 4 and 5, residuals versus fitted values plot and normal probability plot are presented.

If the fitted values plot is suitable, this diagram should be symmetrical in relation to the central line and the points around this point are uniformly scattered. This situation shows the variance of errors is constant. As it can be seen in Figure 4, the points are randomly distributed and do not follow a particular model. If, by increasing the fitted values (horizontal axis), the residual values were regularly decreasing or increasing, and the location of points created a conic or symmetrical funnel, then this model could not be used to continue the analysis.

It can be seen from Figure 5 that the residuals have fallen approximately along a straight line, representing a normal distribution.

5.1 Effect of individual factors on Δ R_a

5.1.1 Effect of material

In this study the effect of MAF process on three different types of materials which are commonly used in medical engineering were investigated. As it is evident from the Figure 6, the surface roughness of steel 316 LVM obtained after MAF process is the least among the three examined metals (maximum ΔR_a). However, MAF process has not had much effect on titanium, and magnesium has a surface roughness between titanium and steel. This can be attributed to the mechanical properties of these metals. The compressive and tensile strength of titanium is higher than the other two metals. Wang et al. also theoretically and experimentally investigated the effect of the workpiece material on surface roughness in ultraprecision raster milling [32]. It was shown that material elastic recovery

Table 3. Experimental design and responses.

No	Material	Abrasive powder	Morphology of magnetic particles	Rotational speed	Machining time	ISR (μm)	FSR (μm)	ΔR_a
						0.81	0.54	0.33
2	1	2	1	1	1	0.87	0.51	0.41
3	1	1	2	1	1	0.78	0.53	0.32
4	1	2	2	1	1	0.83	0.61	0.26
5	1	1	1	2	1	0.9	0.54	0.4
6	1	2	1	2	1	0.76	0.36	0.53
7	1	1	2	2	1	0.89	0.6	0.33
8	1	2	2	2	1	0.76	0.52	0.31
9	1	1	1	1	2	0.81	0.45	0.45
10	1	2	1	1	2	0.79	0.46	0.42
11	1	1	2	1	2	0.75	0.41	0.45
12	1	2	2	1	2	0.81	0.36	0.55
13	1	1	1	2	2	0.87	0.24	0.72
14	1	2	1	2	2	0.76	0.39	0.49
15	1	1	2	2	2	0.79	0.38	0.52
16	1	2	2	2	2	0.79	0.24	0.69
17	2	1	1	1	1	0.9	0.64	0.29
18	2	2	1	1	1	0.75	0.57	0.24
19	2	1	2	1	1	0.82	0.27	0.67
20	2	2	2	1	1	0.76	0.45	0.41
21	2	1	1	2	1	0.86	0.45	0.48
22	2	2	1	2	1	0.79	0.64	0.19
23	2	1	2	2	1	0.89	0.25	0.72
24	2	2	2	2	1	0.76	0.34	0.55
25	2	1	1	1	2	0.8	0.56	0.3
26	2	2	1	1	2	0.87	0.53	0.39
27	2	1	2	1	2	0.76	0.36	0.53
28	2	2	2	1	2	0.91	0.43	0.53
29	2	1	1	2	2	0.86	0.44	0.49
30	2	2	1	2	2	0.87	0.58	0.33
31	2	1	2	2	2	0.76	0.29	0.62
32	2	2	2	2	2	0.81	0.29	0.64
33	3	1	1	1	1	0.89	0.61	0.31
34	3	2	1	1	1	0.88	0.67	0.24
35	3	1	2	1	1	0.88	0.6	0.32
36	3	2	2	1	1	0.76	0.1	0.87
37	3	1	1	2	1	0.79	0.65	0.18
38	3	2	1	2	1	0.76	0.59	0.23
39	3	1	2	2	1	0.81	0.29	0.64
40	3	2	2	2	1	0.9	0.57	0.37
41	3	1	1	1	2	0.79	0.58	0.26
42	3	2	1	1	2	0.83	0.65	0.22
43	3	1	2	1	2	0.81	0.43	0.47
44	3	2	2	1	2	0.88	0.26	0.7
45	3	1	1	2	2	0.81	0.64	0.21
46	3	2	1	2	2	0.76	0.59	0.23
47	3	1	2	2	2	0.83	0.41	0.51
48	3	2	2	2	2	0.85	0.31	0.63

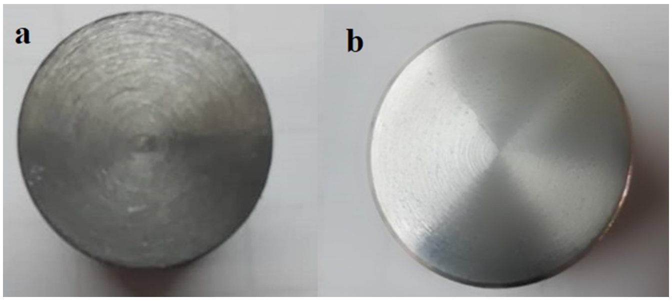

Fig. 3. Surface quality of steel 316LVM sample (a) Initial state, (b) After MAF process.

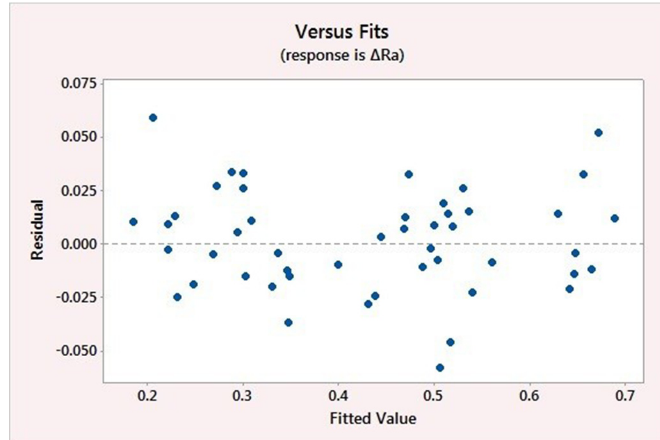

Fig. 4. Residuals vs. Fitted values plot.

Table 4. Analysis of variance (multi-factor ANOVA) for change in surface roughness (ΔR_a).

Source	DF	Seq SS	Contribution (%)	Adj SS	Adj MS	F-Value	P-Value
Material, M	2	0.027811	3.11	0.002045	0.001023	0.64	0.539
Abrasive powder, A	1	0.000461	0.05	0.013297	0.013297	8.38	0.011
Morphology of magnetic particles, μ	1	0.274176	30.65	0.247690	0.247690	156.07	0.000
Rotational Speed, R	1	0.044974	5.03	0.048164	0.048164	30.35	0.000
Machining Time, T	1	0.099094	11.08	0.047813	0.047813	30.13	0.000
$M*A$	2	0.009777	1.09	0.033044	0.016522	10.41	0.001
$M^*\mu$	2	0.184972	20.68	0.122638	0.061319	38.64	0.000
M^*R	2	0.031364	3.51	0.042992	0.021496	13.54	0.000
M^*T	2	0.113124	12.65	0.142135	0.071067	44.78	0.000
$A^*\mu$	1	0.045842	5.12	0.027357	0.027357	17.24	0.001
A^*R	1	0.001511	0.17	0.000003	0.000003	0.00	0.968
A^*T	1	0.026057	2.91	0.030904	0.030904	19.47	0.001
μ^*R	1	0.005862	0.66	0.008312	0.008312	5.24	0.037
μ^*T	1	0.003319	0.37	0.003903	0.003903	2.46	0.138
R^*T	1	0.002419	0.27	0.002419	0.002419	1.52	0.236
Error	27	0.023806	2.66	0.023806	0.001587		
Total	47	0.894570	100.00				

R-Sq = 97.34%   R-Sq (adj) = 93.79%   R-sq (pred) = 84.78%.

affects chip thickness removed during finishing. However, process parameters can decrease the effect of workpiece material such as hardness and feed rate.

5.1.2 Effect of morphology of magnetic abrasive particles

As already mentioned, two types of magnetic abrasive particles were selected in different shapes, which were equally weighted in the experiments. rod-shaped abrasive particles and spherical abrasive particles are two of the most common types of abrasive particles. Figure 7 indicates that the rod-shaped abrasive particles are far more effective on the surface finish, which can be attributed to the cutting edges in this type of particles.

In fact, the rod-shaped particles play a role as a cutting tool, while the spherical particles not only not have cutting edges but also it was observed that they were attached to each other in the magnetic field (like chain beads, but perpendicular to the surface of the work-piece), and fluctuated by moving the magnetic field and thus they did not have much effect on material removal process.

5.1.3 Effect of machining time

The effect of machining time may be predictable. As it is expected, as with other finishing methods, the efficiency of MAF process improves by increasing the process time. It is seen in Figure 8 that increasing the machining time has led

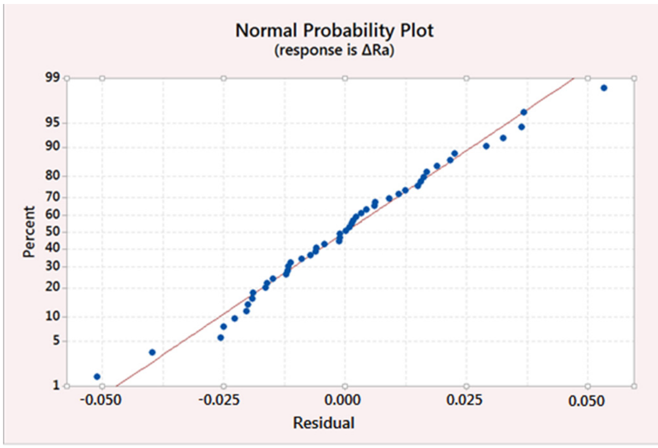

Fig. 5. Normal probability vs. residual plot.

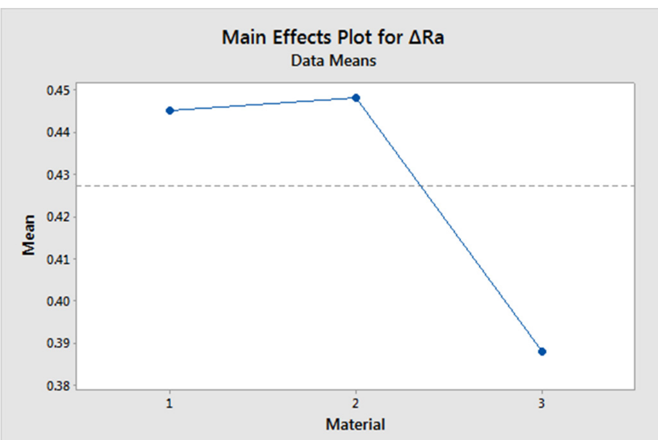

Fig. 6. The effect of MAF process on three different materials (1 = AZ31, 2 = Steel 316Lvm, 3 = Ti-6Al-4V).

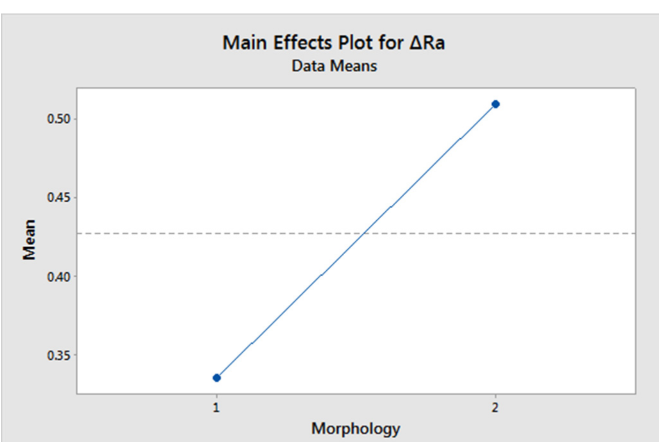

Fig. 7. The effect of abrasive particle morphology on ΔR_a (1 = Spherical particles, 2 = Rod-shaped particles).

to decrease in surface roughness. This effect may be due to the fact that magnetic abrasive particles stay in finishing area for additional time and cutting edges of the abrasive particles remove more defects of the work-piece surface.

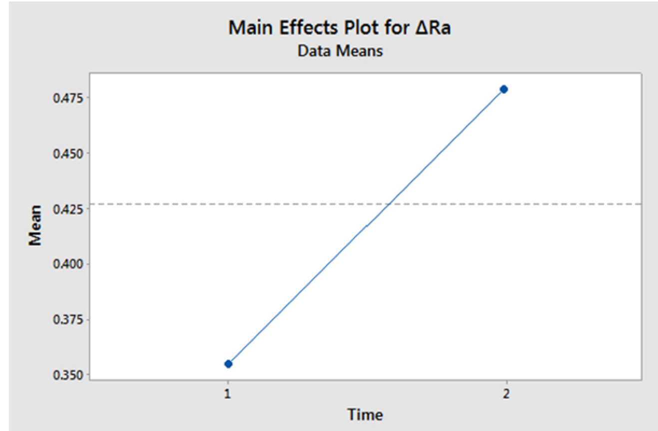

Fig. 8. The effect of the machining time on ΔR_a (1 = 30 min, 2 = 60 min).

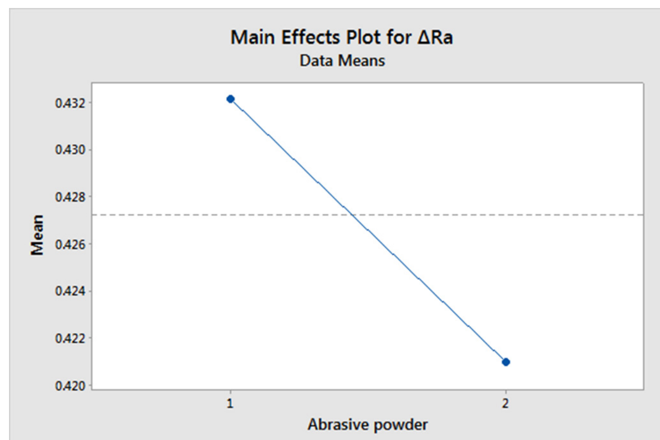

Fig. 9. The effect of abrasive powder on ΔR_a (1 = Al_2O_3, 2 = TiO_2).

5.1.4 Effect of abrasive powder

The effect of abrasive powders (non-magnetic particles) is much less than the other parameters and is negligible. However, as shown in Figure 9, alumina powder (Al_2O_3) has a slightly better effect on surface finishing in comparison to titanium oxide powder (TiO_2). Sincethe ploughing of work-piece surface bypowder particles depends on the magnetic abrasive particles (they are placed on the edges of the magnetic abrasive particles), their effect is less than the magnetic abrasive particles.

5.1.5 Effect of rotational speed

According to Figure 10, as the speed of machining increases, the surface quality improves. It can be said that at higher rotational speeds, hit rate of abrasive particles to the surface of the work-piece increases and thus more peaks are removed from the surface. Of course, this effect is less than the effect of morphological parameter. Since with increasing the rotational speed, the abrasive particles start to be separated from the magnet and are not involved in the removal of material. Therefore, the threshold of particle separation from the magnet should be considered first and then proceeded to increase the speed.

5.2 Interaction effects

One of the most important advantages of designing experiments with the full factorial method is to evaluate the effect of each parameter, which allows us to compare the effect of each parameter with the rest. The results of interaction effects are shown in Figure 11.

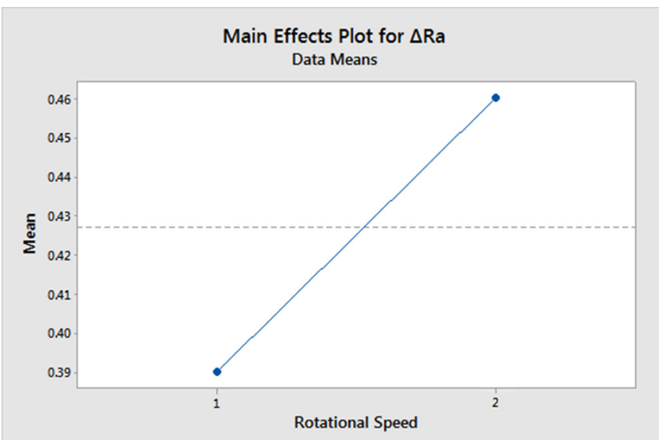

Fig. 10. The effect of rotational speed on ΔR_a (1 = 90 rpm, 2 = 180 rpm).

5.2.1 The effect of material and morphology

As can be observed in Figure 11, there is a strong interaction between material and morphology. This interaction effect is greater than the interaction of other parameters with each other. Therefore, when designing and setting the finishing machine, the effect of these two parameters should be considered simultaneously. It means that when both parameters are at their best, the least surface roughness will be achieved. As already explained, the rod-shaped morphology more improves surface roughness, and this fact is well observed in the figure for materials of steel and titanium. However, in the case of magnesium, there is a slight difference between the surface qualities obtained by two different types of magnetic abrasive particles.

5.2.2 The effect of material and machining time

As it is clear, increasing the machining time has led to decrease in surface roughness. However, the effect of increasing the time for different metals is not the same, and the greatest change in surface roughness has occurred in steel. The amount of improvement in surface roughness after doubling the machining time is approximately 24% for steel, but this value is lower for magnesium and titanium. The different effects of the machining time can be attributed to the different properties of steel, titanium and magnesium. Each of them has a different elastic modulus and yield strength, which leads to a different material removal rate. When the abrasive particles hit the workpiece surface, the applied force must be greater than a

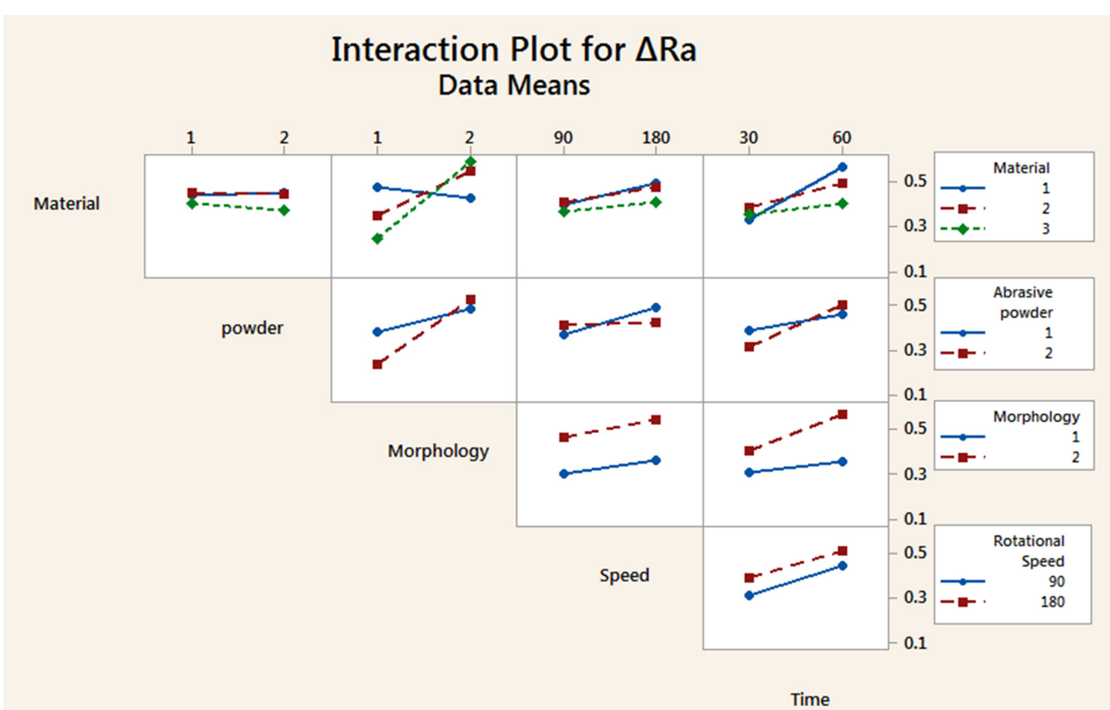

Fig. 11. Interaction plot for ΔRa.

critical force to cause plastic deformation and eventually material removal. Some research has shown that the presence of elastic recovery (elastic modulus / yield strength) decreases the surface roughness in finishing process because it reduces the material removal rate [32–35]. Therefore, material with the highest elastic recovery (steel in this study) has the best surface roughness in the same process conditions.

5.2.3 The effect of material and abrasive powder

The effect of abrasive particles on different surfaces varies. The use of alumina abrasive powder for steel and titanium work-pieces has been more effective than titanium dioxide. However, in the case of magnesium work-pieces, the result is reversed and using titanium dioxide powder has led to better surface quality.

5.2.4 The effect of material and rotational speed

The results of the experiments show that the surface quality increases with increasing the rotational speed of the magnet but the amount of improvement was not the same for all three materials. The greatest effect was seen for magnesium work-piece.

6 Conclusion

In this study, the effect of the morphology of magnetic abrasive particles in MAF along with four other process parameters, including material, machining time, speed of finishing operation, and the type of abrasive powder were evaluated. MAF setup was prepared using a permanent magnet. Full factorial technique of design of experiment was employed to investigate the effect of the mentioned parameters on surface roughness. MAF was performed on three commonly used metals in orthopedic implants i.e., titanium, magnesium and stainless-steel alloy 316LVM. Based on the results presented above, the following conclusions can be drawn.

– According to the ANOVA table, the morphology of abrasive particles and the machining time are the most dominating parameters, making the contribution to the total variability of as much as 30.65% and 11.08%, respectively. Besides, the interactions of material with morphology of abrasive particles, and material with machining time were found to be reasonably significant.
– The results showed that the rod-shaped abrasive particles are far more effective on the surface finish in comparison with spherical abrasive particles, which can be attributed to the cutting edges in this type of particles. In contrast, spherical magnetic abrasive particles are spherical balls that are only bonded to the work-surface with magnetic force, and sometimes rolled with a magnetic field, and are less involved in material removal.
– The surface quality of steel 316LVM obtained after MAF process is the best among the three examined metals. This can be attributed to the mechanical properties of these metals which affect the amount of chip and chip thickness removed during MAF.
– As it was expected, increasing the machining time has led to decrease in surface roughness.
– The results also showed that the effect of abrasive powders (non-magnetic particles) is much less than the other parameters and is negligible. However, alumina powder (Al_2O_3) has a slightly better effect on surface finishing in comparison to titanium oxide powder (TiO_2).
– It was seen that the speed of machining was one of the other most significant parameters in MAF. As the speed of machining increases, the surface quality improves. However, due to occurring abrasive particle separation from the magnet, there is a threshold for the speed.
– In the present study, since the main focus was on the morphology of the abrasive particles, some parameters such as the size of the non-magnetic abrasive particles, strength of the magnetic field and working gap, were considered constant. In the future studies, the simultaneous effect of these parameters on a broader scale will be examined, as well as numerical analysis to model the material removal rate in the process, taking into account all the influential parameters. Besides, investigation of the surface roughness of a hip joint implant after MAF process is going to be made as a case study. In this case, the risk of material transfer by MAF process is also going to be evaluated.

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