EXPERIMENTAL STUDY ON VIBRATION-ASSISTED MAGNETIC ABRASIVE FINISHING FOR INTERNAL SURFACE OF ALUMINIUM TUBES

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ABSTRACT: This paper designed a new apparatus and was set to polish the internal surface of aluminum tube in the presence of axial vibration (AV) for the poles. Several parameters influenced the quality of polished surface during magnetic abrasive finishing. The effect of such parameters has been the subject of most research to achieve the best finished surface with desired characteristics. This paper employed a statistical approach to investigate the effects of four parameters; mesh size of the abrasives, the weight of the abrasive powders, the number of cycles and especially vibration frequency of the poles on surface roughness and material removal weight in finishing process. Design of experiments (DOE) methods and analysis of variance were applied to determine the significant factors. Microscopic view of the working surface was also presented to better understand the parameters effect on the finished surface.

KEYWORDS: *Magnetic abrasive finishing, Aluminum tube, Axial vibration, ANOVA.*

1.0 INTRODUCTION

With an increasing need for machined components with high surface quality in high-tech industries, the demand on new finishing methods has been steadily increasing. In other words, it is difficult to finish geometrically complex parts with high accuracy and minimal surface defects by conventional grinding and polishing techniques. To minimize the surface damages, gentle finishing conditions with low level of controlled forces are required [1].

In the magnetic abrasive finishing (MAF) process, forces are controllable and material removal is in molecular or atomic scales. Therefore, this method is capable of producing surface finish of the order of few nanometers without any surface defects [2]. MAF can be applied for polishing the flat plates [3] as well as internal and external surfaces of tube type work pieces [4, 5]. For these exclusive characteristics of MAF technique, its application is burgeoning mostly in aerospace and manufacturing of medical instruments industrials which involve the precise features with super finished surfaces.

MAF performance and efficiency can be affected by the input parameters of the process. Thus far, some of these parameters have been investigated by researchers. A magnetic assisted finishing method for internal polishing of long tubes was introduced in 1994 [6]. The finishing pressure and magnetic flux density in finishing area were measured when a different arrangement of magnetic poles is applied to polish the internal surface of tubes [7].

Wang and Hu [4] performed some polishing tests on the tubes made from different alloys in order to find the effects of some parameters such as rotational speed, abrasive volume and finishing time on the process outputs and it is found that an increase of rotational speed can result in more material removal and better surface roughness as long as the rotation of the abrasive brush is smooth. DOE and response surface method were applied to investigate the effect of the parameters on plate MAF process [8]. They examine the microscopic changes in the surface texture resulting from the MAF process. In addition to the surface roughness measurement, atomic force and scanning electron microscopy were carried out to gain insights of the wear pattern of the finished surface of steel plates. Yamaguchi et al. [5] compared the effect of different abrasive powders on surface improvement in the internal polishing process of bent tubes by performing the MAF process on the external surface of a steel shaft. The magnetic abrasive particles (MAPs) as the machining tool of MAF influence the finishing efficiency and the final surface quality. The surface morphologic structure shows that the finishing ability of sintered MAPs is greater than simply mixed MAPs [9].

Im et al. [10] observed the desirable influence of axial vibration on the surface improvement. In surface polishing approach by combining planetary motion (PM) with two dimensional vibration-assisted magnetic abrasive finishing, PM results in uniform, intersecting, and closely packed polishing paths which contributes to better surface quality within a shorter processing time [11]. The effect of the machining time and working gap on the surface roughness was investigated in ultrasonic-assisted magnetic abrasive finishing process. Achieving the superior surface finish in a short time is the advantage of this process [12]

There are still several aspects of the process that require more studies. One of those aspects is the exact effect of the change in the axial vibration frequency of the magnetic poles in internal finishing of the tubes. An innovative design of the finishing apparatus provides a simultaneous rotational movement and axial vibration for the poles in this work. Moreover, the tests are done on aluminum tubes that have not taken into an adequate consideration in previous research compared to other materials. The optimized lubricant percentage in abrasive mixture is estimated through some preliminary tests and then applied for the designed tests. The effect of vibration frequency and three other parameters: mesh size of the abrasive particles, weight of the abrasive brush and number of process cycles were statistically investigated using response surface method (RSM). Finally, microscopic effect of the process on surface texture is explained using atomic force microscopy (AFM).

2.0 EXPERIMENT SETUP CHARACTERISTICS

Figure 1 shows the external view of experimental setup. The aluminum tube was fastened in the three-jaw chuck of the lathe and so, can rotate. The apparatus was mounted on the cross slide of the lathe machine. Four Nd–Fe–B permanent magnets (20mm×10mm×10mm) were mounted in a cylindrical yoke and their arrangement was flexible and the distance between the pole tips and external surface of the tube was adjustable to accommodate various tube diameters and control the strength of magnetic field. The rotation of the yoke was transmitted by an electromotor motor. Alternatively, the tube could rotate to produce a relative speed between working surface and the abrasive brush. Using another electric motor equipped by an eccentric disc provided the simultaneous axial vibration for yoke and poles.

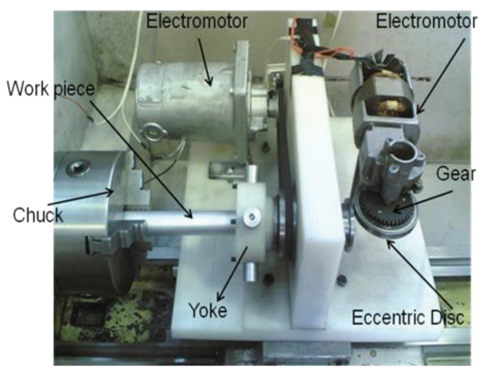


Figure 1: Experimental set up

3.0 OPTIMUM VALUE OF THE LUBRICANT

In general, lubricant was used to reduce the friction between the abrasive and inner surface of the tube as well as to cool the finishing area and eject chips from the finishing area. Adding oil to the powders made it dense and avoided abrasive particles to flow away from finishing area especially at high speeds. Because the total volume of abrasive brush (including abrasive powder and oil) was selected as one of the factors for DOE in this study, it is necessary to fix the percentage (ratio) of added oil in order to eliminate the effect of oil volume during the main tests. The optimum ratio of oil volume could be estimated in preliminary tests and then, applied for the main experiments. The lubricant volume varied from 0.1 to 1 ml. Other tests conditions were rotational speed of poles: 460 rpm, magnetic abrasive powders: steel grits (mesh size: 70 #), weight of abrasive powders: 3 gr, number of process cycles: 2 and working gap: 1 mm.

Figure 2 shows the changes in material removal and final surface roughness (Ra) versus lubricant volumes. The measurement devices and approaches for surface roughness and removed material weight were the same as for the main tests. Using more volume of the lubricant in the abrasive brush led to more material removal and also a better surface roughness. However, the required condition for the smooth relative motion of the abrasive brush against the inner surface of the tube had to be considered. If the lubricant volume grows excessively, material removal would slightly decrease because the oversupply of lubricant may act as a delimiter (barrier) between abrasives and the working surface [13]. Therefore, there is an optimum point for lubricant volume. Considering the best surface roughness that was achieved at 0.4 ml as the lubricant volume, the optimum lubricant volume to abrasives weight ratio would be regulated at (0.4 / 3) = 0.13. Thus, the added oil volume would change as the weight of the abrasive powders -as one the input variables in DOE tests-, changed in order to meet this constant ratio in each test.

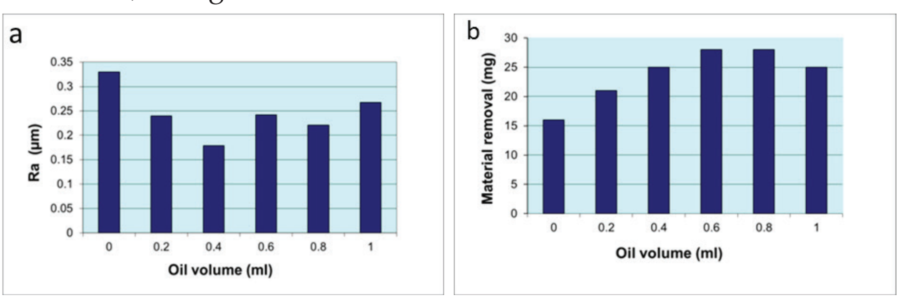


Figure 2: Change in (a) final Ra and (b) material removal with lubricant volume

4.0 DESIGN OF EXPERIMENTS AND PROCEDURE

Response surface method (RSM) was used to examine the relationship between the response variables and the set of quantitative experimental variables. The purpose was to study the effect of four input parameters: axial vibration frequency, mesh size of the abrasives, weight of the abrasive brush and the number of the process cycles on two outputs: ultimate surface roughness (Ra) and material removal weight (MRW) in magnetic abrasive finishing process. The present study was established based on the Box-Behnken design which recommended 27 designed tests regarding the number of the inputs in this case. Variable factors and their levels are shown in Table 1. MINITAB -statistical software- was employed to design the tests and analyze the experimental records. The percentage of the added oil in abrasive brush was set at the optimum value considering the previous section results were kept constant for all 27 tests. The initial and final Ra, before and after MAF respectively, were measured using a mobile roughness measurement device (Mahr Perthometer M2). The change in the tube's weight occurred because material removal was also measured for each test using a digital balance.

Table 1 Variable factors

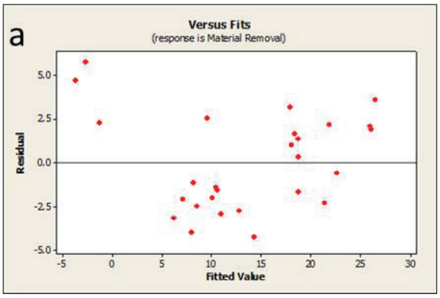
Factors	Factor Levels		
	1	2	3
Weight of magnetic abrasive powders (gr)	1	3	5
Mesh number of the abrasive particles (#)	70	120	170
Number of cycles	1	2	3
Frequency of axial vibration of the poles (Hz)	0.67	1.3	2

5.0 EXPERIMENTAL RESULTS AND DISCUSSION

Analysis of variance (ANOVA) and regression analysis were performed to determine significant factors and factors interactions and also, to establish a relationship between factors and responses.

5.1 Data Analysis for Material Removal and Ra

Figures 3a and 3b are the diagrams of residuals corresponding fitted values of the material removal weight and final (ultimate) Ra. Random distribution of points showed that the value of the variance was not constant and thus, the model was capable to correctly anticipate the response for this output.



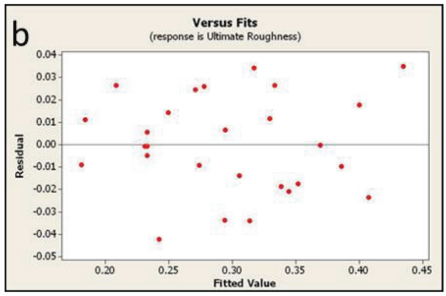


Figure 3: Residuals versus fitted values plot for (a) MRW and (b) final Ra

5.2 Analysis Of Variance for Material Removal Weight and Ra

ANOVA is commonly employed by experimenters because it covers the shortcomings of graphical assessment. The ANOVA for MRW is illustrated in Table 2. The number of cycles, powder weight, mesh size, the square of the weight and the cycle number were the factors which present P-value as lower than the α-level of confidence which was assumed to be 0.05 [14] and based on this modeling, had a significant effect on the MRW. The vibration frequency was an insignificant factor for MRW. In Table 3, the ANOVA for final Ra was presented. Number of cycle, mesh number, weight of the powders and frequency were the factors which present a P-value as lower than 0.05. The square of these factors except frequency showed to be significant too. Values R-Sq and R-Sq(sdj) indicated that the model fitted the data well.

Table 2 ANOVA for MRW

Term	Coef.	SE Coef.	T	P
Constant	-0.014966	0.007134	-2.1	0.049
mesh	-0.000155	0.00001996	-7.77	0.00
weight	0.012865	0.002109	6.1	0.00
cycle	0.023667	0.005556	4.26	0.00
frequency	-0.000376	0.0015	-0.25	0.805
weight^2	0.0017344	0.0003416	-5.08	0.00
cycle^2	0.004437	0.001366	-3.25	0.004
R-Sq = 88.29% R-Sq(pred) = 77.75% R-Sq(adj) = 84.78%				

Table 3 Analysis of variance for final Ra

Predictor	Coef.	SE Coef.	T	P
Constant	0.9446	0.1025	9.21	0.00
mesh	-0.004491	0.00119	-3.77	0.001
weight	-0.07872	0.0189	-4.16	0.001
cycle	-0.20827	0.04982	-4.18	0.001
frequency	-0.0622	0.01304	-4.77	0.00
cycle^2	0.03882	0.01226	3.17	0.005
weight^2	0.010133	0.003066	3.31	0.004
mesh^2	0.00002231	0.00000491	4.55	0.00
R-Sq=87.3%	R-Sq(pred) = 73.11%	R-Sq(adj)=82.6%		

5.5 Main Effects

Figures 4 and 5 depict the plots of main factor effects on ultimate Ra and MRW, respectively. The data mean value was used to determine each factor's effect. According to Figure 4, weight of the abrasives, number of cycles and frequency have inverse relation with the final surface roughness. Hence, by increasing these parameters, Ra significantly decreased. The mesh size had significant effect on surface roughness and in lower values of mesh number (large size of particles) more improvement in surface roughness could be achieved. Furthermore, the frequency factor among the four input factors seems to be insignificant on the MRW based on Figure 5.

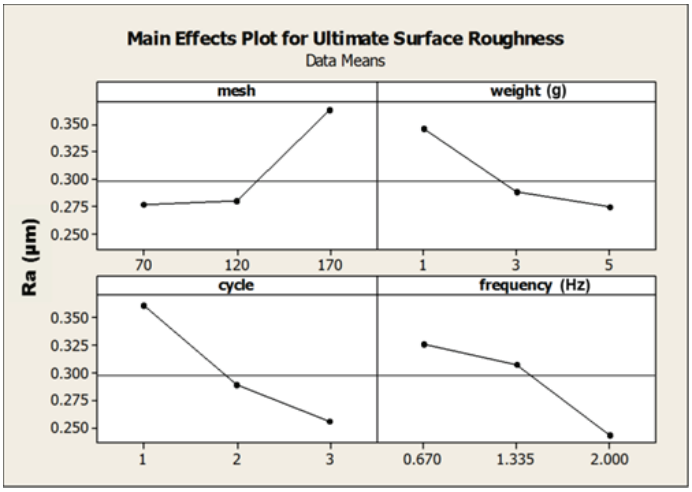


Figure 4: Main effects plot for final Ra

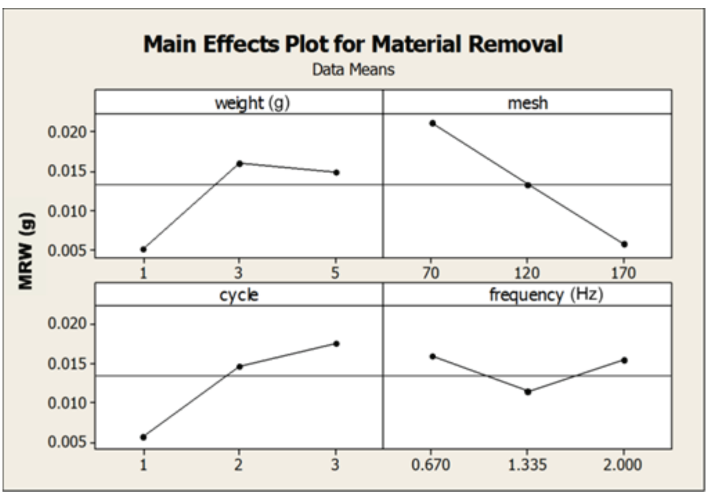


Figure 5: Main effects plot for MRW

5.5.1 Effect of Powder Weight

The more MRW was observed in higher amounts of powder as shown in the diagrams. In addition, a better surface roughness was achievable using more amount of powder. However, this influence is negligible in more values of powder weight. The fact is that by increasing the powder weight, the number of the abrasive particles rose and it would have a positive effect on the surface improvement in a certain time period. On the other hand, it is obvious that the strength of magnetic poles had a constant value and also, the finishing area had a certain capacity to attract the abrasive particles. Thus, after the maximum value, additional amount of powder might not even touch the surface and might be rejected or thrown out of the finishing zone especially at higher rates when the normal force was less and the centrifugal force was sensibly larger. Consequently, there was an optimum weight in which the most MRW and the best final Ra happened and by increasing the powder weight, no significant effect on the MRW and final Ra was observed.

5.5.2 Effect of Vibration Frequency

The graphs showed that the vibration frequency did not have significant influence on MRW while it decreased the final Ra. Axial vibration of the poles helped refreshing the abrasive brush in the finishing zone and this resulted in removing the surface picks more efficiently. In other words, the existence of the vibration did not change the magnitude of the finishing pressure -which was responsible for MRW changes- but, the place of pressure exertion.

Therefore, by increasing the vibration frequency, the dispersion degree of surface roughness values decreased and smoother surface would be achieved. However, application of very high frequencies is not recommended due to the risk of adverse effect on density of the abrasive brush and uniformity of the finishing process.

5.5.3 Effect of Number of the Cycles

Assuming that feed rate and the finishing length are constant, an increase in the number of cycles reflects an increase in the time of the finishing process. Figures 4 and 5 illustrate that when the process continues (increase of the number of cycles), abrasive particles have comparatively more time in order to act on the surface and this will cause more material removal and surface improvement.

5.5.4 Effect of Mesh Number

The magnetic force on larger particles is more compared to small particles ,hence, the more pressure and consequently, deeper scratches and more material removal occurs if the larger particles are used for finishing [4]. An optimum point for this effect may be defined because if the size of the particles size exceeds a specific value, the material removal could be decreased due to the lack of enough cutting edges able to reach the surface and remove the material. It is declared in previous researches also, that the smaller particles have the potential to produce better (lower) surface roughness [15] whereas according to Figure 4, surface roughness improves when the larger powder particles are used in this work. To explain this unexpected phenomenon, the duration time of the process might be considered. Regarding the time of the process in each test performed in this study, it seems that abrasive particles did not have enough time to reach the minimum possible roughness. If the process continued to reach the saturated condition of the process, smaller particles would produce a better roughness. In other words, the reduction in surface roughness took places “sooner” when larger particles were applied as the abrasive tool. In short, it is recommended to perform the MAF process in multi-steps especially for higher efficiency (smoother surface in a shorter time) in industrial applications. In the first steps, larger abrasive particles might be used to reduce the surface roughness in a short time and after reaching a saturation condition, smaller particles would be applied to reach the possible minimum roughness.

5.6 Atomic Force Microscopy

Figure 6 is a 3D presentation of a 20 μm × 20 μm area of the surface texture before MAF process. The maximum peak was around 0.2 μm high relative to the zero level.

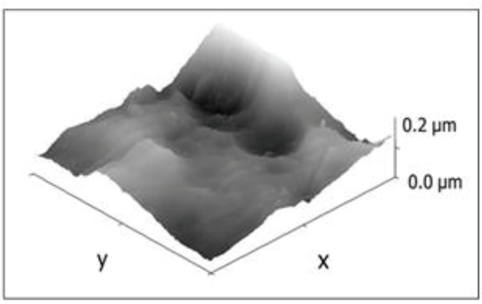


Figure 6: 3D view of a sample area of the surface before MAF

Figure 7 is related to the surface texture after one cycle of MAF process using three grams of abrasive powder (mesh size #120) and with vibration frequency set on 2 Hz. As illustrated, the roughness was significantly improved and the maximum peak height was reduced to 80 nm. However, more MAF cycles were still needed to achieve a smoother surface. If the process continued for three cycles, the large sized peaks could be removed and a relatively smooth surface with less roughness could be produced. The maximum peak height was around 40 nm that showed 50% improvement in surface finish in this case.

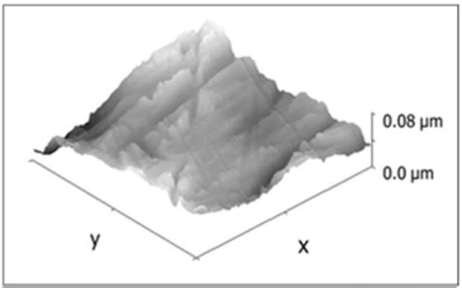


Figure 7: 3D view of a sample area of the surface after one cycle MAF

Table 4 gives more quantitative information related to projected area in AFM photos that helps to compare the changes in surface texture before and after MAF process. The quantitative data presented in Table 4 is obtained for a limited sample area and direction of the surface only for a comparison purpose and thus, cannot be used as the whole surface roughness or other surface characteristics in macro scale.

Table 4 Statistical data about roughness of the projected area in AFM photos

Parameters (statistical quantities)	Before MAF	After MAF (one cycle)	After MAF(three cycles)
Projected area (µm2)	400	400	400
Ra (nm)	210.3	77.1	39.6
Rms(nm)	282.9	107.5	53.7

6.0 CONCLUSION

1- The effects of four parameters on the final surface roughness and material removal weight during MAF process for internal surfaces of aluminum tubes have been investigated experimentally. The experiments are conducted using a new setup which provides the simultaneous axial vibration and rotation of the poles and make it possible to study the effect of vibration frequency as well.

2- The role of the lubricant has been experimentally examined and the optimum percentage of the added oil volume to the abrasive brush is ascertained and applied for the main tests in this research.

3- RSM method is applied to design the experiments and then, the highly effective parameters on the MAF outputs are determined.

4- Increasing the number of cycles (process time), the weight of the abrasive brush and the particle size could result in more material removal at the conditions in which the tests are performed. A better surface roughness will also be reached when the number of cycles (process time) and the weight of the abrasive brush increase. These results are valid as long as the process is uniform and the abrasive brush is dense and to remain in the finishing area.

5- The abrasive mixture with larger particles has the capability of polishing the surface sooner; but finer particles can be applied in next step to achieve a relatively smoother surface if a higher efficiency is needed for industrial applications.

6- The frequency of the axial vibration of the poles does not have a significant impact on MRW. However, Ra is influenced by this factor and the higher frequency improves the surface finish. However, this efficacy may lose its color at higher frequencies if it leads to the disturbance of the smooth and regular relative movement of abrasive brush during the process.

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