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Research Paper

Investigation of Mass Magnetic Abrasive Finishing Process on Compressor Blades

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Abstract
Attempts at research across various industries to achieve high-quality surfaces have led to the development of new finishing processes. Magnetic Abrasive Finishing is a novel technique where a magnetic field is employed to control an abrasive tool. Gas turbine compressor blades are among the industrial components requiring high surface quality due to their exposed surfaces. The reduction in surface roughness on these components has a significant impact on the efficiency of motor turbines. This paper focuses on studying the Magnetic Abrasive Finishing process parameters for the free surfaces of Titanium blades. Using a mass Magnetic Abrasive Finishing machine, the influence of powder weight, type of abrasive particles, and gap on the variation of surface roughness is investigated through statistical methods such as the response surface. The fabrication of the machine and determination of magnet polarity are carried out using Maxwell simulation software. The Factorial method is employed for experiment configuration. Mechanically alloyed powders produced by ball mills are used in this study. Results demonstrate that employing the magnetic abrasive method can reduce the surface roughness of the blade by up to 33%. The empirical model derived from regression analysis is utilized to predict the variation in surface roughness. Variance analysis of the experimental results indicates the significance of all studied parameters. Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) are employed for a qualitative evaluation of the results.

Keywords
Magnetic Abrasive Finishing, Free Form Surfaces, Compressor Blade, Magnetic Flux Density, Response Surface Method

1. Introduction
one section of the queue of the manufacturing process can affect the produced surface directly. There are different ways changes in the manufacturing process influence the produced surface. Finishing is a fragile part of the production process and based on its functionality can be performed differently.

Higher quality of the surface and lower roughness is the common goal of all finishing processes. The urging need for higher surface qualities and the disability of conventional methods led to the invention of new finishing methods. In most of the processes in which there is a tool with high rigidity achieving high surface quality is almost impossible. However, in processes with flexible tools surface finish in terms of Nanometers is achievable. In conventional methods, current tools have dimensional and shape limitations and should not make mechanical contact with the workpiece, while in many cases like finishing of medical equipment or brittle parts, this contact can initiate defects in the workpiece. Therefore a finishing method that can finish surfaces with different shapes has flexibility and leads to a reduction of the advert effect of physical contact is valuable. The Finishing process on free surfaces with intricate shapes is more difficult than on other surfaces. Currently, mostly manual methods are used. This method is time-consuming, inaccurate, and very expensive[1].

Surface roughness possesses an undeniable influence on the lifetime of some equipment e.g. dies [2]. Dies surface quality also strongly affects the quality of the produced work pieces. Generally, dies have surfaces with intricate 3D curves. On the other hand, the magnetic abrasive finishing process is among those that in recent years developed monumentally. Magnetic abrasive brush which is shaped by a magnetic field is very flexible and can conform to different surfaces and curves. In this process, the finishing tool is not rigid; therefore there is no need to manufacture different tools for different curvatures. Small micron-size abrasive particles along with their formability can reach any intricate surface and curvature [3]. Self-sharpening, high conformity, lower temperature increase in comparison with other processes, desirable control on imposing force to particles, and imposing negligible shear stress to the workpiece surface with no surface micro-crack initiation are some of the advantages that caused the fast growth of this process [4]. Figure 1 shows the MAF process on curved surfaces [5]. The re-solidifying layers which are very common in electro-discharge machining and are prone to crack initiation can be eliminated using the MAF process [6]. Additionally, due to the small imposing force- micro Newton or less- the penetration depth of abrasive particles is limited to less than 1μm. thus, this process does not alter the dimensional and geometrical tolerances of the workpiece.

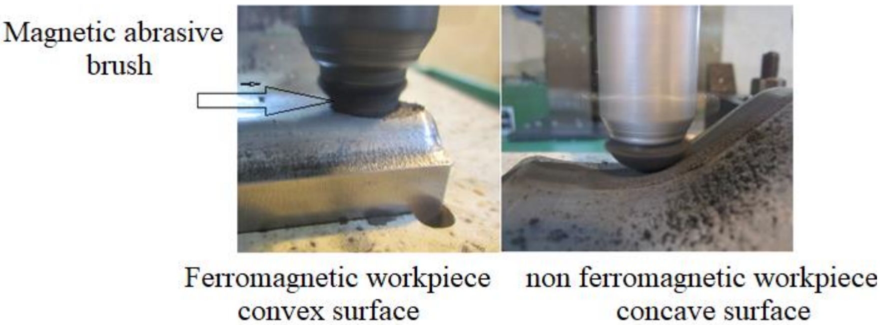

Figure 1. MAF process over a freeform surface [5]

Uniform quality finished surface can be achieved with automatic control of the process parameters [7]. In most previous studies and experiments MAF process was applied over flat or cylindrical (internal/external) surfaces [8]. Ching Tin et al. studied process parameters like rotational speed, feed rate, lubricant, finishing gap, and particle amount on the MAF process over 304 stainless steel surfaces with a smooth curvature using the Taguchi method and they reported a decrease in surface roughness from 1.58μm to 1.02μm [9]. Shahuyaei Yen and Shinmura investigated the effect of vibration on MAF over surfaces with very smooth curvature [10]. Vibration with very low amplitude and high frequency stimulated the workpiece in vertical, horizontal, and combined directions and its effect on a magnetic field, pressure on abrasive particles, and efficiency of the process was studied.

Jiung D-Kim et al. introduced a novel method to finish die surfaces [11]. In this technique no CNC system was applied and using guiding rollers the magnet swept the path and the MAF process was accomplished. The Selected workpiece had smooth curvature with low concavity or convexity. Zank et al. in 2000 investigated the NURB curve's theory and its effect on the MAF process [11]. Ding et al. studied the time parameter and its impact on surface roughness reduction in concave/convex surfaces [12]. Masahiro Anzay studied the MAF process over sparked die surfaces and a reduction in re-solidifying layers was achieved [13].

One of the components with free surfaces which is very common is compressor blades in air engines and gas turbines. Blade's airfoil and its surface quality are very effective in its performance. The Gas turbine compressor's blade has a complicated shape with thick roots and airfoil with varied thicknesses. These blades are usually made of high-strength materials like Titanium alloys [14]. A common alloy in aeronautical and power plant industries is Ti-6Al-4V. Good corrosion, oxidation, and fatigue resistance are this alloy's remarkable properties. Due to its high thermal properties, it can keep much of its strength during the machining process. The High reactivity trait in this alloy causes high abrasion and failure in tools. On the other hand, its weak thermal conductivity results in high heat production in the cutting zone. Due to the low machinability of Titanium alloys and their undesirable effect forging the blades seems cost-effective. Besides, the surface quality of the blades is considerable in its performance along with motor efficiency. Previous studies revealed that the blade's surface roughness has an inevitable role in turbine efficiency reduction. Surface roughness especially in inlet vane and attack edge is very prominent. with the hot forging of Titanium and following a fast cooling sequence, there comes a layer rich in alpha phase which is called the surface alpha layer. This layer is brittle and it provides a good ground for micro-crack initiation and reducing workpiece lifetime. Electrochemical machining is a method to omit this layer [15]. As mentioned before, in industrial applications especially aeronautical industries, in addition to surface alpha layer elimination, surface quality, and roughness are very critical, because the strength property of the workpiece relies on its surface roughness. Figure 2 illustrates a typical blade used in gas turbines.

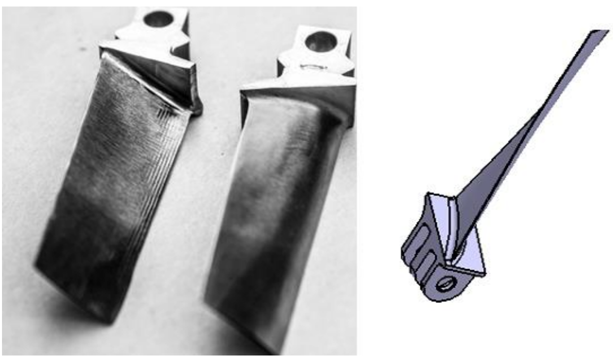

Figure 2. Compressor blade in turbine motors

In previous studies, the MAF process over 2-D and 3-D die surfaces was applied to CNC systems. Figure 1 shows the application and curvature of the workpiece. Maintain a uniform material removal, 3-axis and 5-axis CNC machines are necessary for the MAF process over the blade surfaces with intricate curvature. Therefore, to increase the efficiency of preparation and better alignment of surfaces a novel finishing machine based on the MAF process is designed and manufactured. The

Number of magnets and their configuration, and finishing gap according to magnetic flux density imposed on abrasive particles are determined using simulation and design of experiments methods. Then, using statistical approaches and variance analysis the effect of influential parameters on the change in surface roughness is specified. Additionally, the fabrication method for a new powder of abrasive particles is elaborated.

2. Materials, and methods

2.1 Design and manufacturing of magnetic abrasive finishing machine

to increase the efficiency of MAF, it seems that developing a new MAF machine that can perform finishing on more than one workpiece simultaneously is very beneficial. The whole idea is rooted in mass finishing. The only difference is that in mass finishing the movement of abrasive particles on the workpiece surface is rather arbitrary and random-like. Therefore, there is a low level of control on the whole process. In the mass finishing process using the rotational movement of the vessel, workpiece or vibrational stimuli produces turbulence and mixture in abrasive particles and with the movement of the abrasive particles material removal occurs in an arbitrary mode. In the present designed machine using big meshes of magnetic abrasive powders in comparison with the mass finishing process, these particles are forced to move by applying a magnetic field, and with the collision of particles to the surface of the workpiece micro material removal in the form of micro cutting happens. The Speed of the abrasive particles varied with the speed of the controlling magnets. An analogy of this machine in which using magnets tiny pins was forced to move and contact workpiece surface edge cleaning and polishing processes were performed have been already conventional in industries. However, it should be noted that even in these machines the process does not have high accuracy and since rather big components collide to the surface the process is not in the form of micro-cutting and instead erosion happens due to imposed impacts. One of the advantages of the MAF process is reducing the tensional Residual stress instead, compressive Residual stress emerges in the workpiece, and considering the small size of abrasive particles imposed forces are small. While, using ferromagnetic pins instead of particles the impact and abrasion, especially in brittle materials or those with a brittle layer on the surface lead to crack growth and propagation and dramatically decrease the life span of the workpiece.

Sparked or wire-cut pieces that have recast layers are included in the abovementioned. It is clear that in the MAF mass process that kind of impact which leads to crack growth and propagation does not exist. Figure 3 shows a laboratory functional machine.

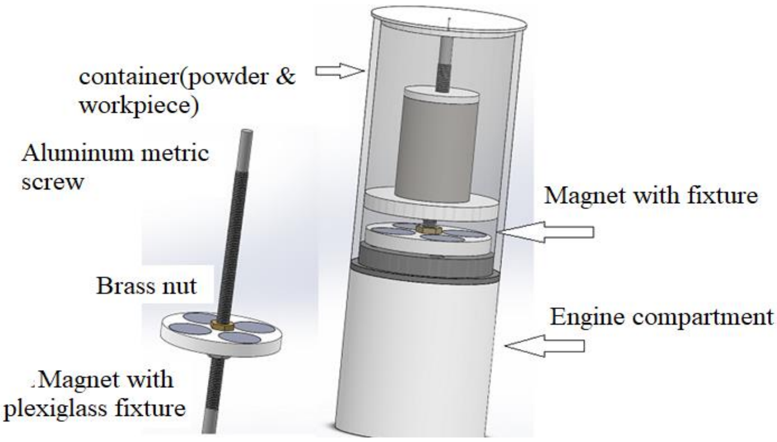

Figure 3. Schematic of MAF mass machine

It can be seen from Figure 4 that in addition to magnets below the workpiece, there are four magnets in the center of the hollow cylinder and beside an internal wall of the vessel and also there is a cubic container. These components rotate by rotating the central shaft of the machine. Due to the existence of centrifugal forces to avoid particles concentrating beside the external wall, inner magnets stop them and keep some particles near the internal wall.

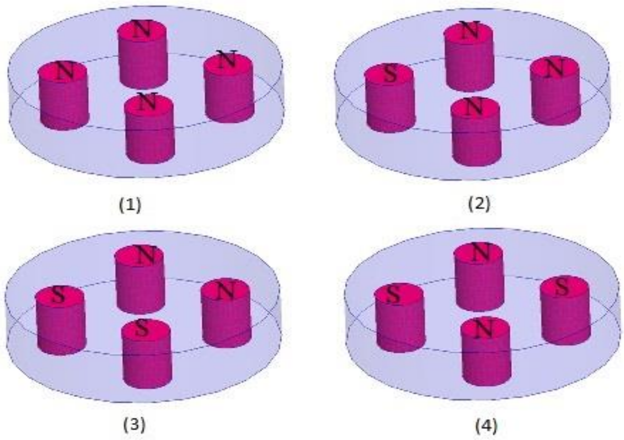

Figure 4. Different arrangements of magnets

All parts used in this machine, the main power screw, nuts, bolts, and vessel, are made of non-ferromagnetic materials. Therefore, there would be no interference in magnetic flux density distribution.

2.2 Simulation and measuring magnetic flux density

To find the number of magnets beneath the workpiece surface simulations were performed. Another parameter was the configuration of poles, similar and different poles, which was pursued with simulation and measurements. Table 1 lists the assumed parameters as well as their variations in different simulations.

Table 1. simulation parameters

Simulation inputs	1	2	3	4
magnet size(mm)	Ø30×10	$\emptyset 16 \times 20$	-	-
number of magnets	3	4	-	-
configuration of magnets	1	2	3	4

Figure 5 illustrates the place of the magnet in the fixture using a simulation approach. It should be noted that according to Table 1, two sizes of the magnet were used to investigate the impact of each disk (diameter bigger than height) and cylindrical magnets (diameter smaller than height). All magnets were permanent ones made of Nd-B-Fe in N35 grade. In the simulation, similar to a fabricated machine, all parts' material was nonferromagnetic.

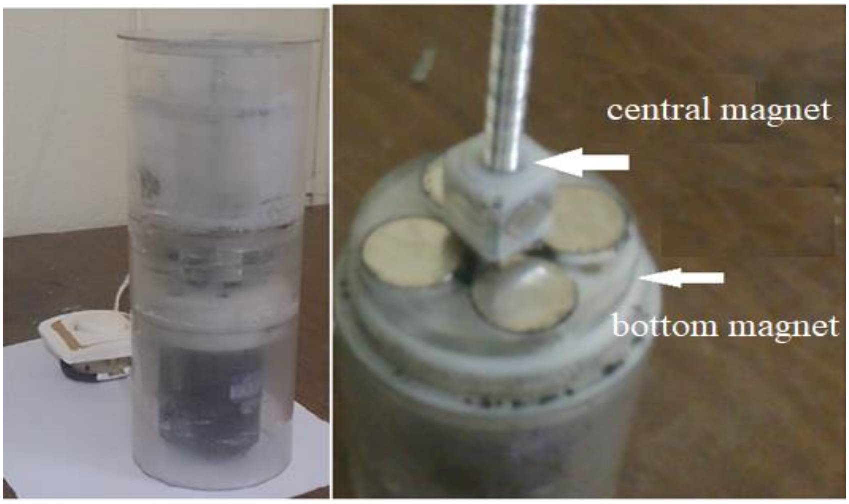

Figure 5. Location and setting condition of magnetic poles (16×Ø20mm) in plexiglass fixture

Based on statistical methods required number of simulations was determined with the Minitab v1.6 software package using factorial mixed levels methodology. To perform simulations, the numerical model produced by Ansoft Maxwell finite element software was applied. After FEM simulation, variance analysis was performed and effective parameters and process set points that lead to optimal magnetic flux density were specified. Figure 6 shows the variation in magnetic flux density with changes in size and setting condition of magnets. The diagram shows the average magnetic flux density on the diametric path defined over the fixture surface. This path passes through the center of two magnets.

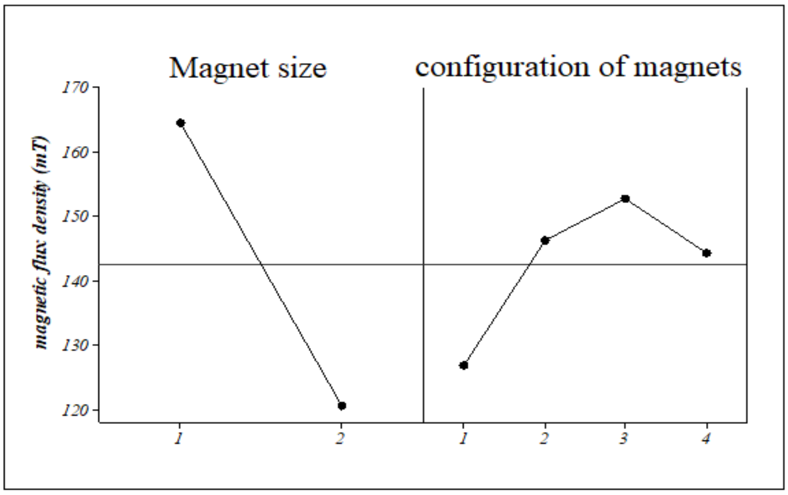

Figure 6. The effect of different parameters on magnetic flux density

Figure 7 shows magnetic flux density distribution in a 4-magnet configuration with a magnet size of Ø30×10mm at 5-millimeter distance to the fixture surface. It should be mentioned that the distance between the surface of the magnets and to cylindrical vessel in addition to the lower sheet thickness equals 5 millimetres and this distance can be set differently.

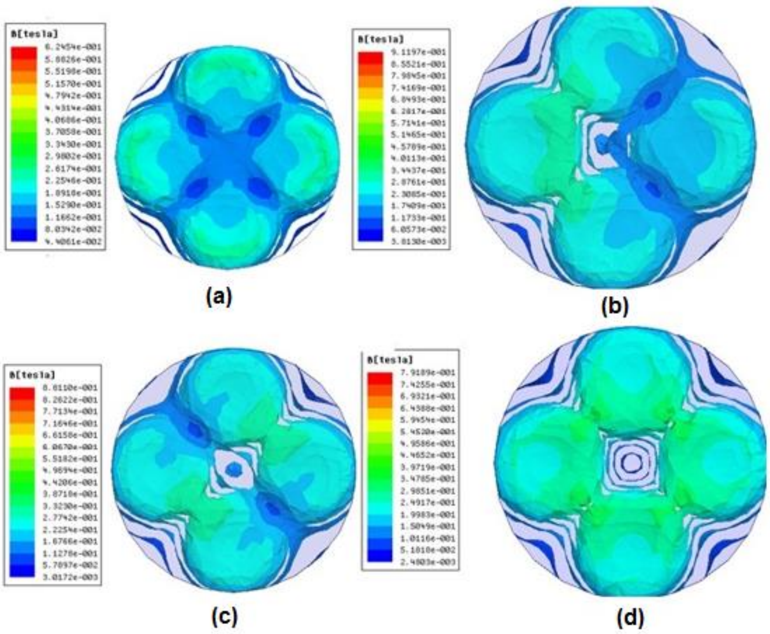

Figure 7. Magnetic flux density distribution in 5 mm distance from fixture-10*30 Nd-Fe-B magnets

Based on the diagrams in Figure 6 it can be inferred that disc magnets produce higher density averages. However, if measuring was done on the magnet surface magnetic flux density would be higher for cylindrical magnets in comparison with disk magnets. Here, with the current configuration, due to the higher surface of the disk magnet, the average of the magnetic flux density is higher over the path. Moreover, it can be seen from Figure 6(c) that the highest magnetic flux density even though there is not a big difference between configurations Figures 6(b) and 6(d). Considering better symmetry which causes more uniformity in particles colliding the workpiece surface (Figures 6(c) and 6(d)) are better choices. It is worth saying that considering the natural movement of the particles due to centrifugal forces and their concentration neat external wall, the higher magnetic flux density near the internal wall can improve the simultaneous uniform rotation of the powder in the vessel. Therefore, Figure 6(d) is selected for experiments. to evaluate the simulated model, measuring of magnetic flux density is performed using a Tesla meter PHWBE, there is a difference between measured values and simulation results, for a 5 mm distance from the fixture surface for configuration number 2. this difference is attributed to the decrease or hysteresis of the magnetic field in reality while in simulation no hysteresis was assumed. The general trend correlates well and the discrepancy is an average of 11.3% which is acceptable. Figure 8 shows the configuration of particles in different conditions.

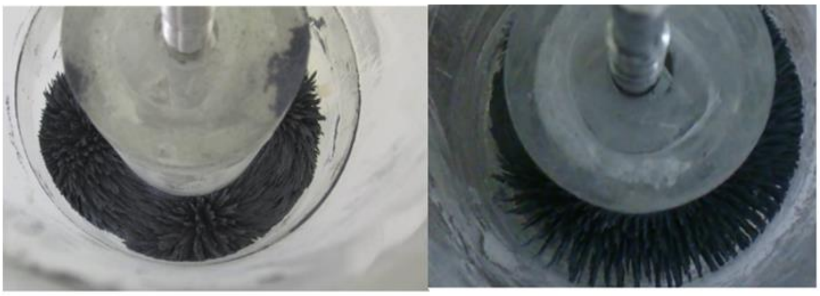

Figure 8. The placement of particles in similar and dissimilar polar conditions of the magnets

2.3 Magnetic abrasive powder

After the design and manufacture of the machine and specifying the number and configuration of the magnets, magnetic abrasive particles should be investigated Applying a small amount of lubricator not only helps to decrease friction and acts as a cooling substance; it also provides a bond, even though a weak one, between abrasive and ferromagnetic particles. This type of compound is used in processes in which powder is directly in contact with magnets (Figure 1). Figure 9 shows bonded and unbounded powder.

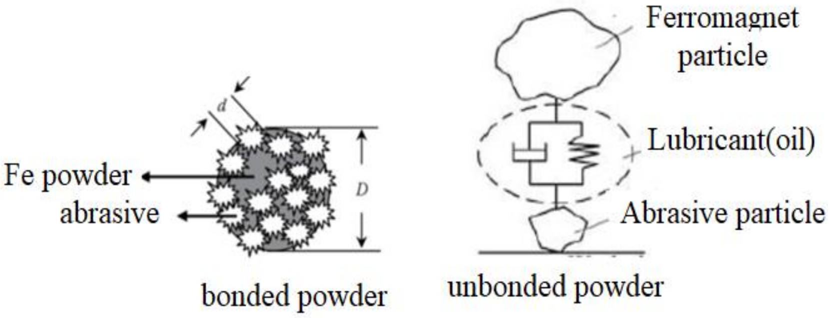

Figure 9. Magnetic bonded and unbonded powder [3]

However, in the current configuration, there is a 5 mm distance between the powder and the magnet which introduces nonuniformity in the behavior of the powder. Using bonded powder with lubricant when the total volume is low does not rotate with a magnet due to its high viscosity and dough-like state of the mixture. When the total volume is high, due to an increase in ferrous particles a powerful force is produced between magnet poles and ferrous particles which prevents the magnet itself from rotating. When unbonded powder without lubricant is applied, in a few moments abrasive particles concentrate on the inner side of the external wall. Since abrasive particles are not ferromagnetic in the primary stage of the process due to centrifugal forces they are thrown away and after colliding with the external wall they concentrate on the inner side.

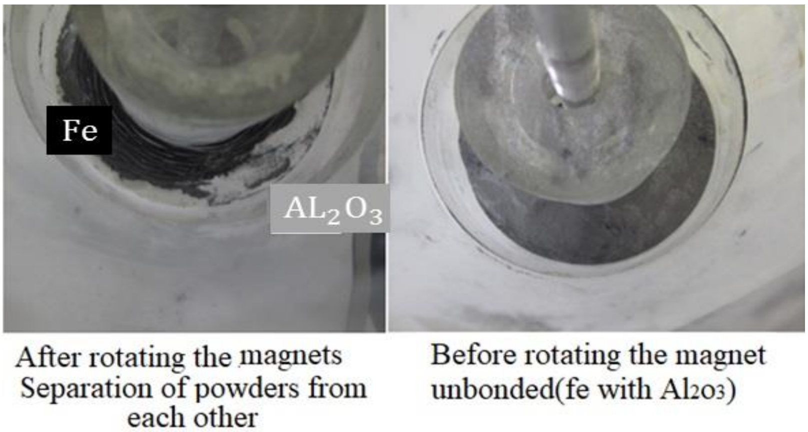

Figure 10. The separation of un-bonded powder

Therefore, the only option is to use bonded powder. The only difference is that here bonded powder produced by the mechanical alloy method is used. Alloying is done with a planetary ball mill machine and small metallic balls of different sizes. Figure 11 shows a schematic of the ball milling process.

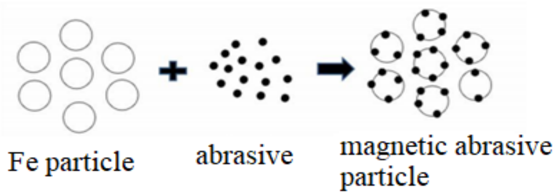

Figure 11. Schematic view of the mechanical alloying

Figure 12 shows the planetary ball milling machine that is applied in the present investigation.

Figure 12. Planetary ball milling machine

There are parameters required to be specified to produce a certain mechanical alloy from powders. Used powders with their characteristics are listed in Table 2. to shield the powder from the atmosphere and prevent powder oxidation, inner gas Argon is applied. Furthermore, metallic balls are used in 3 different sizes.

Table 2. Process parameters of mechanical alloying

Parameter	
type of mill	planetary (ball mill)
speed of ball mill	250 rpm
milling media (ball)	chrome hardened steels
size of balls	Ø 20,10,5
milling atmosphere	Argon
milling temperature	room temperature
Ferro magnet & abrasive powder	Fe#) 400+(Abrasive#)800(
amount of powder	Fe(45gr)+abrasive(15gr)
weight ratio(ball/powder)	5
alloying time	1h(20 min on-10min off)
abrasive	Al_2O_3, SIC, B_4C

The characteristics of the used abrasives are listed in Table 3.

Table 3. Physical and mechanical properties of the abrasives

Abrasive	Density (g/cm^3)	Hardness (Mohs)	Hardness (kg/mm^2)	H_v(Gpa)
SIC	3.1	9.7	2480	24.5
Al_2O_3	3.9	9.4	2100	17.5
B_4C	2.52	9.9	2750	28.4

Particle morphology is investigated using a 20 KV set of LEO/ZIESS 1450VP Scan Electron Microscopy (SEM). Moreover, Energy-dispersive X-ray spectroscopy (EDX) is used to analyze the elements and confirm the quality of the produced powder. Figure 13 shows the qualitative results of these tests.

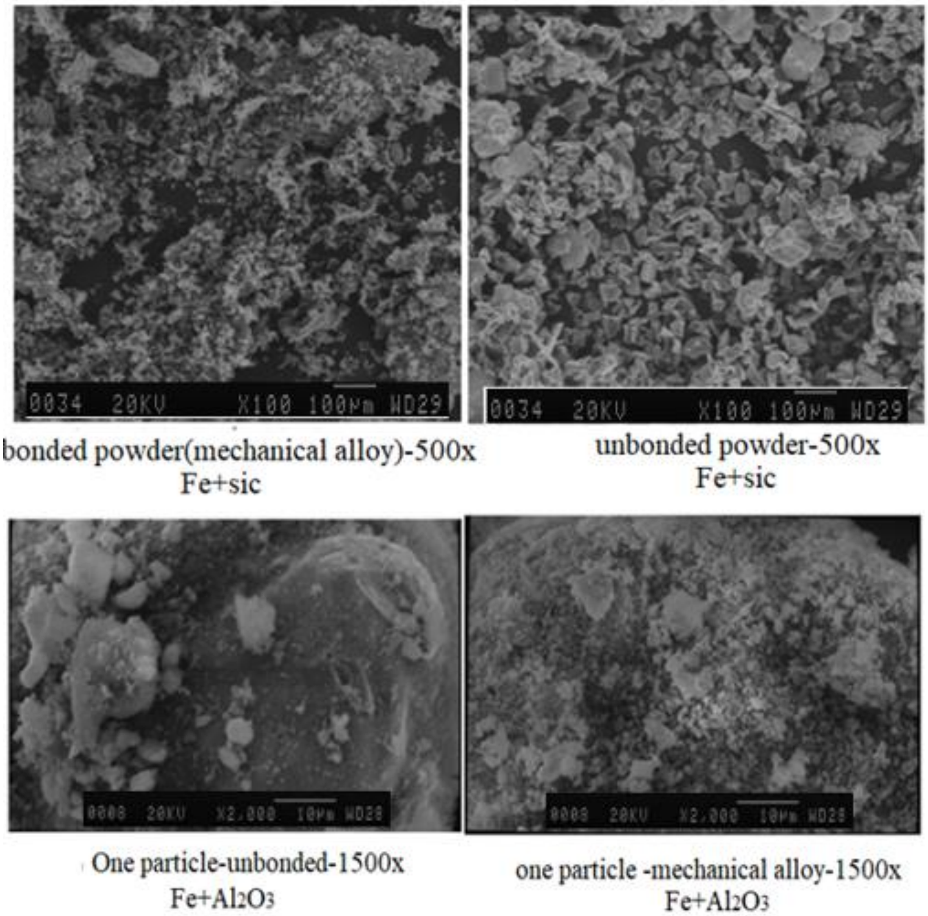

Figure 13. SEM images of different ferrous, aluminum oxide, and Silicon carbide compounds in magnifying ratios of 500x, and 1500x

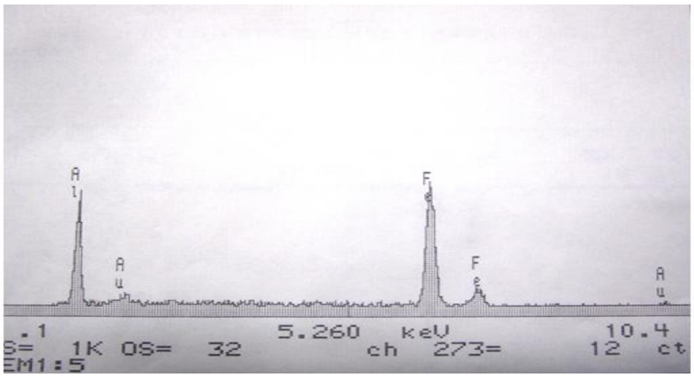

Figure 14. Energy-dispersive X-ray spectroscopy (EDX) of mechanically alloyed particles

2.4 Analytical analysis

Different steps of manufacturing and design of the magnet's configuration and also producing desired abrasive powder were discussed at the moment. Next, the performance of the process on the workpiece is investigated. According to Preston law polishing, the material removal in the polishing process can be described as Equation (1) [16]:

$$M = K.\,P.v..t \qquad (1)$$

Where M is material removal volume, P is finishing pressure, v is cutting speed, t is process time and K is a constant value. As can be explained according to Equation (1), performance is related to pressure or force imposed on particles and also particles' cutting speed. Process pressure and force can be computed using Equations (2) and (3).

$$F = V\chi\mu_0 H \frac{\partial H}{\partial \chi} \tag{2}$$

$$P = \frac{B^2}{2\mu_0}(1 - \frac{1}{\mu_m}) \tag{3}$$

Where V is the volume of the magnetic particle, H,∂H/∂x is the intensity of the magnetic field and its gradient respectively, μ_0 is Vacuum permeability, χ is the magnetic sensitivity coefficient and B is magnetic flux density. According to Equations (1) to (3) it is clear that the imposed force depends on magnetic particle material, the size of the magnetic particle, ferromagnetic- abrasive fractional volume in the compound, and the total volume of the powder. On the other hand, process force changes with variations in magnetic field intensity. The intensity of the produced magnetic field with a permanent magnet depends on the type, shape, and power of the magnet, and in electrical magnets, it depends on the number of wire coils, core diameter, and input current. Moreover, with a change in the distance between the magnet and the surface of the workpiece, the intensity of the magnetic field varies. The material of the workpiece is magnetically effective. The rotational speed and feed rate are also effective on imposed forces. The magnetic abrasive finishing process relies on several parameters. Investigating all parameters is time- consuming and cost ineffective. In this study, one of the statistical methods- full factorial design - is applied. Considering three input parameters each in three different levels experiments are planned. After performing experiments using the response surface method and variance analysis the effect of each parameter and the interaction of parameters on surface quality was obtained. Applying regression analysis, an empirical equation to predict surface roughness variation is applied.

2.5 Properties and specification of experiments

The important output of the magnetic abrasive finishing process is surface roughness. The higher the surface quality is –the higher the reduction in surface roughness- the better the performance of the process. Before experimentation, the surface of all workpieces was submerged into the ultrasonic bath and acetone solution for 20 minutes, and then their surface roughness was measured using a subchronic 3+ set with a cut-off of 0.8 and according to DIN EN IS 0274:1998 standard [17]. Each measurement was repeated for at least three times and the average value was considered. As can be seen, the entire surface does not have a constant surface roughness and different areas show different surface quality. Figure 15 shows the measuring procedure of the surface roughness. It is worthwhile that the measuring probe should be perpendicular to the measuring path and machining traces. Considering different free surfaces, the workpiece should be rotated for measurements. Experimental constant values are listed in Table 4.

Table 4. experimental constant values

Item	condition
workpiece	Ti-6Al-4v
abrasive size	#800
Fe size	#400
weight ratio (magnetic/abrasive)	3.1
lubricant	Not used
magnet type	N35
time (min)	30min
rotational speed(rpm)	500rpm

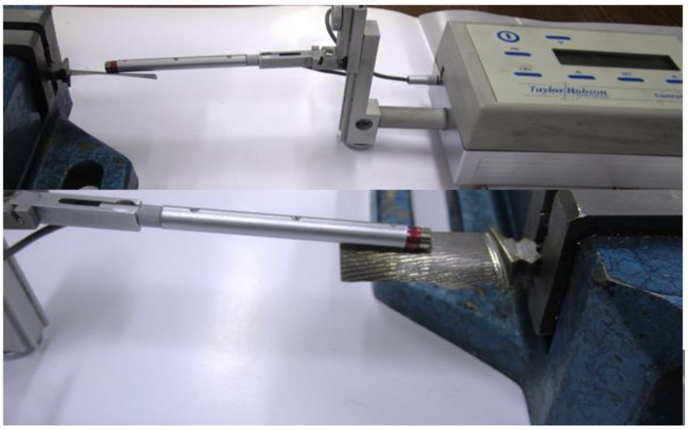

Figure 15. Measurement procedure of surface roughness of compressor blade

The Rotational speed is set to 500 rpm using a dimer and rotational speed sensor for each set of experiments new fresh powder is used. Figure 16 shows the blades and their setting condition in the machine.

Figure 16. Blade and its setting condition in MAF machine with abrasive powder

2.6 Response surface method

RSM is among the mathematical and statistical methods used for modeling and analysis of those problems which are functions of many variables. The aim of RSM is statistical modeling and optimization [18]. The principle of RSM is a design of experiments and statistical optimization. The Design of experiments is a powerful tool in saving time and cost of experiments and also developing and modifying them. Specifying the accuracy of the experiments, governing mathematical model, presenting parameters interaction diagrams, experiment optimization and reliability of the model's accuracy corresponding to experiments are some of RSM advantages. Furthermore, this method can model the relation between inputs and response of an experiment and present it as a second-order linear regression equation. The General form of the equation is similar to Equation (4).

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i \chi_i + \sum_{i=1}^{k} \beta_{ii} {\chi_i}^2 + \sum_i \sum_j \beta_i \chi_i \chi_j + \varepsilon \qquad (4)$$

The Presented model can predict the behavior of the output based on input parameters in all variable ranges and can specify the optimum points.

In this study taking into account the magnetic powder volume, type of abrasive particles, and distance between the magnet and vessel surface (gap), 3^3 full factorial experiments are performed, and using the response surface method, and central composite design (CCD) modeling is done. Table 5 shows input variables and their variation range in three coded units. The response of the experiment is the reduction percentage of surface roughness that can be described using Equation (5).

$$\Delta Ra(\%) = (\text{initial roughness surface- finish roughness surface})/(\text{initial roughness surface}) \times 100 \qquad (5)$$

Table 5. Levels of independent variables

factors	-1	0	+1
type of abrasive(A)	SIC	AL_2O_3	B_4C
amount of powder(mL)V	160	320	480
gap(mm)G	3.5	5	6.5

Considering the volume of the vessel and considering different heights, the powder volume can be specified in three different levels. Moreover, using the pitch of a metric screw 3 different distances (gaps) can be specified. Figure 17 shows the gap distance.

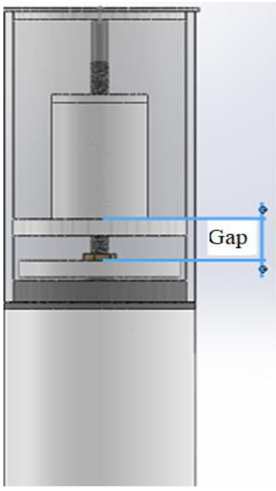

Figure 17. Defined gap; distance between the upper face of the magnet fixture to the upper surface of the vessel

Minitab software package is used to analyze the results and also to obtain coefficients of the governing equation. To avoid possible errors all experiments were performed randomly and not based on their order in the table. Using the response surface method and data analysis a second-order regression equation was derived for each input parameter using an approximation of the experimental data point and later the optimization was performed.

3. Results

According to the results of experiments, findings from ANOVA are shown in Table 6.

Table 6. ANOVA outputs for surface roughness variation based on different inputs in the MAF process

source	The sum of squares SS	degree of freedom DF	Mean square MS	F-value	P-value
Model	357.147	9	39.683	15.44	0.000
A	103.514	1	103.514	40.27	0.000
V	0.851	1	0.851	0.33	0.043
G	169.681	1	169.681	66.00	0.000
A^2	0.929	1	0.929	0.36	0.556
V^2	5.661	1	5.661	2.20	0.156
G^2	38.735	1	38.735	15.07	0.001
A·V	2.251	1	2.251	0.95	0.343
A·G	0.650	1	0.650	0.25	0.621
V·G	34.675	1	34.675	13.49	0.002

Due to the need for 95% reliability in engineering experimentation, values lower than 0.05 for P are considered to specify the effect of each model parameter. Thus, the ANOVA table after modification and deleting insignificant terms can be represented according to Table 7 when terms are listed in order.

Table 7. Modified ANOVA on surface roughness for significant parameters

Source	The sum of squares SS	Degree of freedom DF	Mean square MS	F-value	P-value
model	347.456	5	69.491	27.33	0.000
A	103.514	1	103.514	40.71	0.000
V	0.851	1	0.851	0.33	0.032
G	169.681	1	169.681	66.74	0.000
G^2	38.735	1	38.735	15.23	0.001
V·G	34.675	1	34.675	13.64	0.001

Press value decreased from 116.137 to 83.5438 after modification which assures better accuracy after amendment. Un-coded regression governing the equation of the model can be presented in Equation (6).

$$\Delta R = 5.27 + 0.0024A + 0.7V - 0.9231G + 0.3172\,G^2 - 0.085\,V \times G \qquad (6)$$

Considering values R-sq= 86.68 % and R-sq (adj)= 83.51% and diagrams of the distribution of residual, depicted in Figure 18, an appropriate correlation is discernible.

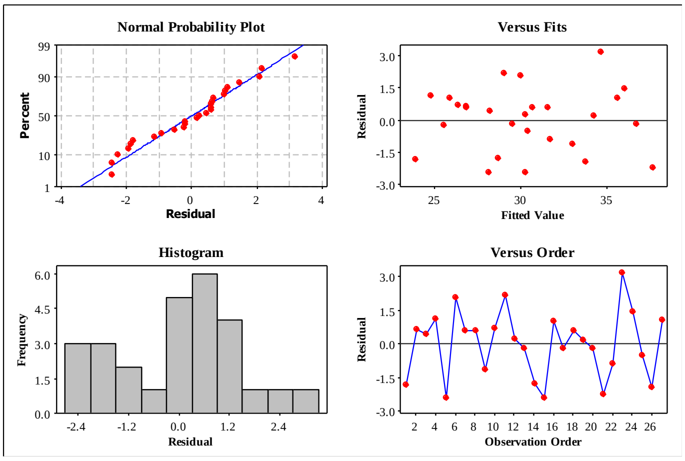

Figure 18. Diagrams for residual distribution

4. Discussion

In this section based on the model corresponding to the experimental data and considering effective parameters it is attempted to explain the effect of gap, powder type, and powder volume. Therefore, first, each parameter is investigated and later the interaction of parameters will be discussed.

4.2 Effect of gap

Considering the value of F and the coefficients in the regression equation gap is the most effective parameter on surface roughness variation. It can be seen from Figure 19 that much decrease or increase in the gap adversely affects the variation in surface roughness. In higher gaps, the magnetic flux density imposed on particles decreases. Therefore, lower forces are exposed to particles and particles do not move about the rotating magnets. So, they stay almost unmoved and do not contribute to material removal. The result is a decrease in surface roughness variation. Moreover in lower gaps, primarily it seems to expect higher forces imposing on particles and better movement of the particles. However, it is observed that with a decreasing gap a chain between negative, and positive poles is weaker compared to the side area of the magnet and therefore more particles stand still.

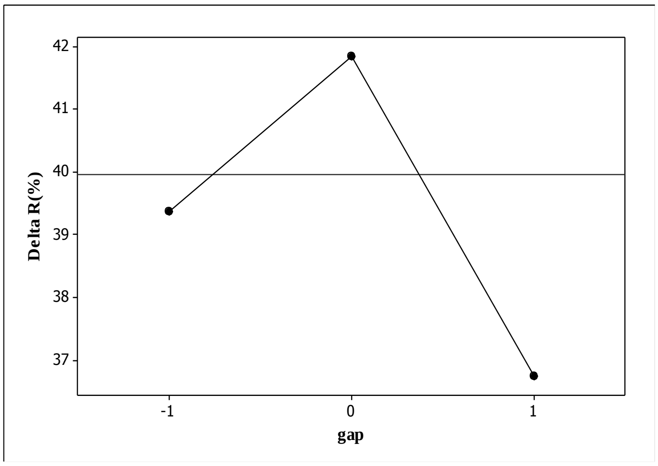

Figure 19. Effect of a gap on surface roughness variation

It was observed that during the process, when the chain between the opposite poles includes a higher volume of particles better material removal occurs. And whenever the stand-still chain is bigger on the magnet surface weak material removal is expected. Figure 20 shows the evolution of the chain between opposite poles and also stand still chain. It can be inferred from a picture that, nevertheless the difference in surface roughness variation when the middle gap changes to a high gap is greater than when the middle gap changes to a low gap.

Figure 20. The development of chain and stand-still chain between opposite poles of the magnet

4.3 Effect of powder volume

It is clear that with an increase in powder volume, the number of abrasive particles increases, and micro-cutting and achieving a smooth surface occurs sooner. one of the advantages of increasing the volume of the powder is the higher efficiency of the process. In all MAF processes, initial surface roughness decreases with time passing. Generally, a huge amount of material removal takes place in the early stage of the process and a lot of picks and valleys of roughness are vanished so fast and surface roughness reduces steeply. However, the slope of this reduction decreases and even there are some cases where particles can produce undesired traces on the workpiece and increase surface roughness. A steeper change in surface roughness in the early stage of the process manifests a higher efficiency of the process itself. The Increase in the powder volume affects this increase in efficiency. On the other hand, considering the dimensions of the blades, more powder volume covers the entire blade's surface, and material removal occurs in one step. Otherwise, two or more steps are required or even the blade should be inversely mounted in the machine after the first step.

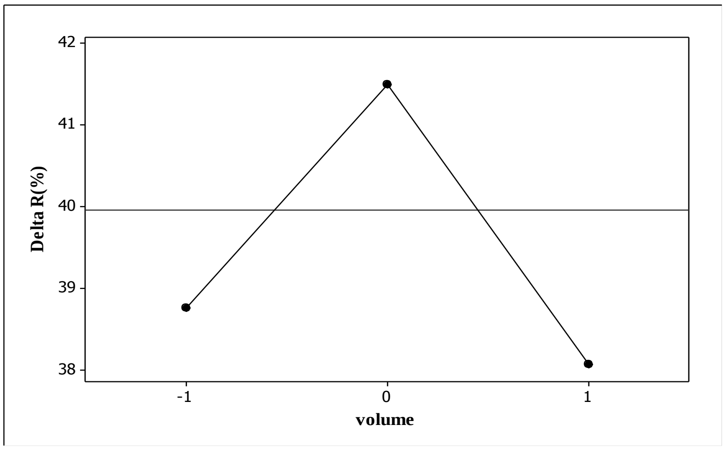

Figure 21. The effect of powder volume on surface roughness variation

From Figure 21 it can be inferred that with an increase in powder volume surface roughness variation increases however there is a halt to this change. With higher increases in powder volume, the magnetic flux density imposed on the powder is not able to move the abrasive slurry and consequently process does not work well which leads to a decrease in surface roughness variation.

4.4 Effect of type of abrasive particle

In producing abrasive powder using mechanical alloying with a ball milling machine in addition to ferrous which was presented in all compounds three different types of abrasive particles were used. These different particles possess almost the same magnetic properties and they are all non-ferromagnetic. It was also tried that the ingredient has a homogenous compound with a similar particle size (800 #). However, in particle morphology, mechanical properties like hardness, toughness, and Yong modulus are different. From SEM images it can be seen that particles made of sic and b4c have a semi-hexagonal-cone shape with sharp edges. Aluminium oxide is more in the form of a sphere-hexagon. Moreover, sic is very brittle which means that in the process it is not eroded, instead it is broken through crack tracks and changes into some smaller particles. In other words, it has a good self-sharpening property. It should be noted that getting smaller in broken particles and increases in the surface of the particles causes their escape from the powder volume due to high rotational speed and even if they stay in a powder slurry they can produce a very small cutting depth and practically they are incapable of decreasing surface reduction. Results reveal that particles based on their shape and particle's hardness produce different effects on the workpiece surface.

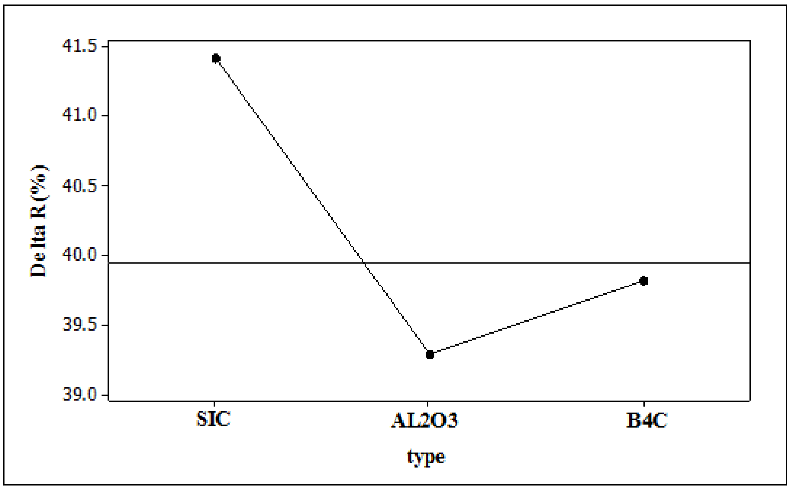

Figure 22. The effect of the type of abrasive particle on surface roughness variation

Figure 22 implies that SIC abrasive powder provides the highest reduction in surface roughness. B_4C may produce scratches on the surface due to its high hardness. It might be true to replace SIC with B_4C if a lower process time is chosen.

4.5 The interaction effect of the parameters

Figure 23 shows that the best result can be obtained in the moderate level of gap and powder volume. The dome shape of the diagram confirms the mentioned inference.

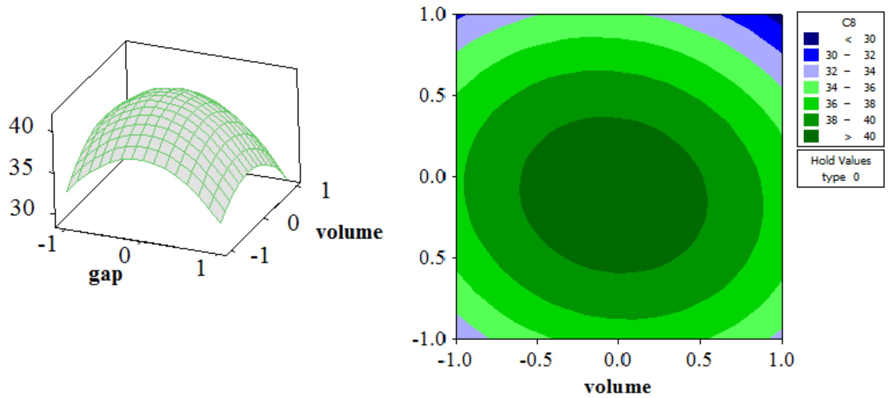

Figure 23. The effect of gap and powder volume interaction on surface roughness variation

As can be seen from Figure 24 it can be implied that when aluminum oxide abrasive particles are used, the gap should be set to the middle level to achieve feasible results. The saddle-like shape of the diagram defines the relation between the type of abrasive particle and the amount of finishing gap.

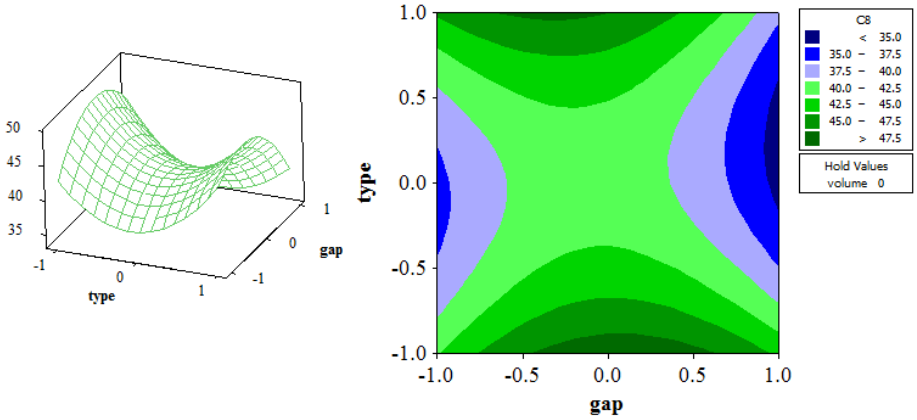

Figure 24. The effect of gap and powder type interaction on surface roughness variation

Findings also introduce a saddle-like relation between the powder volume and its type. This is described in Figure 25 in which when using aluminum oxide the maximum decrease in surface roughness is achieved when the middle level of powder is selected.

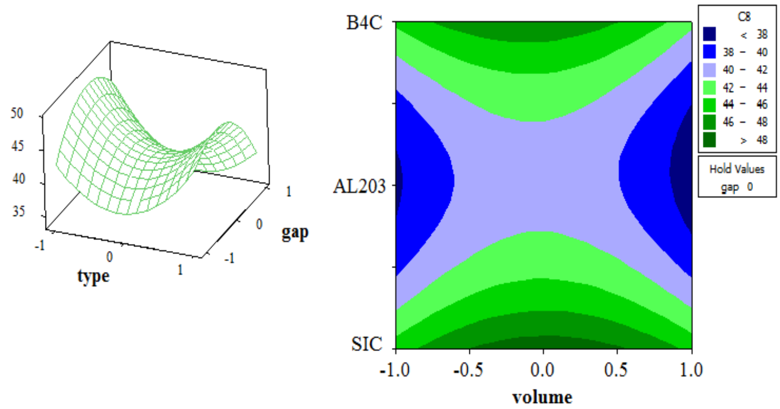

Figure 25. The effect of powder type and powder volume interaction on surface roughness variation

4.6 Qualitative analysis

Considering AFM and SEM images, illustrated in Figures 26 and 27, it can be seen that micro machining was taken place with a micro-cutting mechanism in titanium compressor blades. Trace of previous machining and grinding processes are observable before the final finishing process.

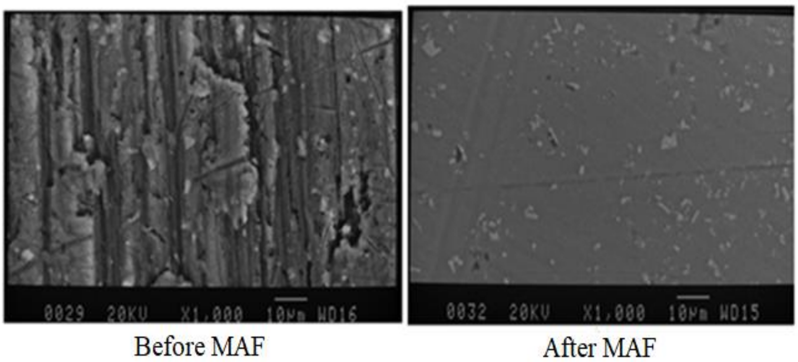

Figure 26. SEM images of the work piece surface before and after finishing the process

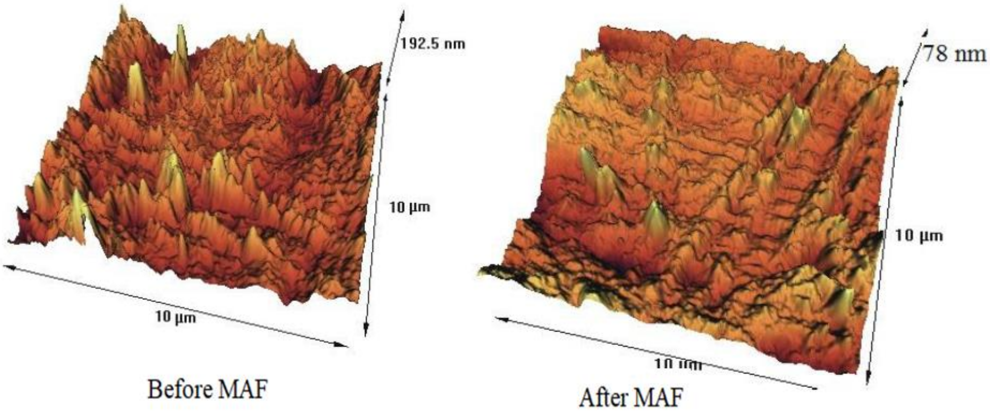

Figure 27. AFM images of the work piece surface before and after finishing the process

5. Conclusion

In studying the MAF process, first, the size and configuration of the magnets are specified using finite element analysis along with experimentation for evaluation of the numerical method. The discrepancy between simulation and experimental measurements of magnetic flux density was 11.3%.

To eliminate the problems of un-bonded particles which are segregation in rotation of the magnets, bonded particles are produced using the mechanical alloying machine. SEM images, EDX analysis, and performance of the powder in the process all reveal the efficiency of the introduced method and particles in the MAF process. Variance analysis on the experimental outputs shows that gap, powder volume, and abrasive type are influential on the variation of surface roughness. With regression analysis, an empirical mathematical model in the form of an equation with linear and second-order polynomials was derived to predict the variation in surface roughness. Applying moderate powder volume and gap with sic abrasive particles the highest reduction can be achieved (33%). AFM and SEM images before and after the MAF process confirm the efficiency of the process.

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