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Study of the Effect of Magnetic Abrasive Finishing on the Material Removal of AA1100 Aluminum Alloy

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Abstract

This study evaluates the performance of magnetic abrasive finishing (MAF) of aluminum alloy in terms of achieving materials removal (MR). A vertical milling machine is used to perform the finishing process using a developed MAF unit that consists of an inductor made out of a 150 mm long and 20 mm diameter iron core wound with 1500 turns and 0.5 mm copper wire. The commutator and magnetic pole are attached at the top and bottom of the inductor, respectively. The required current is supplied using a DC power supply. The South Pole workpiece is a 100×50×3 mm^3 plate of AA 1100 aluminum alloy, whereas the magnetic pole represented the North Pole. Pole rotational speed, applied current, and abrasive finishing time was selected as input parameters of the MAF with three-level of (270, 600. 930 rpm; 0.5, 1, 1.5 Amp; 6,9,12 min). The L9 orthogonal array of the Taguchi method was utilized to examine the impact of each independent input. The obtained results clarify that applied current was the most effective factor in terms of its contribution (63.16%) in the produced MR, followed by time finishing and rotational speed.

Keywords: *Magnetic abrasive finishing, aluminum alloys, material removal, ANOVA.*

1. Introduction

A remarkable need for machined components with high surface quality in high-tech industries has steadily increased for new finishing methods. However, it is hard to machine complex parts with defect-free and precise dimensional finishing by normal grinding and polishing operations. To reduce surface imperfections, appropriate machining conditions with minimum cutting forces are required [1].

Magnetic abrasive finishing (MAF) is one of the important super-finishing methods that is capable to generate fine surface finish for various shapes and geometries at the scale of nanometers without causing surface damage, particularly for miniature and complex parts [2]. External and internal cylindrical shapes, as well as flat surfaces, can be finished by the MAF process which opens the way for many high-tech parts with different sizes and geometries to acquire high surface finishing and dimensional accuracy [3,4,5].

Figure 1 shows the principal workflow of the MAF process in a simple form. The setup illustrates that the MAF consists of a rotatable magnetic pole that is positioned at a predetermined gap and attracts the magnetic-abrasive particles (MAPs), to form a flexible magnetic brush (FMAB) that plays as a multiple-cutting tool to finish the well-clamped workpiece (W.P). The workpiece-magnetic pole represents the S-N poles pair. The MAPs consist of Ferro-magnetic materials which are usually iron powder while the abrasive particle is often hard carbides, oxides, or nitrides. MAF in nature is a material removal process which means certain forces are responsible to cut material in the chips form. The FMAB applies two types of forces namely; a normal force for micro-indentation due to pressing the action and a tangential force for material removal by relative motion between W.P and FMAB [6].

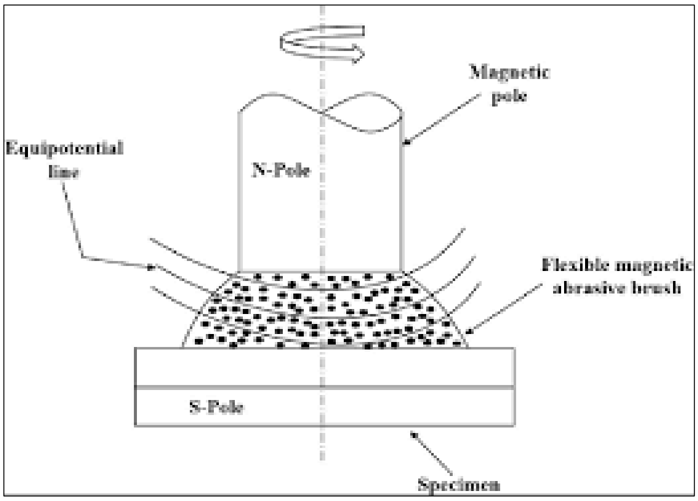

Fig .1. Principle of Magnetic Abrasive Finishing Process [6].

Because of its invention, great efforts have been made to improve the performance of MAF. For instance, Geeng-Wei Changet et al.[7] illustrates that the fundamentals of the MAF process as a finishing operation are investigated by using iron-SiC as magnetic abrasive particles with lubricant to produce unbounded MAPs.

Rotational speed, abrasive volume, and time are studied by Wang and Hu [8] as MAF-independent inputs during the finishing of tubes made of different metallic alloys. The examination illustrated that the removal of material and surface finish are significantly influenced by increasing the rotational speed. Shrikant Thote et al. [9] investigate the impact of iron powder amount, abrasive mesh size, and utilized current when the MAF finishing of stainless steel part. Both surface finish and material removal are improved by increasing the level of those controllable variables.

Joshi, R et al.[10] conduct a study to examine the response of three materials AISI 304 stainless steel, copper, and cast iron to the magnetic abrasive finishing process. The best findings are recorded by the cooper alloy through achieving better material removal and fine surface finishing where the latter was reduced from 0.257 µm to 0.075 µm. A 3% oil is added to the abrasive particles of SiC and Al_2O_3 mixture by Satsang, Prem S et al.[11] who study the additives' effects as well as the working gap and time on the material removal. Because, different mesh sizes are used: 100, 200, and 400. It was revealed that both mesh size and time have a strong effect on material removal. For example, maximum material removal is achieved by the SiC-100 compared with that obtained by Al2O3-400.

The performance of magnetic poles shown in Figure 2 was evaluated by Marwa Khalil et al et al. [12] based on the produced surface finish and material removal. Other parameters are also involved in the investigation like gap, current, time, speeds of the workpiece, and pole. The findings show that workpiece speed was the more influential by achieving 24% compared with other factors.

Fig. 2. Poles geometry [12].

A MAF process is combined with electrolysis (E) by M. R. Muhamad et al. [13] which results in the development of the EMAF process to finish the AA 6063 internal surface tube. In the beginning, the electrolysis produces a thin layer of Al_2O_3 to facilitate the removal of some surface morphology. Later on, this layer was eliminated by MAF to complete the finishing process. The findings proved the effectiveness of developed EMAF by reducing finishing time and cutting forces and recommended low exposure time for electrolysis to avoid the formation thick layer of Al_2O_3 that reduces the surface quality.

Another study was performed by Babar, A. et al. [14] to measure the influence of degrees of time, speed, mesh size, and amount of MAPs during the finishing of flat copper alloy. Based on ANOVA findings, a significant role is played by speed and time to produce minimum Ra and maximum material removal. The generated temperature during the MAF process of CuZn28 brass alloy was evaluated by Ali H. Kadhum [15]. The studied parameters are speed, current, and working gap. The distribution of produced temperature during material removal from the finishing region is measured based on experimental and numerical simulation with an overall difference of less than 9%.

Adhesive abrasive particles are adopted as MAPs by Singh, B et al. [16] during the inner surface finishing of an aluminum tube. The authors find a remarkable effect of rotational speed on the obtained material removal and surface roughness where they record a maximum improvement at optimum parameters of 2.74 mg/min and 81.49 %, respectively Kumar, V et al. [17] processed homogeneous mixture MAPs consisting of iron powder and diamond particles to evaluate its performance in terms of material removal during the finishing of the circular stainless steel section. It can be concluded that as the diamond amount increases, the material removal also increases.

The results of the MAF process using different pole geometries shown in Figure 3 are discussed by Mahmoud Abdallah et al. [18]. They found better MAF performance when using low-angle poles where the roughness and material removal are improved at high speed and medium time and gap.

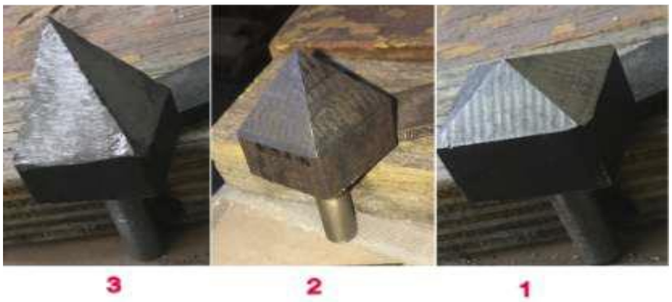

Fig. 3. Pyramid Pole with Different Angles [18].

Huijun Xie and Yanhua Zou [19] applied an alternating magnetic field instead to enhance the surface finish of 304 stainless steel alloy. They used alternating current with sine and square waveforms. The fluctuation behavior of the magnetic clusters in two alternating magnetic fields is noticed and investigated. The authors deduced from the analysis faster fluctuation in the magnetic cluster when utilizing square wave and small magnetic particles. There was a large variety in fluctuation rate in the magnetic cluster between the two waveforms. The surface roughness of the stainless steel plate improves from 328 nm Ra to 14 nm Ra in 40 minutes, according to the findings.

Yulong Zhang and Yanhua Zou [20] adopted an approach to illustrate the influence of correcting the work part surface. The adjusting the MAF parameters like feed speed on various locations based on the profile of the initial un-machined surface. A theoretical examination of this method was performed, as well as the application of this approach to the larger areas. The geometrical accuracy of the work part surface can be efficiently controlled by correctly adjusting the feed speed, according to a series of studies on an aluminum plate (A5052). The experimental findings indicated that within the processed area of 30 x10 mm, the large difference of the workpiece surface finish was lowered from 4.81 µm to 2.65 µm.

Material removal refers to the material amount that has to be removed during any machining process and can be measured based on volumetric material removal or weight difference before and post the cutting process. Material removal is between the two important indexes that are usually taken into account during the assessment of MAF performance in addition to the surface finishing. Therefore, the current study aims to evaluate the performance of MAF in terms of material removal when finishing AA1100 flat aluminum alloy.

2. Materials and Methods

To implement the magnetic abrasive finishing process, a milling machine was utilized to perform the finishing of AA1100 aluminum alloy. The MAF unit shown in Figure 4 incorporates a 150 mm length and 20 mm diameter iron core winded with 1500 turns of 0.5 mm copper wire to make the inductor. The top and bottom of the inductor are attached by the commutator and magnetic pole respectively. The power supply that was used provides a DC current. 100×50×3 mm3 plate of AA 1100 aluminum alloy was used as a South Pole workpiece while the North Pole is represented by the magnetic pole. The compositional analysis of Aluminum alloy being used is depicted in Table.

Fig. 4. MAF unit assembled on milling machine.

Table 1,
The Compositional analysis of AA 1100 alloy.

Element	Zn	Mn	Cu	Be	Si, Fe	Al
Standard	0.1(maximum)	0.05 (maximum)	0.05-0.2	0.0008 (maximum)	0.95 (maximum)	Balance
Real	0.0339	0.0146	0.0596	<0.001	0.361	Balance

Powder of iron-tungsten carbide mixture was used as magnetic abrasive particles (MAPs). The amount of WC in grams is twice the iron powder respective mesh size of 320 and 200. Figure 5a shows the assembled magnetic pole while a flexible magnetic brush (FMAB) is depicted in Figure 5b.

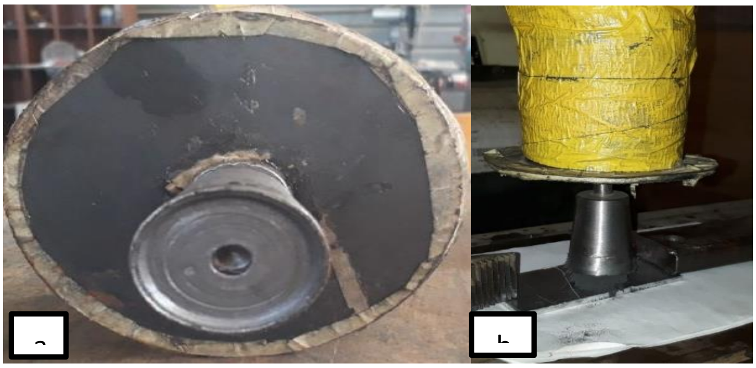

Fig. 5. Magnetic iron poles, a. Pole before applying a magnetic field, and b. Pole with the created magnetic brush.

Regarding the MAF parameters, rotational speed, DC-current, and MAF time are chosen as variable parameters with three levels while other parameters are kept unchanged as illustrated by Tables 1 and 2, respectively.

Table 2,
Selected MAF Parameters and corresponding levels

No.	MAF Parameters	Unit	Parameter Symbol	Level 1	Level 2	Level 3
1	Rotational Speed	R.P.M	A	270 rpm	600 rpm	930 rpm
2	DC Current	Ampere	B	0.5 Amp.	1Amp.	1.5 Amp.
3	Finishing time	Minute	C	6 min	9 min	12 min

Table 3,
Fixed parameters

NO	Parameters	Value
1	Material of Work Piece	Al
	Dimensions of WorkPiece	50 x 100 x 3 mm
2	Ambient Temperature	20 C°
3	Direction of rotation	CCW
4	Abrasive Particles	Fe-WC mixed powder
5	Fe mesh size #	320
6	WC Mesh size #	200
7	Applied Voltage	220 V
8	Gap	1 mm
10	Frequency	50 Hz

Taguchi method for the design of experiment is applied with the L9 orthogonal array using Minitab 17. Table 4 shows the L9 array with coded and actual factors. It consists of nine experimental runs with three variable parameters at different three levels each. The low, medium and high levels of rotational speed, current, and time are 270, 600, and 900 rpm; 0.5, 1, 1.5 Amp; 6, 9, and 12 minutes respectively. The output response that was measured and evaluated in this study is material removal in mg. Figure 6 shows the sensitive balance that is used to measure the weight of the specimen before and after MAF to calculate the net difference in weight for each run referring to the material removal (ΔMR) of that specimen. At the same time, the material removal improvement rate (MRIR) is calculated by using equation 1:

$$MRIR = \frac{\text{Initial MR}-\text{Final MR}}{\text{Initial MR}} * 100\% \qquad \ldots (1)$$

Table 4,
Coded and real MAF parameter of L9 array

Run No.	Rotational speed (rpm)	DC-current (Amp.)	Finishing time (min.)	Rotational speed (rpm)	DC-current (Amp.)	Finishing time (min.)
1	1	1	1	270	0.5	6
2	1	2	2	270	1	9
3	1	3	3	270	1.5	12
4	2	1	2	600	0.5	9
5	2	2	3	600	1	12
6	2	3	1	600	1.5	6
7	3	1	3	930	0.5	12
8	3	2	1	930	1	6
9	3	3	2	930	1.5	9

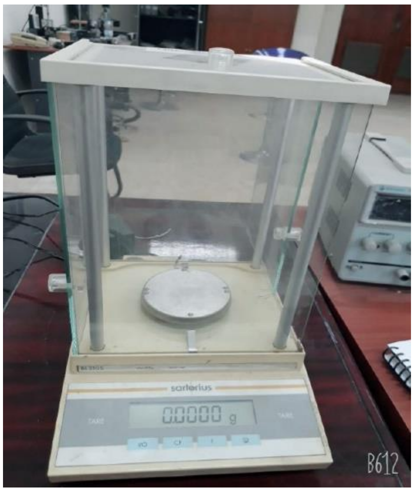

Fig. 6. Sensitive balance device (Model type: Sartorius - readability: 0.1 mg).

3. Results and Discussions

The material removal is measured and material removal rates are calculated and both values are tabulated as in table 5. The maximum and minimum values are also involved within the same table.

Table 5,
Average Improvement of Material Removal (ΔMR).

Run No.	Rotational speed (rpm)	DC current (Amp.)	Finishing time (min.)	ΔMR(g)	MRIR
1	270	0.5	6	0.0018	0.004
2	270	1	9	0.0013	0.003
3	270	1.5	12	0.0067	0.016
4	600	0.5	9	0.0029	0.007
5	600	1	12	0.0047	0.011
6	600	1.5	6	0.0072	0.017
7	930	0.5	12	0.0035	0.009
8	930	1	6	0.0057	0.014
9	930	1.5	9	0.0062	0.015
Max				0.0072	0.017
Min				0.0013	0.003

3.1. Statistical Analysis of the Results

The first step of the discussion is to analyze the achieved results statistically with the aid of ANOVA as depicted in Table 6. The ANOVA results clarify the significance of the model with a 0.05 value. Also, applied DC-current achieves a low p-value of 0.016 which refers to its significance over the other two parameters. The speed and time are not significant. The current also records the highest contribution percentage of 63.16 % followed by time and speed.

Table 6,
Analysis of Variance of Material Removal (MR).

Source	Degree of freedom	Adjusted SS	Adjusted MS	FValue	PValue	Significant parameter	Percentage of Contribution%
Regression	3	0.000028	0.000009	5.16	0.05	Significant	
A Rotational Speed	1	0.000005	0.000005	2.61	0.167	N0t significant	13.16%
B DC Current	1	0.000024	0.000024	12.87	0.016	Significant	63.16%
C Finishing Time	1	0.000007	0.000003	0.66	0.551	N0t significant	18.42
Error	5	0.0000012	0.000002	_	_	_	5.62%

Total	8	0.000038	_	_	_	_	100%

3.2 Regression Model for the MAF Process

A linear regression model is constructed to correlate the material removal with rotation speed, current, and time. Equation 2 shows the developed model that was used to predict the material removal where each parameter has its coefficient in addition to the model constant. If each set of finishing conditions shown in Table 5 is substituted the A, B, and C factors of the regression model, Table 7 will be constructed, which shows the predicted material removal besides the experimental values.

$$\Delta MR = -0.00119 + 0.000003\ A + 0.00397\ B + 0.000011\ C \quad \ldots(2)$$

Table 7,
Predicted and Experimental ΔMR with average % error.

Run No.	Rotational speed (rpm)	DC-current (Amp.)	Finishing time (min.)	ΔMR(g)	Predicted ΔMR
1	270	0.5	6	0.0018	0.001671
2	270	1	9	0.0013	0.003689
3	270	1.5	12	0.0067	0.005707
4	600	0.5	9	0.0029	0.002694
5	600	1	12	0.0047	0.004712
6	600	1.5	6	0.0072	0.006631
7	930	0.5	12	0.0035	0.003717
8	930	1	6	0.0057	0.005636
9	930	1.5	9	0.0062	0.007654

If both experimental and predicted material removal is plotted against experimental runs, Figure 7 is produced. As can be seen from Figure 7, some points are near each other while other points sit at a distance from each other. This can be ascribed to the fact that the linear model can effectively represent linear problems but, material removal processes are non-linear problems in most. Therefore, the model shows some difference between actual and predicted values.

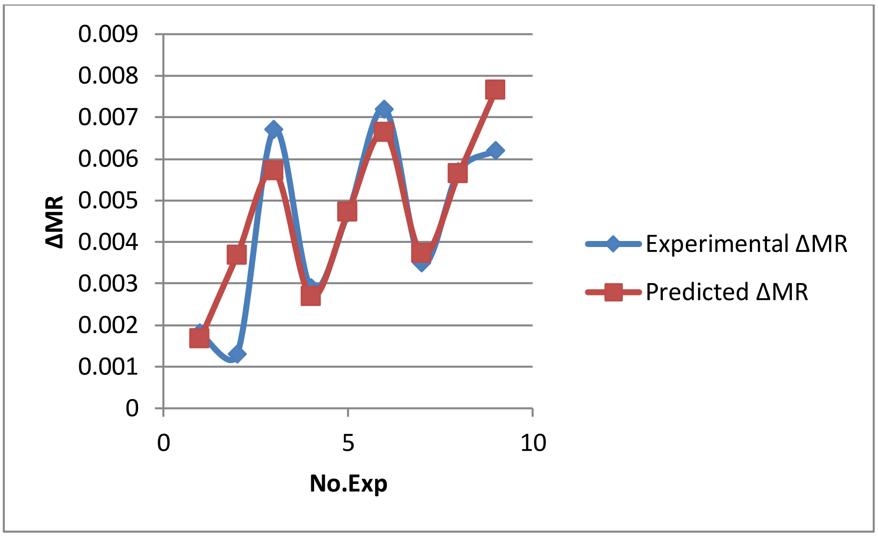

Fig. 7. Experimental and predicted ΔMR.

3.3. Effect of magnetic abrasion parameters on the performance of MAF.

The second step of the discussion is to analyze the magnetic abrasive parameters of the achieved material removal. To perform this analysis and discussion, the main plot effect of means depicted in Figure 8 is introduced here to support our discussion. A statistical analysis that is presented has given a good view of the degree of influence of each parameter on the achieved material removal. The main effect plot of means shows the relationship between the mean of means for material removal (ΔMR) versus the three levels of rotational speed, current, and time. Thus, it is a beneficial graph that enables us to show how material removal is affected by MAF parameters.

The plot reveals that material removal is hugely influenced by the increasing current from low to high levels including medium ones. The average values of ΔMR against current according to what the main plot shows, is ranging approximately from 0.00275 to 0.00675. The corresponding range of ΔMR versus time is lower and that for rotational speed is the lowest. This effect is consistent with what ANOVA has gone with, in terms of impact extent and percentage of contribution where current achieves the highest values followed by rotational speed and time.

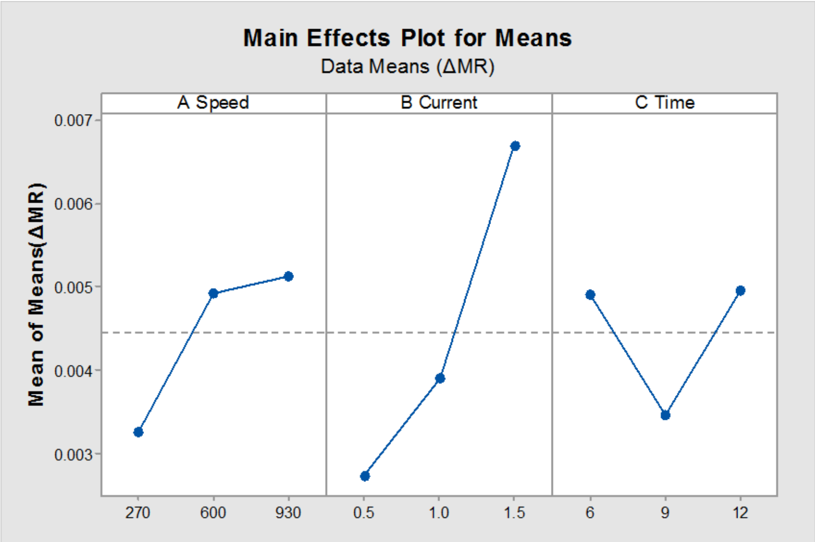

Fig. 8. Plots of Parameters Main Effect Verses Mean ΔMR.

To explain why current was the most effective factor, the fact has been recalled here concerned with the intensity of generated magnetic field where this field is directly correlating to the applied current. In other words, as the current increases, the magnetic flux intensity increases also and this increment is reflected positively in the amount of rigidity for the generated flexible magnetic brush (FMAB) due to that applied current. The more rigid FMAB creates many relatively deep penetrated micro-indentations inside the surface. This action refers to the applied normal forces which are integrated with the tangential force, exerted by the relative motion between rotatable FMAB and the specimen being finished to perform the whole material removal process.

To sum up, a rigid and strong multiple cutting tool (FMAB) has been generated at a high current level (1.5 Amp.) that introduces numerous micro-indentations and introduced to the surface being finished by the action of induced normal forces applied by FMAB to promote more materials removal with the assistant of tangential forces comes from the rotatable magnetic pole to perform MAF process completely.

4. Conclusions

The obtained findings based on the analysis and discussion have enabled us to conclude the following points:

1. The AA 1100 aluminum alloy has been successfully finished by the magnetic abrasive finishing process.
2. The applied current has been the most significant factor and contributor with 63.16% followed by time and speed with percentage contributions of 18.42% and 13.16%, respectively.
3. Maximum material removal has been recorded at low speed (270 rpm), high current (1.5 Amp.), and high finishing time (12 min.).

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دراسة تأثير الانهاء السطحي بالجسيمات الكاشطة المغناطيسية على إزالة المعدن لسبيكة الألومنيوم AA1100

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الخلاصة

تهدف هذه الدراسة الى تقييم أداء الصقل بالجسيمات المغناطيسية الكاشطة لسبيكة الألومنيوم AA1100 من حيث إزالة المعدن (MR). تم استخدام ماكنة تفريز عمودية لإجراء عملية التشطيب باستخدام وحدة MAF مطورة تتكون من مستحث مصنوع من الحديد بطول 150 مم وقطر 20 مم وملفوف ب 1500 لفة من سلك نحاسي بقطر 0.5 مم. تم توصيل المبدل والقطب المغناطيسي في أعلى وأسفل المستحث، على التوالي. تم تجهيز التيار المطلوب باستخدام مصدر طاقة تيار مستمر. مثلت قطعة عمل القطب الجنوبي واليت كانت عبارة عن صفيحة المنيوم ابعادها 100 × 50 × 3 مم 3، بينما مثل القطب المغناطيسي القطب الشمالي. تم اختيار سرعة الدوران والتيار المستمر ووقت الانتهاء كمتغيرات إدخالMAF لعملية الانهاء بالجسيمات المغناطيسية الكاشطه بثلاث مستويات لكل منها (270، 600. 930 دورة في الدقيقة؛ 0.5، 1، 1.5 أمبير؛ 6.9,12 دقيقة). تم استخدام طريقة Taguchi مع المصفوفة المتعامدة L9 لدراسة تأثير كل المدخلات المستقلة. أوضحت النتائج المتحصل عليها أن التيار المطبق كان العامل الأكثر فاعلية من حيث مساهمته بـ (63.16٪) في أزاله المعدن المنتج، تلاه الوقت وسرعة الدوران.