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Statistical Analysis of Metal Removal during Magnetic Abrasive Finishing Process

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ABSTRACT

This work aims to provide a statistical analysis of metal removal during the Magnetic Abrasive Finishing process (MAF) and find out the mathematical model which describes the relationship between the process parameters and metal removal, also estimate the impact of the parameters on metal removal. In this study, the single point incremental forming was used to form the truncated cone made of low carbon steel (1008-AISI) based on the Z-level tool path. Then the finishing was accomplished using a magnetic abrasive process based on the Box-Behnken design of the experiment using Minitab 17 software was used to finish the surface of the formed truncated cone. The influences of different parameters (feed rate, machining step size, coil current, and spindle speed) on metal removal were (32.948, 21.896, 10.587, and 13.907) %, respectively.

Keywords: Single Point Incremental Sheet Forming, Magnetic Abrasive Finishing, Surface roughness, Box-Behnken design, feed rate.

تحليل احصائي لأزالة المعدن خلال عملية الأنهاء بالحبيبات المغناطيسية

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الخلاصة

الهدف من هذا العمل هو اجراء تحليل احصائي لأزالة المعدن خلال عملية الأنهاء بالحبيبات المغناطيسية و ايجاد نموذج رياضي لوصف العلاقات بين متغيرات التشغيل, وكذلك احتساب تأثير هذه المتغيرات على ازالة المعدن. في هذه الدراسة, تم استخدام عملية التشكيل النقطي التزايدي للصفائح لانتاج شكل مخروط مقطوع الراس من سبيكة الفولاذ منخفض الكاربون (1008-AISI) باستخدام مسار العدة Z-level . ثم عملية الانهاء باستخدام عملية الأنهاء بالحبيبات المغناطيسية بالاعتماد على Box-Behnken

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لتصميم التجارب باستخدام برنامج مني تاب 17 لأنهاء سطح المخروط مقطوع الراس . تأثير المتغيرات المختلفة (التغذية, خطوة التشغيل, تيار الملف, و السرعة الدورانية) على ازالة المعدن كانت (32.984، 21.896، 10.587، 13.907)% بالتتابع.

الكلمات الرئيسية: التشكيل النقطي التزايدي للصفائح, الأنهاء بالحبيبات المغناطيسية, الخشونة السطحية, Box-Behnken, التغذية.

1. INTRODUCTION

Magnetic abrasive finishing (MAF) is a surface finishing technique in which a magnetic field is used to force abrasive particles against the target surface **(S.C. Jayswal et al., 2005)**. Magnetic-abrasive finishing of surfaces is achieved by working media with both magnetic and abrasive properties. The magnetic field is acting as a binder of the grains **(Deaconescu, T, 2008; Tudor, and Andrea, 2013).** In MAF, two kinds of forces created by Flexible Magnetic Abrasive Brush (FMAB) are in charge of finishing: (i) normal magnetic force in charge of packing the magnetic abrasive particles and providing micro indentations into the workpiece, and (ii) tangential cutting force in charge of microchipping due to rotation of the FMAB. The FAMB sweep abrasive particles downward opposed to the surface of the workpiece **(Dhirendra K. Singh, 2016)**. In the MAF process, the magnetic field primarily leadership the cutting force and the magnetic abrasive powder, which form a flexible brush. In contrast, the other traditional finishing processes utilize a rigid tool that exposes the workpiece to generous normal stresses, which causes micro-cracks follow-on reduced reliability and strength of the finished part **(S.C. Jayswal et al., 2005; Parmar C. Babulal, 2018)**.

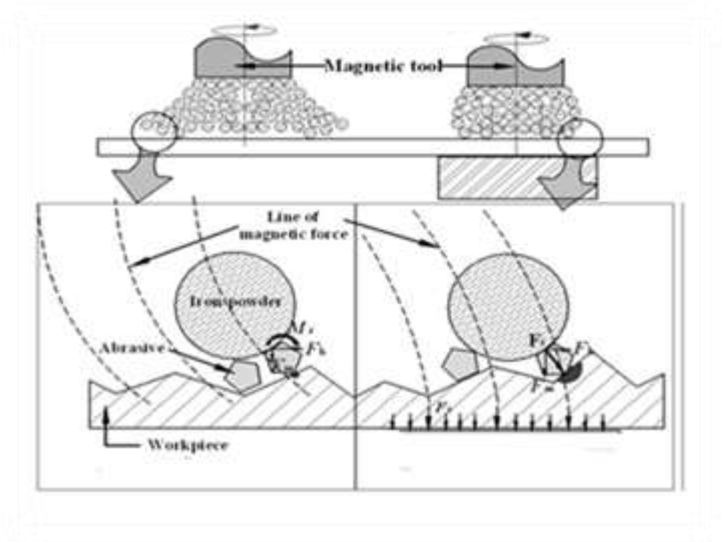


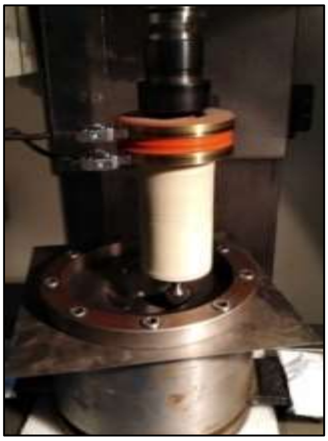
Figure 1. Schematic of mechanism on MAF **(Jae-Seob Kwak, and Chang-Min Shin 2011).**

(M. Sharma and D. Pal Singh, 2013) have investigated surface finishing of SS 305, SS 316, and brass cylindrical workpiece at a different gap, density of magnetic flux, hardness, and speed. The magnetic abrasive powder of Al_2O_3 abrasive and iron particles was utilized. The obtained results show that the initial value of surface roughness was enhanced from 0.257µm to 0.075µm through 3 minutes of machining. **(P. Saraeian et al., 2016)** examined the parameters, including the rotational speed of the workpiece, the working gap, and the size of the abrasive particle on steel AISI 321. The results demonstrated that the abrasive particle size and rotational speed influence the surface roughness (Ra) from the most to the least, respectively. The minimum Ra is obtained through the abrasive particle size of 100µm mesh. **(G. Chandra Verma et al., 2017)** have introduced a novel tool based on magnetic abrasive finishing principle for polishing holes, blind

holes, grooves, and vertical surfaces to finish stainless steel (SS304) pipe. Two permanent magnets with their similar pole were facing each other. The effects of rotational speed, magnetic flux density, abrasive size, and abrasive weight percentage on the percentage change in surface roughness were studied. The analysis showed that the magnetic flux density was the most effective parameter followed by rotational speed. **(Omar C. Kadhum, 2018**) designed and implemented automated machine that can predict the values of working time that obtain the desired values of surface roughness (Ra) and materials removal (MR), through controlling the cutting parameters (voltage of electromagnetic, magnetic pole velocity, working gap and working time) that improves the MAF method. The results indicated that the predicted values for Ra and MR are nearly equal to the values from the automated machine about 95% for Ra, and 97% for MR, that means the automated machine for the MAF process, which were designed and implemented in this study, are very efficient. **(Rui Wang et al., 2018)** evaluated the influence of temperature through the MAF process of Mg alloy bars where the study was carried out on a cryogenic temperature, room temperature, and high temperature. From the results obtained, the excellent performance of the surface roughness occured at room and cryogenic temperatures. But in terms of metal removal rate and diameter change, the high temperature was superior influences. The best values of room temperature (24 °C) and cryogenic temperature (-120 °C) that give the best improvements in surface roughness were 84.21 % and 55 %, respectively. **(Saad K. Shather and Muhamed A.Abd, 2019)** focused on the influence of silicon carbide (SiC) into surface roughness and metal removal rate; the studied parameters were (gap, mesh, and concentration of abrasive). The best surface roughness was obtained when machining workpiece of low carbon steel by silicon carbide (SiC) was 0.007μm at concentration of 33% Si and 67% Fe with gap 2mm, mesh size 200 and maximum metal removal rate was 0.004gm at concentration 25% Si and 75% Fe with gap 1.5mm, mesh size 100.
From the above literature survey, it concluded that few studies have focused on the mathematical modeling of Metal Removal (MR).

2. EXPERIMENTAL SETUP and PROCEDURE

Incremental Sheet Metal Forming (ISMF) is performed on the CNC milling machine. Firstly, the hemispherical head of the cylindrical tool manufactured from tool steel with a diameter (12 mm) is utilized to form the truncated cone shown in **Fig. 2-A**. Then the MAF tool as a second finishing process has been used to finish the required shape. The MAF tool is an electromagnetic spherical tool with a diameter of (20 mm) that illustrated in **Fig. 2-B.** It consists of an iron core covered with copper wire with 4500 turns to produce a high electromagnetic field. The samples of low carbon steel (1008-AISI) sheets were used to perform the 27 experiments. The chemical composition of the workpiece is illustrated in **Table 1**. The magnetic abrasive powder consists of tungsten carbide plus iron powder with mixing ratio 50% with 350°C sintering temperature, then ball milling, and sieving machines were used to get 300 mesh size of the powder. The dimension of the truncated cone is illustrated in **Fig.3**. The magnetic abrasive powder amount was 5 grams, with a 1.5 mm machining gap.



A **B**

Figure 2. A: Single point incremental forming tool and B: MAF tool.

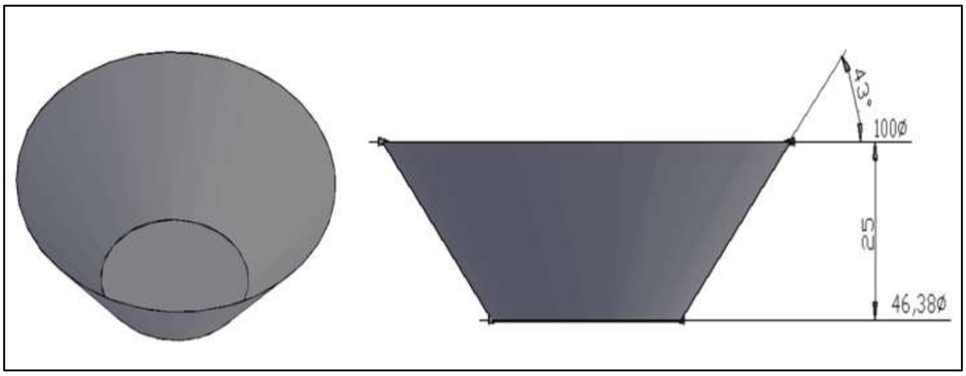


Figure 3. The dimension of the performed truncated cone.

Table 1. Chemical composition of the workpiece (low carbon steel (1008-AISI).

C %	Si %	Mn %	S %	P %	Cr %	Ni %	Mo %	V %	Cu %	Al %	Fe %
0.08	0.02	0.32	0.024	0.014	0.035	0.032	0.002	0.001	0.072	0.044	Bal.

The Box-Behnken design was used in this work because it permits: (i) detection of lack of fit of the model; (ii) estimation of the parameters of the quadratic model **(Najwa S. Majeed and Duaa M. Naji 2018);** and (iii) building of sequential designs. The methodology of Box-Behnken for four factors at three levels is used for applied experiments. The levels and process parameters are illustrated in **Table 2. Table 3** illustrated the parameters setup and the test results. A balance device was used to measure the differences in the weight of the workpieces before and after the MAF process. Metal removal (MR) measured as follow:

$$MR = W\,(\text{before MAF}) - W\,(\text{after MAF}) \quad (1)$$

Table 2. Parameters and their levels.

Parameters	Unit	Level 1	Level 2	Level 3
Rotational Speed (S)	Rev/min	420	580	740
Feed Rate (F)	mm/min	30	40	50
Machining step size (ΔZ)	mm	3	3.5	4
Coil current (I)	ampere	1.7	2.2	2.7

Table 3. Box-Behnken design layout and corresponding results.

Exp. No.	Spindle speed (S) rev/min	Feed rate (F) mm/min	Machining step size (ΔZ) mm	Coil current (I) ampere	Metal removal (MR) g
1	580	30	3.0	2.2	0.052
2	580	50	3.0	2.2	0.029
3	580	30	4.0	2.2	0.035
4	580	50	4.0	2.2	0.007
5	420	40	3.5	1.7	0.025
6	420	40	3.5	2.7	0.015
7	740	40	3.5	1.7	0.020
8	740	40	3.5	2.7	0.050
9	420	30	3.5	2.2	0.030
10	420	50	3.5	2.2	0.005
11	740	30	3.5	2.2	0.050
12	740	50	3.5	2.2	0.022
13	580	40	3.0	1.7	0.030
14	580	40	4.0	1.7	0.013
15	580	40	3.0	2.7	0.048
16	580	40	4.0	2.7	0.025
17	580	30	3.5	1.7	0.035

18	580	50	3.5	1.7	0.015
19	580	30	3.5	2.7	0.061
20	580	50	3.5	2.7	0.028
21	420	40	3.0	2.2	0.030
22	420	40	4.0	2.2	0.004
23	740	40	3.0	2.2	0.046
24	740	40	4.0	2.2	0.023
25	580	40	3.5	2.2	0.043
26	580	40	3.5	2.2	0.044
27	580	40	3.5	2.2	0.043

3. RESULTS AND DISCUSSION

Twenty-seven experiments have been performed to investigate the influence of input parameters on the process response, namely the MR. The machining characteristics values of MR, the obtained and predicted data are given in Table 4. Regression analysis was used to determine the relationship between input variable parameters and the process response. The mathematical model was developed by Response Surface Methodology (RSM). The obtained RSM model of MR is given in Eq. (2). The percentage of error represents the difference between predicted and observed value divided by the observed value for all responses. As a result, the prediction accuracy of the developed model has appeared acceptable, as illustrated in **Table 4.**
The obtained RSM model of MR is:

$$MR = -0.570 + 0.00497\,F + 0.2204\,\Delta Z + 0.0795\,I + 0.000251\,S - 0.000046\,F^2 - 0.03200\,\Delta Z^2\ 0.02050\,I^2 - 0.000250\,F\times\Delta Z - 0.000650\,F\times I - 0.00600\,\Delta Z\times I + 0.000009\,\Delta Z\times S + 0.000125\,I\times S \quad (2)$$

The equation used in the determination of predication error is:

$$\text{Prediction error } \% = \frac{|\text{Actual value} - \text{predicted value}|}{\text{Actual value}} \times 100\% \quad (3)$$

Table 4. MAF machining characteristics values .

No.	(F) mm/min	(ΔZ) mm	(I) ampere	(S) rpm	Actual MR (g)	Predicted MR (g)	Error %
1	30	3.0	2.2	580	0.052	0.0532	2.3076
2	50	3.0	2.2	580	0.029	0.0295	1.7241
3	30	4.0	2.2	580	0.035	0.0343	2.0000
4	50	4.0	2.2	580	0.007	0.0057	18.5714
5	40	3.5	1.7	420	0.025	0.0215	14.0000
6	40	3.5	2.7	420	0.015	0.0163	8.6666
7	40	3.5	1.7	740	0.020	0.0185	7.5000
8	40	3.5	2.7	740	0.050	0.0533	6.6000
9	30	3.5	2.2	420	0.030	0.0317	5.6666
10	50	3.5	2.2	420	0.005	0.0071	42.0000
11	30	3.5	2.2	740	0.050	0.0502	0.4000
12	50	3.5	2.2	740	0.022	0.0226	2.7272
13	40	3.0	1.7	580	0.030	0.0319	6.3333
14	40	4.0	1.7	580	0.013	0.0136	4.6153
15	40	3.0	2.7	580	0.048	0.0497	3.5416
16	40	4.0	2.7	580	0.025	0.0254	1.6000
17	30	3.5	1.7	580	0.035	0.036 0	2.8571
18	50	3.5	1.7	580	0.015	0.0163	8.6666
19	30	3.5	2.7	580	0.061	0.0573	6.0655
20	50	3.5	2.7	580	0.028	0.0246	12.1428
21	40	3.0	2.2	420	0.030	0.0275	8.3333
22	40	4.0	2.2	420	0.004	0.0046	15.0000
23	40	3.0	2.2	740	0.046	0.0430	6.5217
24	40	4.0	2.2	740	0.023	0.0231	0.4347

25	40	3.5	2.2	580	0.043	0.0433	0.6976
26	40	3.5	2.2	580	0.044	0.0433	1.5909
27	40	3.5	2.2	580	0.043	0.0433	0.6976
Average error %							7.0837

Analysis of variance (ANOVA) technique has been utilized to determine dominating parameters and to check the effectiveness of the model for the response of the machining process. The analysis of variance ANOVA for MR is presented in **Table 5**.

Table 5. ANOVA for MR.

sources of variation	DF	SS	MS	F-Value	P-Value
Model	14	0.006143	0.000439	58.02	0.000
F	1	0.002054	0.002054	271.61	0.000
ΔZ	1	0.001365	0.001365	180.54	0.000
I	1	0.000660	0.000660	87.28	0.000
S	1	0.000867	0.000867	114.64	0.000
F×F	1	0.000114	0.000114	15.09	0.002
ΔZ×ΔZ	1	0.000341	0.000341	45.13	0.000
I×I	1	0.000140	0.000140	18.52	0.001
S×S	1	0.000616	0.000616	81.50	0.000
F×ΔZ	1	0.000006	0.000006	0.83	0.381
F×I	1	0.000042	0.000042	5.59	0.036
F×S	1	0.000002	0.000002	0.30	0.595
ΔZ×I	1	0.000009	0.000009	1.19	0.297
ΔZ×S	1	0.000002	0.000002	0.30	0.595
I×S	1	0.000400	0.000400	52.89	0.000
Residual Error	12	0.000091	0.000008		
Total	26	0.006234			

where:
DF= Degrees of freedom
SS= Sum-of-squares
MS= Mean squares
F-Value= ratio is computed by dividing the MS value by another MS value.

P-value = probability value. Each value in the above table more than 0.05 is considered non-significant to the process response due to the level of confidence is 95% **(Kamil J. Kadhim, 2019)**.

The main effect plot is illustrated in **Fig.4**. From this plot, it is clear to see that higher feed rate means lower metal removal, where extra magnetic abrasive passes through the machining gap with lower values of the feed rate of the pole, which causes an improvement in the metal removal. On the other hand, increasing the feed rate causes the abrasive particle to pass quickly, and little metal is removed from the machining zone. From the main effect plot illustrated in **Fig.4**, it is clear that increasing the machining step size has a similar effect of increasing feed rate. Lower values of ΔZ allowed the more the magnetic abrasives will pass through the working zone at the same time, thus, improving the metal removal. The material removal rate increases with the increase of magnetic flux density. The material removal is significantly affected by the current. When the rotational speed of the magnetic pole increases the MR also increases. The smoothly rotated abrasive causes material removal to increase when the pole revolution increases. The irregular jumbling of the abrasive occurs at higher rotational speed, where the centrifugal force acting on each abrasive is higher with faster pole revolutions, which produces higher frictional force. A higher magnetic force is needed to the exposure of the friction force to sustain fine rotation of the magnetic abrasive when the revolution rate of pole increases the degree of abrasive jumbling increases, which causes material over-removal by the aggressive strikes of the jumbling abrasive. The percentage contribution of parameters to MR is shown in **Fig.5**. The interaction effects between (S and I, S and F, I and ΔZ, S and ΔZ, I and F, and ΔZ and F) are illustrated in **Fig.6**. As it is shown in **Fig. 6 A,** the maximum MR was obtained when higher levels of both S and I. From **Fig.6 B,** the MR was in lower values when the S is at minimum levels, and F is at a higher level. The higher values of ΔZ and lower I, means low MR, as it is illustrated in **Fig.6 C**. High S and low values of ΔZ produces higher MR as it is shown in **Fig.6 D**, the MR has higher values when I is high, and F is low. Also, when ΔZ is low, and F is low, as it is illustrated in **Fig.6 E and Fig.6 F,** respectively.

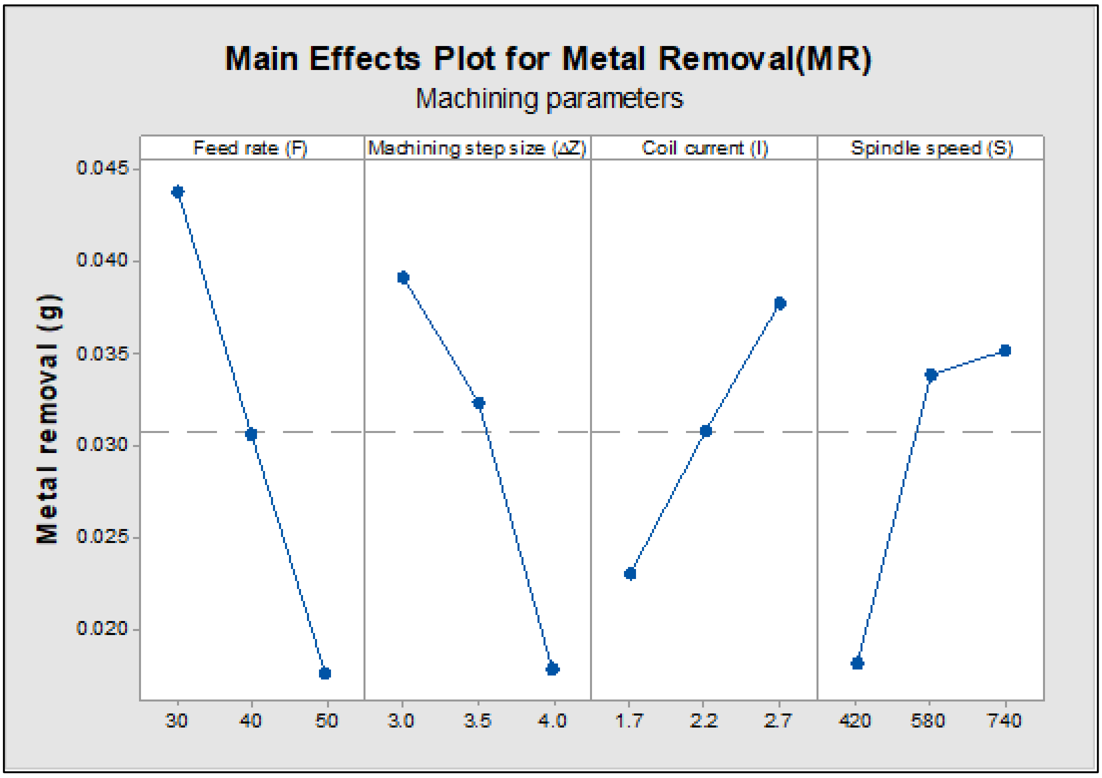


Figure 4. Main effect plot for Metal Removal (MR).

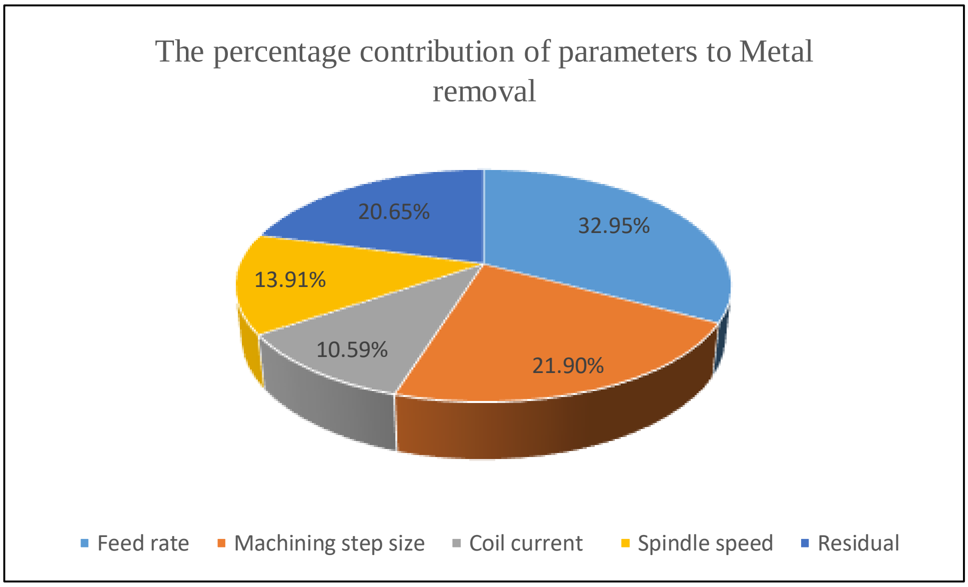


Figure 5. The percentage contribution of parameters to Metal Removal.

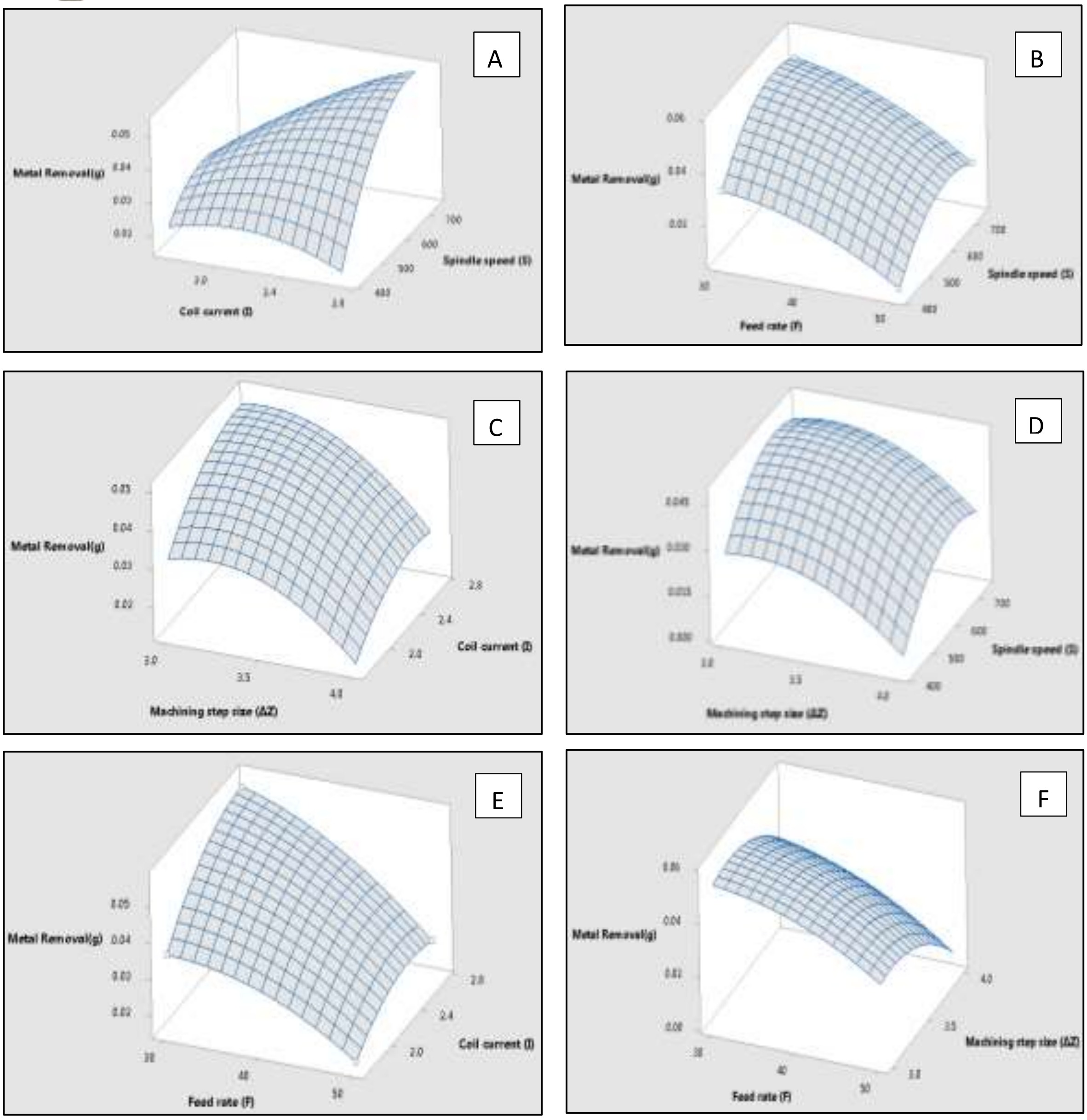


Figure 6. Combination effects of (F, ΔZ, I, and S) on MR.

4. CONCLUSIONS

The following conclusions are drawn:

- The high accuracy of the prediction model within the experimental data was with an average error (7.0837%).
- The input parameters have significantly influenced the MR response.
- The most significant parameter was the feed rate, and the miner significant parameter was the coil current.
- From statistical analysis, it can be concluded that the contribution percent of machining parameters (F, ΔZ, I, and S) were (32.948, 21.896, 10.587, and 13.907) %, respectively.

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