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Investigation on Torque and Thrust Forces in Radial Drilling of Copper Alloys

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Abstract

As a part of research over improvement of machining process; cutting forces, metal removal rate (MRR) and surface finish on mechanical elements has become quite significant in the operational and aesthetical point of view. To enhance accuracy and precision by adopting energy saving techniques, manufacturing firms are adopting automated systems in order to achieve manufacturing excellence. In the present work, the effect of various process parameters like spindle speed, feed, and drill diameter on torque, thrust force, MRR and surface finish in radial drilling process for copper alloys (copper, brass and bronze) are investigated by using Box Behnken Design. Three factors/three levels were used and total 15 experiments were performed. The coefficients were calculated by using regression analysis and the model was constructed. The adequacy of the developed model was checked using analysis of variance (ANOVA) technique. By using the mathematical model, the main and interaction effect of various process parameters on torque, thrust force, MRR and surface finish are studied.

Keywords: Drilling, copper alloys, DOE, torque, thrust

I. INTRODUCTION

Drilling is one of the important machining processes, which is commonly used in all types of industries. However, the quality of the drilled hole depends upon the raw material and the drilling conditions used. Drilling speed, feed, drill helix angle and cutting fluid plays an important role in maintaining the quality of the drilled hole.

II. LITERATURE REVIEW

Becker *et al*. conducted experiments on Ti- 6Al-4V at 183 m/min cutting speed and 156 mm^3/s material removal rate (MRR) using a 4 mm diameter WC-Co spiral point drill [1].

The effect on drill life, thrust force, torque, energy, and burr formation were evaluated. They investigated tool wear mechanism, hole surface roughness, and chip light emission and morphology for high- throughput drilling.

Singh *et al*. developed an electric discharge drill machine (EDDM) to produce micro holes in conductive materials [2]. A brass rod of 2 mm diameter was selected as a tool electrode. The best parameters such as pulse on-time, pulse off-time and water pressure were studied for best machining characteristics. This investigation presents the use of Taguchi approach for better MRR in drilling of Al-7075.

Haq *et al*. developed an approach for the optimization of drilling parameters on drilling Al/SiC metal matrix composite with multiple responses based on orthogonal array with grey relational analysis [3]. Experiments were conducted on LM25-based aluminium alloy reinforced with green bonded silicon carbide of size 25 µm (10% volume fraction).

Naveen *et al*. investigated the effects of the drilling parameters, speed and feed, on the damage factor in drilling composites glass, hemp and sandwich fibers with different fiber volume fractions (i.e. 10, 20 and 30%) [4]. The objective of this paper was to decrease the damage factor of composite materials with different fiber volume fractions, by varying drill parameters such as speed and feed. The composite material had the size of100×50×3 mm and the drill diameter was 6 mm.

Tyagi *et al*. adopted Taguchi method to study the drilling of mild steel with the help of CNC drilling machining operation with high speed steel tool [5]. Singh *et al*. carried out drilling on glass fiber reinforced plastics using L_{27} Taguchi orthogonal array [6]. The

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effect of spindle speed, feed rate and drill diameter on thrust force and torque in drilling of GFRP composites are studied. The results indicated that the model can be effectively used for predicting the response variable by means of which delamination can be controlled.

Stringer *et al*. analyzed the burr formation in drilling [7]. Tolouei-Rad *et al*. analyzed the drill tool geometry, materials and coatings, for selecting the best tool and cutting parameters that would result in the lowest machining cost or highest profit rate [8].

Rahman *et al*. presented the effect of drilling parameter such as spindle speed, feed rate and drilling tool size on material removal rate (MRR), surface roughness, dimensional accuracy and burr [9]. In this work, a study on optimum drilling parameter for HSS drilling tool in micro-drilling processes in order to find the best drilling parameter for brass as a work piece material, was done. It is understood that surface roughness is mostly influenced by spindle speed and feed rate. As the spindle and feed rate increases, the surface roughness will decrease.

Kumar *et al*. adopted Taguchi method to investigate the effects of drilling parameters such as cutting speed (5, 6.5, 8 m/min), feed rate (0.15, 0.20,mm/rev) and drill tool diameter (10, 12, 15 mm) on surface roughness, tool wear by weight, material removal rate and hole diameter error in drilling of OHNS material using HSS spiral drill [10]. L_{18} Taguchi orthogonal array was adopted for conducting the experiments.

From the literature review, it is understood that most of the researchers concentrated on cutting forces. Also, very few works are reported on copper. Considering the above remarks, we have intended to carry out drilling on copper, since it is easy to machine with HSS drill bit.

III. EXPERIMENTAL PROCEDURE AND ANALYSIS

Commercial copper, brass and bronze of size 20 mm thick was taken and using steel rule and scriber the specimen was divided into 15 subdivisions to facilitate drilling process. Three input parameters were chosen, namely, spindle speed, feed rate and drill diameter. The levels and values of chosen parameters are presented in Table 1. Design of experiments (DOE) was used to select the design matrix. Experiments were performed as per Box Behnken Design matrix for three factors and three levels.

Total 15 combinations of experiments were carried out in dry machining condition. Torque and thrust forces were recorded using dynamometer and surface finish values were measured using Talysurf for the 15 conditions.

Table 1: *Parameters and their Limits.*

	Levels		
Parameter	**–1**	**0**	**+1**
Spindle speed (rpm)	180	280	450
Feed rate (mm/sec)	0.13	0.21	0.33
Drill diameter (mm)	8	10	12

Design Matrix

Drilling was done in dry condition without any coolant as per the design matrix and the measured values of cutting forces, MRR and surface roughness are reported in Tables 2 to 4 for copper, brass and bronze respectively in dry machining.

Development of Empirical Models

Using MINITAB 14 statistical software package, the significant coefficients were determined and final model was developed using second order polynomial equation to estimate cutting forces and surface finish of the plain milling slots in dry machining. Only significant coefficients were included in the polynomial equations [11, 12].

Checking the Adequacy of the Developed Model in Dry Machining

Analyzes of variance (ANOVA) for the developed models are presented in Tables 5 to 7. The F-value (Fisher’s) obtained were within the limit for 95% confidence level. Hence the developed models are adequate

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Copper

$$Torque=-18.110+0.499X_1+272.984X_2-19.915X_3-0.0001X_1^2-163.932X_2^2+2.587X_3^2+0.228X_1X_2-0.052X_1X_3-32.750X_2X_3$$

$$Thrust=24.566-0.059X_1-599.718X_2+24.048X_3-0.0001X_1^2+477.118X_2^2-1.966X_3^2+0.310X_1X_2+0.001X_1X_3+42.282X_2X_3$$

$$MRR=0.87817+0.00142X_1-3.04801X_2-0.22449X_3-0.0001X_1^2-2.47731X_2^2+0.00872X_3^2+0.00334X_1X_2+0.00013X_1X_3+0.45596X_2X_3$$

$$Surface\ Finish=17.0391-.00118X_1-21.3279X_2-2.4439X_3+0.0001X_1^2-+2.8472X_2^2+0.1043X_3^2-0.0173X_1X_2+0.00001X_1X_3+2.6341X_2X_3$$

Brass

$$Torque=39.840+0.032X_1+103.191X_2-12.439X_3+0.0001X_1^2-252.196X_2^2+0.821X_3^2-0.050X_1X_2-0.009X_1X_3+5.541X_2X_3$$

$$Thrust=-107.652+0.018X_1+188.487X_2+18.661X_3+0.0001X_1^2-239.184X_2^2-0.642X_3^2-0.007X_1X_2-0.011X_1X_3-2.950X_2X_3$$

$$MRR=1.34132+0.00042X_1+2.52997X_2-0.42723X_3+0.000001X_1^2-7.15247X_2^2+0.02432X_3^2+0.00252X_1X_2+0.00001X_1X_3+0.18345X_2X_3$$

$$Surface\ Finish=6.97090-.00356X_1-2.4492X_2-0.84941X_3+0.000001X_1^2+1.34549X_2^2+0.02935X_3^2-0.01220X_1X_2+0.00052X_1X_3+0.80202X_2X_3$$

Bronze

$$Torque=-1.5279-0.0555X_1-26.7001X_2+2.6453X_3+0.00001X_1^2-2.9687X_2^2-0.1640X_3^2+0.0369X_1X_2+0.0031X_1X_3+3.0080X_2X_3$$

$$Thrust=-106.247+0.006X_1+176.347X_2+18.829X_3+0.0001X_1^2-222.309X_2^2-0.662X_3^2+0.028X_1X_2-0.010X_1X_3-2.744X_2X_3$$

$$MRR=9.1794-0.0184X_1-11.5116X_2-0.7595X_3+0.0001X_1^2+17.4913X_2^2+0.0142X_3^2-0.0052X_1X_2+0.0007X_1X_3+0.6957X_2X_3$$

$$Surface\ Finish=2.40376-0.00123X_1-0.84377X_2-0.29290X_3+0.000001X_1^2+0.46396X_2^2+0.01012X_3^2-0.00421X_1X_2+0.00018X_1X_3+0.27656X_2X_3$$

Where, X_1, X_2, and X_3 are the coded values of spindle speed, feed rate and drill diameter.

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Table 2: *Experimental Results for Copper.*

Exp No.	Spindle Speed (rpm)	Feed Rate (mm/sec)	Drill Diameter (mm)	Torque (N-m)	Thrust (N)	MRR (kg/sec)	Surface Finish (µm)
1	180	0.13	10	20.66	42.33	0.12118	1.85
2	450	0.13	10	19.66	40.00	0.42530	1.65
3	180	0.33	10	47.66	76.66	0.25640	2.54
4	450	0.33	10	49.00	84.50	0.75180	1.37
5	180	0.21	8	27.00	58.00	0.17070	2.20
6	450	0.21	8	27.66	56.00	0.38190	1.49
7	180	0.21	12	81.33	35.50	0.37140	2.94
8	450	0.21	12	28.66	33.00	0.75130	2.27
9	280	0.13	8	15.00	66.50	0.15220	1.88
10	280	0.33	8	36.66	63.66	0.29720	1.10
11	280	0.13	12	74.00	25.50	0.40250	1.89
12	280	0.33	12	67.00	57.33	0.88880	3.20
13	280	0.21	10	32.66	34.50	0.41450	1.61
14	280	0.21	10	30.33	61.33	0.41360	1.61
15	280	0.21	10	40.66	66.00	0.36570	1.41

Table 3: *Experimental Results for Brass.*

Exp No.	Spindle Speed (rpm)	Feed Rate (mm/sec)	Drill Diameter (mm)	Torque (N-m)	Thrust (N)	MRR	Surface Finish (µm)
1	180	0.13	10	3.66	17.00	0.17780	2.48
2	450	0.13	10	5.00	15.25	0.42660	2.46
3	180	0.33	10	10.66	27.25	0.37340	2.84
4	450	0.33	10	8.25	24.00	0.80770	2.38
5	180	0.21	8	6.25	13.50	0.14807	2.68
6	450	0.21	8	5.75	13.00	0.51310	2.42
7	180	0.21	12	24.00	33.66	0.64980	2.45
8	450	0.21	12	12.25	18.50	0.98870	2.84
9	280	0.13	8	3.50	11.00	0.14666	2.13
10	280	0.33	8	6.66	20.33	0.49906	2.73
11	280	0.13	12	8.75	13.75	0.39840	2.29
12	280	0.33	12	17.50	23.00	0.92960	3.46
13	280	0.21	10	6.75	21.50	0.42000	1.95
14	280	0.21	10	7.75	21.00	0.43300	2.82
15	280	0.21	10	8.50	20.33	0.43460	2.63

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Table 4: *Experimental Results for Bronze.*

Exp No.	Spindle Speed (rpm)	Feed Rate (mm/sec)	Drill Diameter (mm)	Torque (N-m)	Thrust (N)	MRR (kg/sec)	Surface Finish (µm)
1	180	0.13	10	3.66	15.5	0.1625	1.02
2	450	0.13	10	3.66	15	0.4645	1.37
3	180	0.33	10	8.33	28	0.4043	2.46
4	450	0.33	10	5.33	31	1.2618	1.99
5	180	0.21	8	4.25	14	0.1843	2.39
6	450	0.21	8	4	13	0.5096	1.06
7	180	0.21	12	6	33.5	0.478	1.45
8	450	0.21	12	9.33	18.5	0.9842	1.11
9	280	0.13	8	2.75	11	0.18559	2.01
10	280	0.33	8	4.75	20.75	0.3952	1.65
11	280	0.13	12	5.75	13.75	0.4214	0.78
12	280	0.33	12	10	23.5	0.9505	1.26
13	280	0.21	10	5.75	21.5	0.599	1
14	280	0.21	10	6.75	21	0.4704	0.89
15	280	0.21	10	6.25	20.33	0.4608	1.27

Table 5: *ANOVA Table for Copper.*

Analysis of Variance for Torque						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	9	5094.64	5094.64	566.07	4.29	0.062
Linear	3	3653.14	476.77	158.92	1.20	0.398
Square	3	420.26	426.18	142.06	1.08	0.438
Interaction	3	1021.24	1021.24	340.41	2.58	0.166
Residual Error	5	659.52	659.52	131.90		
Lack-of-Fit	3	600.80	600.80	200.27	6.82	0.131
Pure Error	2	58.71	58.71	29.36		
Total	14	5754.16				
Analysis of Variance for Thrust						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	9	3361.9	3361.9	373.55	2.17	0.204

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Linear	3	2663.5	408.9	136.29	0.79	0.549
Square	3	333.1	326.3	108.75	0.63	0.626
Interaction	3	365.4	365.4	121.79	0.71	0.588
Residual Error	5	862.5	862.5	172.49		
Lack-of-Fit	3	284.5	284.5	94.83	0.33	0.811
Pure Error	2	578.0	578.0	288.98		
Total	14	4224.4				
Analysis of Variance for MRR						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	9	0.692167	0.692167	0.076907	20.89	0.002
Linear	3	0.626207	0.016648	0.005549	1.51	0.321
Square	3	0.019165	0.019511	0.006504	1.77	0.270
Interaction	3	0.046795	0.046795	0.015598	4.24	0.077
Residual Error	5	0.018406	0.018406	0.003681		
Lack-of-Fit	3	0.016848	0.016848	0.005616	7.20	0.124
Pure Error	2	0.001559	0.001559	0.000779		
Total	14	0.710573				
Analysis of Variance for Surface Finish						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	9	4.91592	4.91592	0.546213	72.55	0.000
Linear	3	2.53239	1.01664	0.338881	45.01	0.000
Square	3	1.02153	1.00336	0.334454	44.42	0.000
Interaction	3	1.36200	1.36200	0.454000	60.30	0.000
Residual Error	5	0.03764	0.03764	0.007529		
Lack-of-Fit	3	0.01098	0.01098	0.003659	0.27	0.843
Pure Error	2	0.02667	0.02667	0.013333		
Total	14	4.95356				

Table 6: *ANOVA Table for Brass.*

Analysis of Variance for Torque						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	9	379.686	379.686	42.1873	5.74	0.034
Linear	3	273.557	37.484	12.4948	1.70	0.281
Square	3	74.072	73.608	24.5360	3.34	0.114
Interaction	3	32.056	32.056	10.6855	1.45	0.333
Residual Error	5	36.745	36.745	7.3490		
Lack-of-Fit	3	35.204	35.204	11.7345	15.22	0.062
Pure Error	2	1.542	1.542	0.7708		
Total	14	416.431				
Analysis of Variance for Thrust						

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Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	425.628	425.6276	47.2920	2.82	0.133
Linear	3	329.559	62.4468	20.8156	1.24	0.388
Square	3	59.574	59.6043	19.8681	1.18	0.404
Interaction	3	36.494	36.4943	12.1648	0.72	0.579
Residual Error	5	83.922	83.9217	16.7843		
Lack-of-Fit	3	83.232	83.2324	27.7441	80.50	0.012
Pure Error	2	0.689	0.6893	0.3446		
Total	14	509.549				
Analysis of Variance for MRR						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	9	0.909341	0.909341	0.101038	17.31	0.003
Linear	3	0.843494	0.035841	0.011947	2.05	0.226
Square	3	0.055428	0.056073	0.018691	3.20	0.121
Interaction	3	0.010420	0.010420	0.003473	0.60	0.645
Residual Error	5	0.029184	0.029184	0.005837		
Lack-of-Fit	3	0.029056	0.029056	0.009685	151.05	0.007
Pure Error	2	0.000128	0.000128	0.000064		
Total	14	0.938525				
Analysis of Variance for Surface Finish						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	9	1.04719	1.04719	0.11635	0.78	0.648
Linear	3	0.69717	0.10200	0.03400	0.23	0.873
Square	3	0.05513	0.05137	0.01712	0.12	0.947
Interaction	3	0.29489	0.29489	0.09830	0.66	0.611
Residual Error	5	0.74410	0.74410	0.14882		
Lack-of-Fit	3	0.32564	0.32564	0.10855	0.52	0.711
Pure Error	2	0.41847	0.41847	0.20923		
Total	14	1.79129				

Table 7: *ANOVA Table for Bronze.*

Analysis of Variance for Torque						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	9	51.1879	51.1879	5.6875	2.48	0.165
Linear	3	43.4948	6.2115	2.0705	0.90	0.502
Square	3	2.3296	2.2624	0.7541	0.33	0.805
Interaction	3	5.3635	5.3635	1.7878	0.78	0.554
Residual Error	5	11.4637	11.4637	2.2927		

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Lack-of-Fit	3	10.9637	10.9637	3.6546	14.62	0.065
Pure Error	2	0.5000	0.5000	0.2500		
Total	14	62.6516				
Analysis of Variance for Thrust						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	9	470.064	470.0640	52.2293	2.81	0.134
Linear	3	376.331	61.8847	20.6282	1.11	0.428
Square	3	60.065	59.8557	19.9519	1.07	0.440
Interaction	3	33.667	33.6673	11.2224	0.60	0.641
Residual Error	5	93.022	93.0220	18.6044		
Lack-of-Fit	3	92.333	92.3327	30.7776	89.31	0.011
Pure Error	2	0.689	0.6893	0.3446		
Total	14	563.086				
Analysis of Variance for MRR						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	9	1.53966	1.53966	0.17107	1.64	0.305
Linear	3	0.88528	0.48691	0.16230	1.55	0.310
Square	3	0.40958	0.40925	0.13642	1.31	0.369
Interaction	3	0.24480	0.24480	0.08160	0.78	0.553
Residual Error	5	0.52222	0.52222	0.10444		
Lack-of-Fit	3	0.48321	0.48321	0.16107	8.26	0.110
Pure Error	2	0.03901	0.03901	0.01951		
Total	14	2.06188				
Analysis of Variance for Surface Finish						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	9	0.124517	0.124517	0.013835	0.78	0.648
Linear	3	0.082898	0.012128	0.004043	0.23	0.873
Square	3	0.006556	0.006108	0.002036	0.12	0.947
Interaction	3	0.035064	0.035064	0.011688	0.66	0.611
Residual Error	5	0.088478	0.088478	0.017696		
Lack-of-Fit	3	0.038720	0.038720	0.012907	0.52	0.711
Pure Error	2	0.049758	0.049758	0.024879		
Total	14	0.212996				

Where,
DF=Degrees of Freedom, SS=Sum of Squares, MS=Mean Square, F=Fishers Ratio.

Scatter Plots

Scatter plots were drawn between actual and predicted values of torque, thrust, MRR and surface finish of the drilling, which revealed that the actual and predicted values were close to each other with in the specified limits (Figures 1 to 12).

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Scatter Plots for Copper

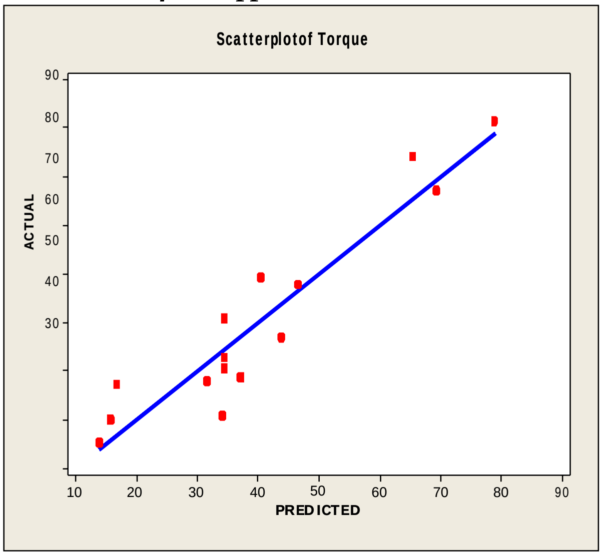


Fig. 1: Scatter Plot for Torque (Copper).

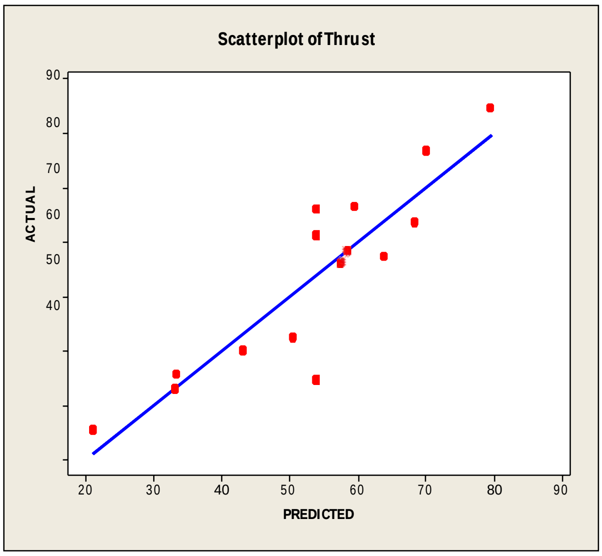
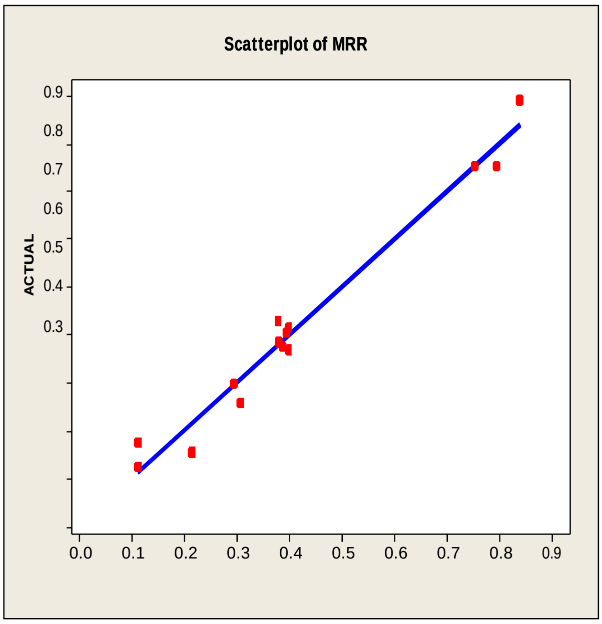


Fig. 2: Scatter Plot for Thrust (Copper).



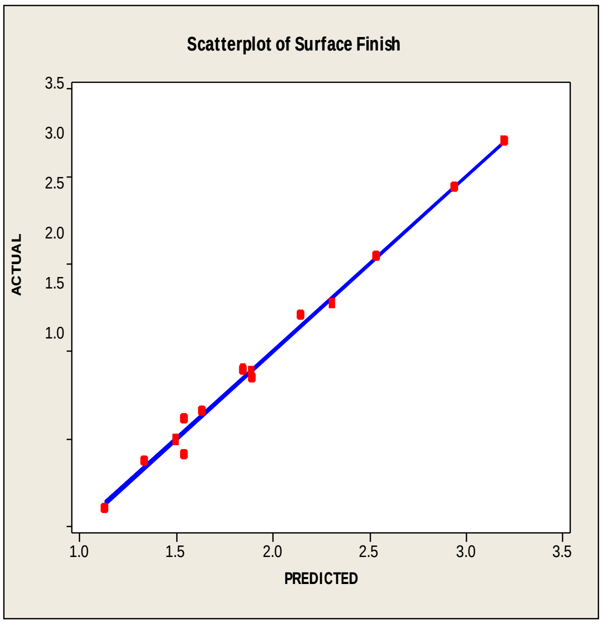


***Fig. 3:** Scatter Plot for MRR (Copper). **Fig. 4:** Scatter Plot for Surface Finish (Copper).*

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Scatter Plots for Brass

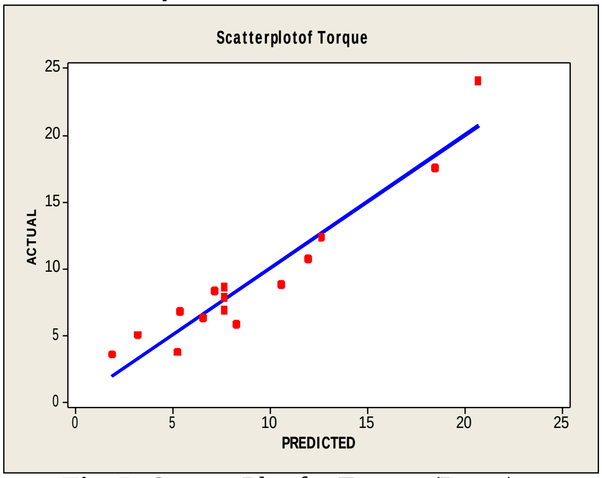

Fig. 5: *Scatter Plot for Torque (Brass).*

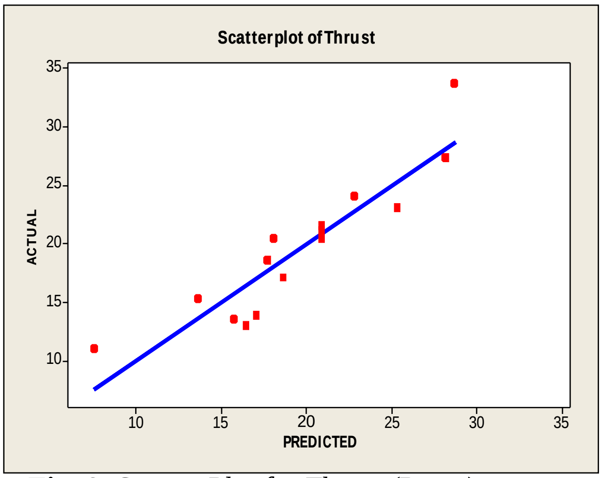

Fig. 6: *Scatter Plot for Thrust (Brass).*

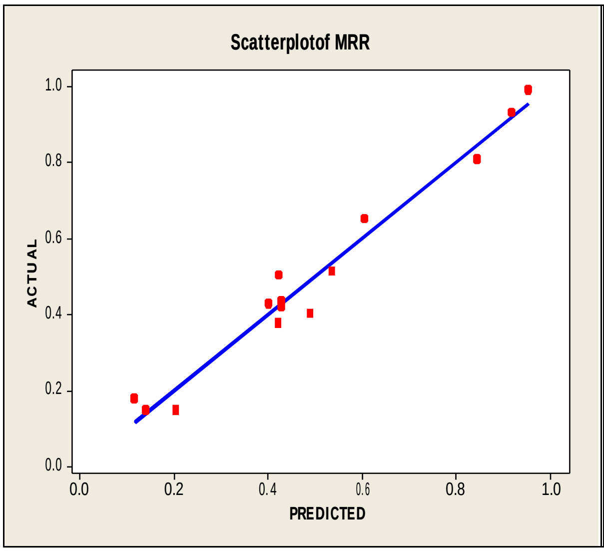

Fig. 7: *Scatter Plot for MRR (Brass).*

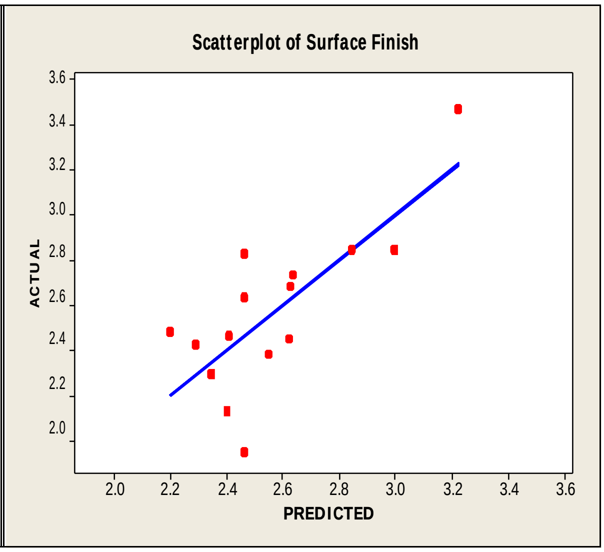

Fig. 8: *Scatter Plot for Surface Finish (Brass).*

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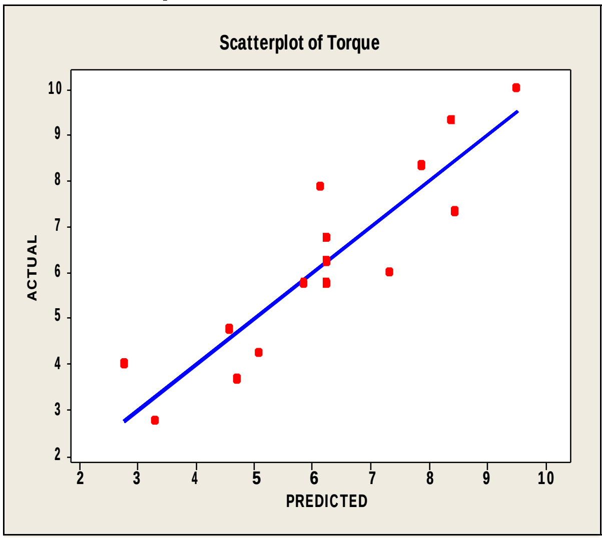
Scatter Plots for Bronze



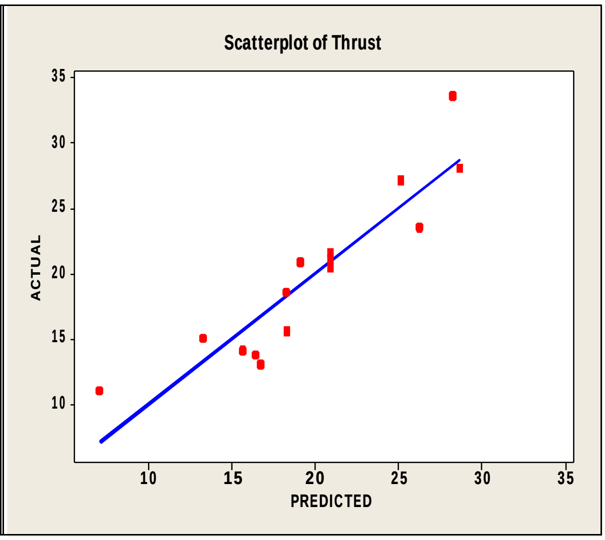
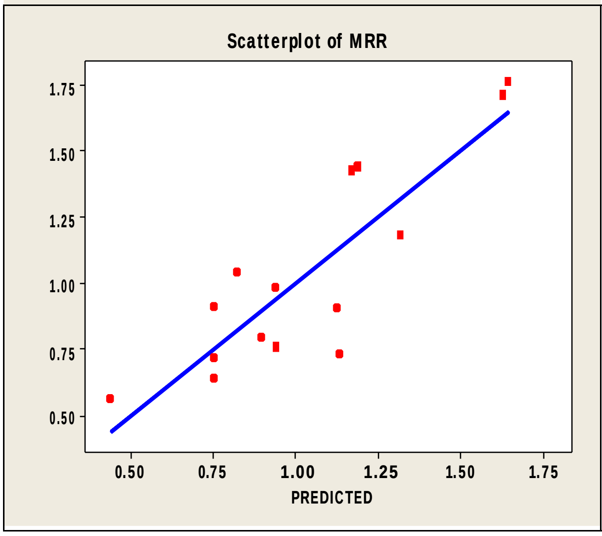


Fig. 9: *Scatter Plot for Torque (Bronze).* ***Fig. 10:*** *Scatter Plot for Thrust (Bronze).*



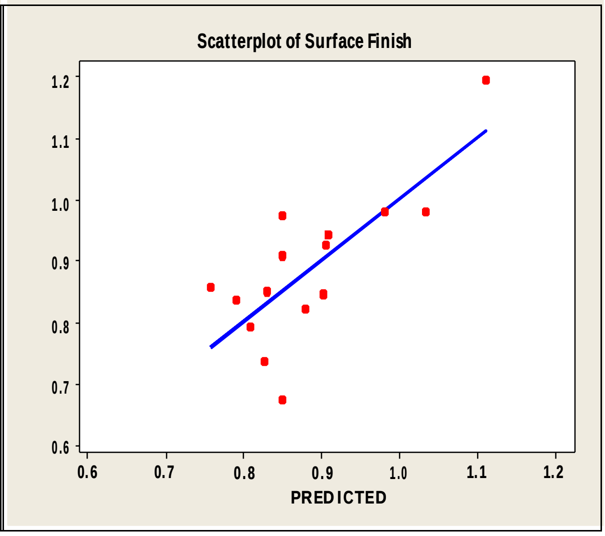


Fig. 11: *Scatter Plot for MRR (Bronze).* ***Fig. 12:*** *Scatter Plot for Surface Finish (Bronze).*

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IV. Effect of Process Variables

Main Effects on Copper

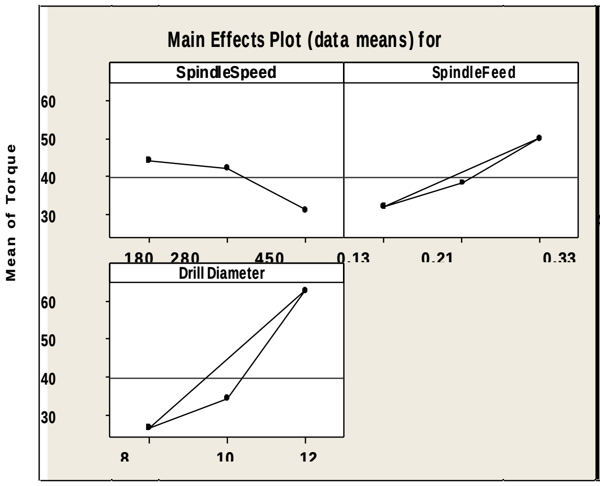
Graphs are drawn for each drilling parameter separately (Figures 13 to 16) and the following observations are made:

- Torque value decreases with increase in spindle speed and increase with increase in spindle feed and drill diameter.
- Thrust values remain constant with spindle speed, however it increases with spindle speed and decreases with increase in drill diameter.
- Metal removal rate (MRR) increases with increase in spindle speed, spindle feed and drill diameter.
- Surface finish is improved with increase in spindle speed, however it is poor with increase in spindle feed and drill diameter.
-

Main Effects on Brass

Graphs are drawn for each drilling parameters separately (Figures 17 to 20) and the following observations are made:

- Torque value decreases with increase in spindle speed and increase with increase in spindle feed and drill diameter.
- Thrust value decreases with increase in spindle speed and increase with increase in spindle feed and drill diameter.
- Metal removal rate (MRR) increases with increase in spindle speed, spindle feed and drill diameter. Surface finish is improved with increase in spindle speed, however it is poor with increase in spindle feed and drill diameter.



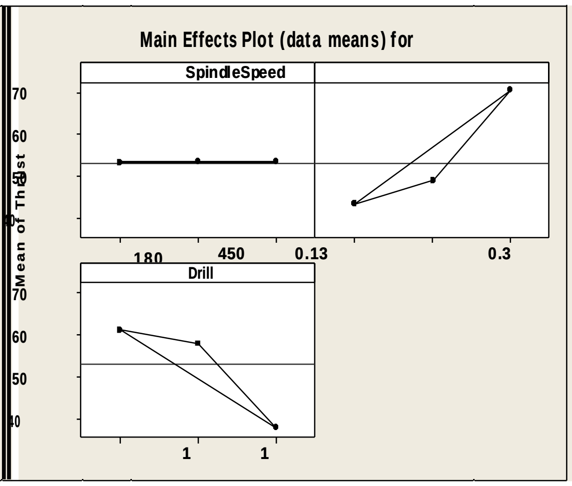


Fig. 13: *Main Effect on Torque (Copper).* ***Fig. 14:*** *Main Effect on Thrust (Copper).*

Main Effects on Brass

Graphs are drawn for each drilling parameters separately (Figures 21 to 24) and the following observations are made:

- Torque value decreases with increase in spindle speed and increase with increase in spindle feed and drill diameter.
- Thrust value decreases with increase in spindle speed and increase with increase in spindle feed and drill diameter.
- Metal removal rate (MRR) increases with increase in spindle speed, spindle feed and decrease with drill diameter.
- Surface finish is improved with increase in spindle speed, however it is poor with increase in spindle feed and drill diameter.

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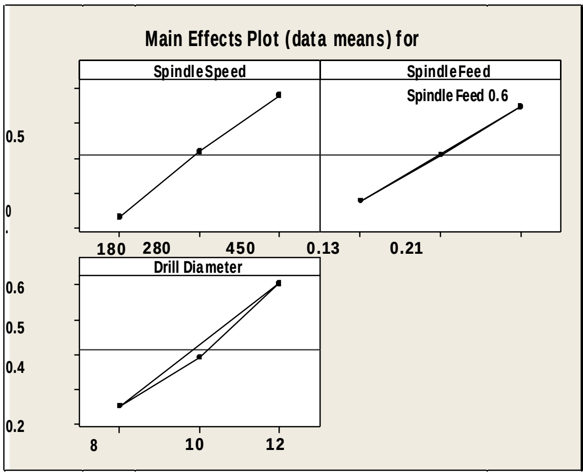


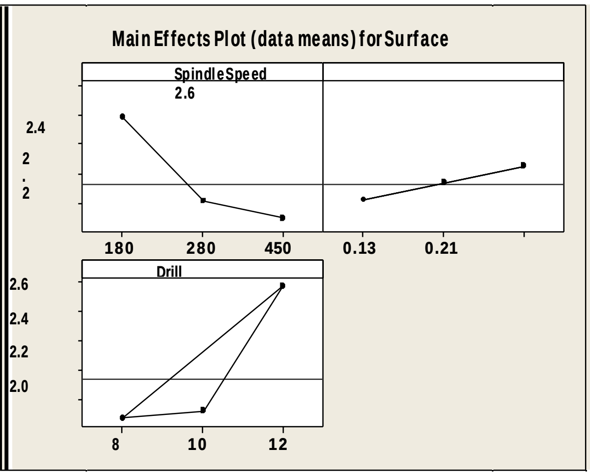
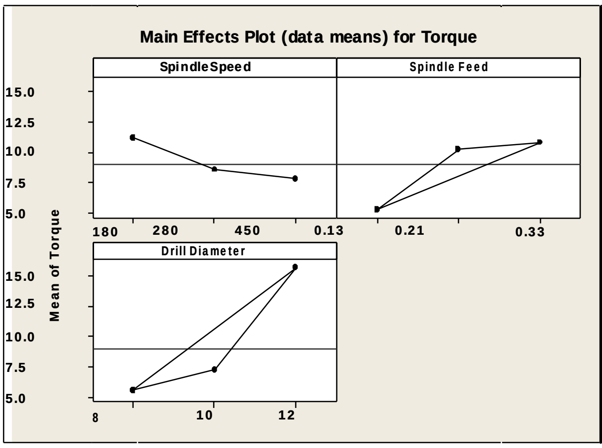


Fig. 15: *Main Effect on MRR (Copper).* ***Fig. 16:*** *Main Effect on Surface Finish (Copper).*



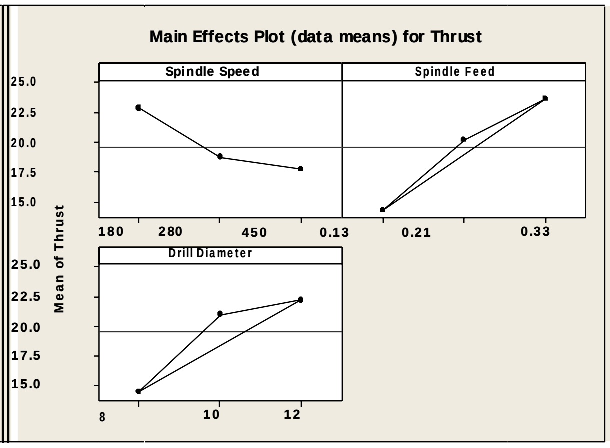
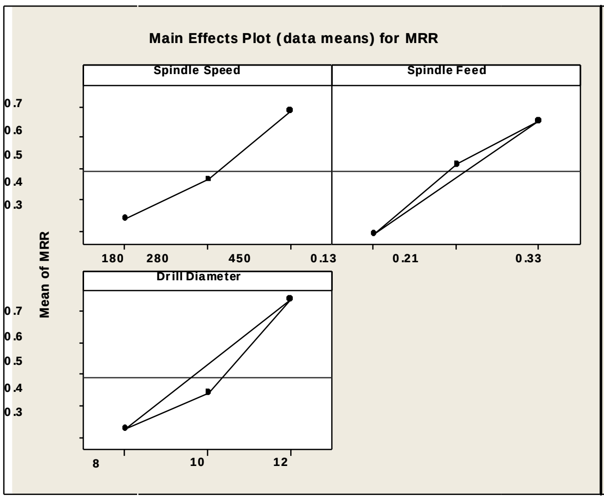


Fig. 17: *Main Effect on Torque (Brass).* ***Fig. 18:*** *Main Effect on Thrust (Brass).*



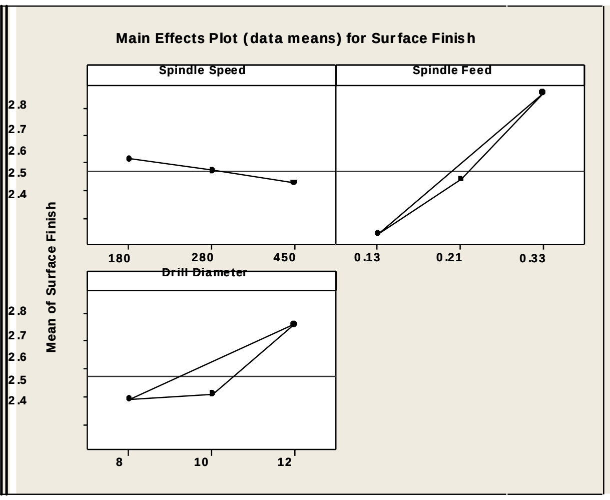


Fig. 19: *Main Effect on MRR (Brass).* ***Fig. 20:*** *Main Effect on Surface Finish (Brass).*

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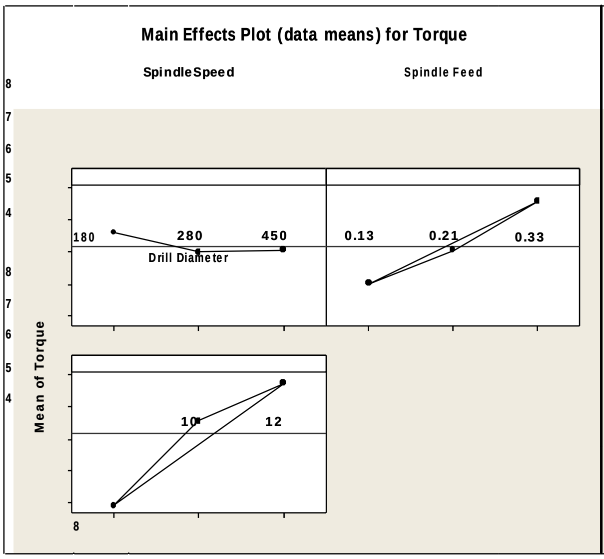

Fig. 21: *Main Effect on Torque (Bronze).*

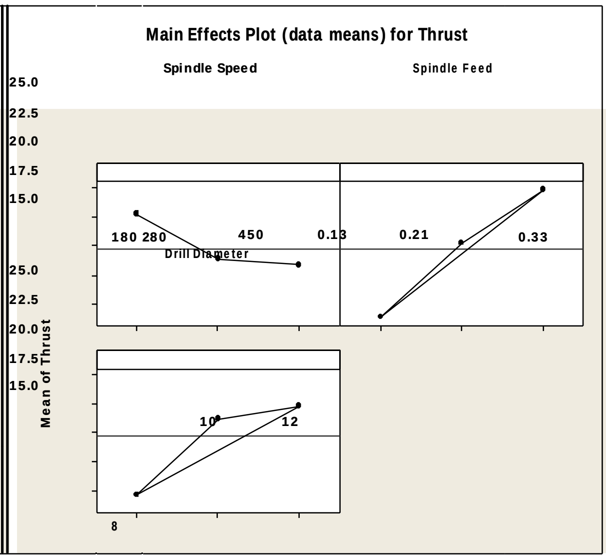

Fig. 22: *Main Effect on Thrust (Bronze).*

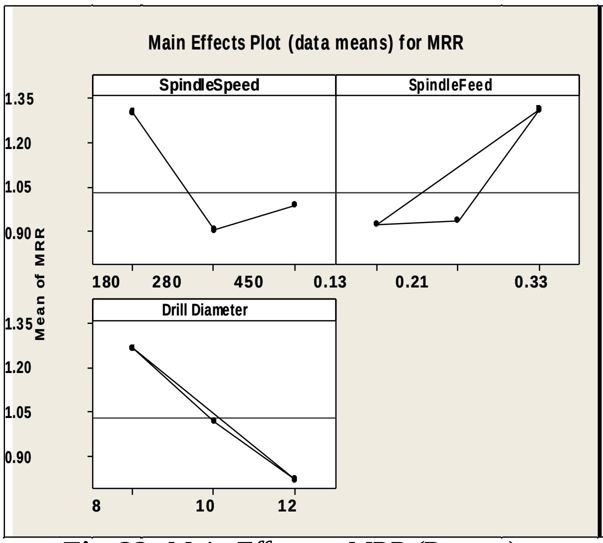

Fig. 23: *Main Effect on MRR (Bronze).*

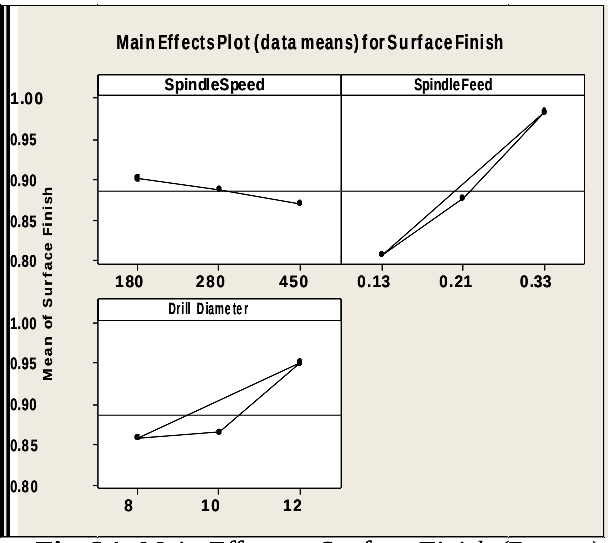

Fig. 24: *Main Effect on Surface Finish (Bronze).*

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Chip Behavior in Drilling Process

The chip behavior for copper, brass and bronze are presented in Figures 25 to 27 respectively. Drilling of pure copper produces continuous chips; whereas discontinuous chips are obtained in brass and bronze. Metal removal rate is high in case of brass.

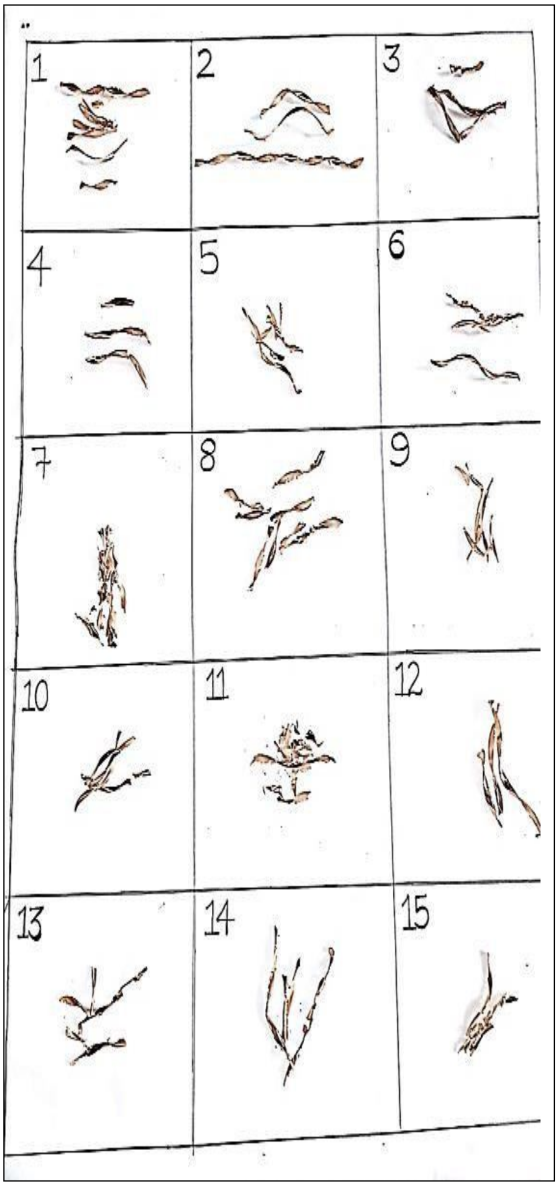

Fig. 25: *Chip Behavior in Copper.*

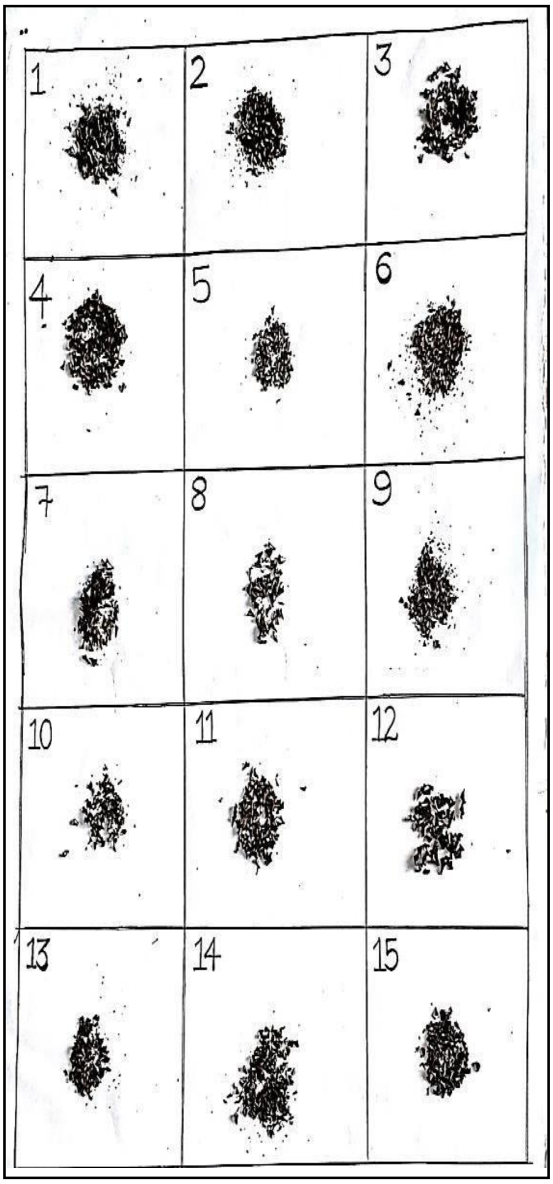

Fig. 26: *Chip Behavior in Bronze.*

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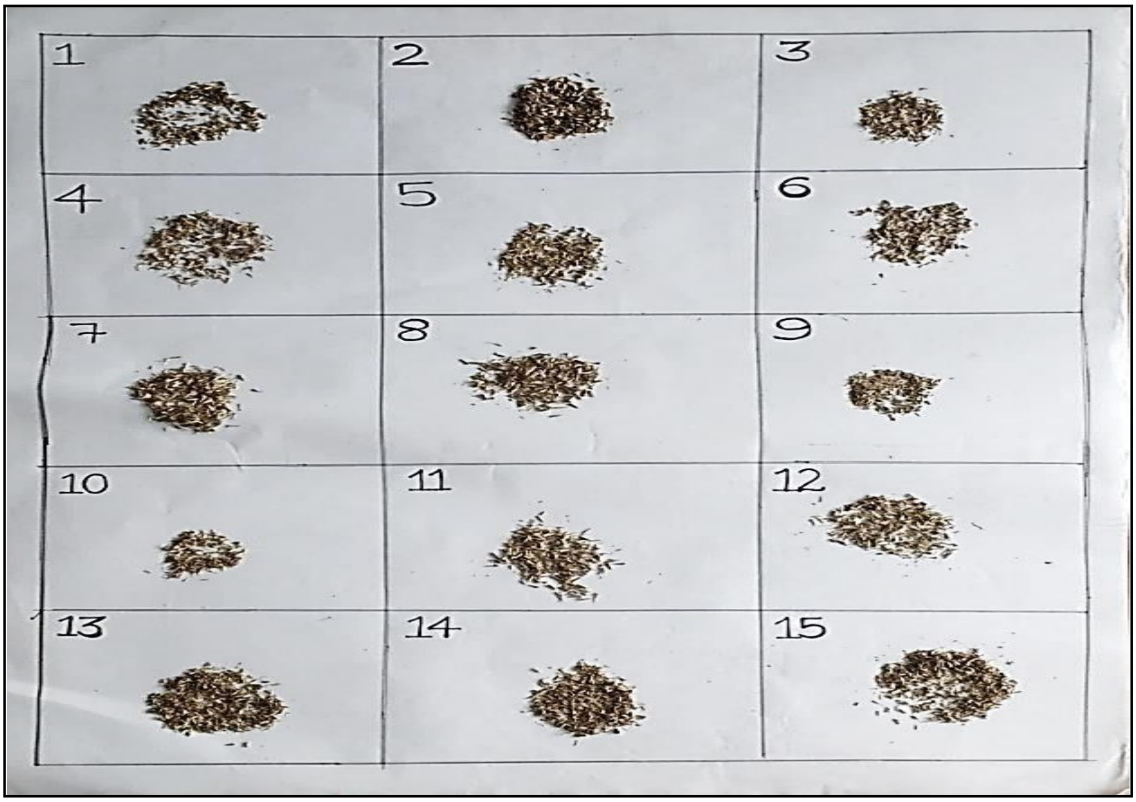

Fig. 27: *Chip Behavior in Brass.*

V. CONCLUSIONS

From the experiments performed, the following conclusions are drawn:

- Empirical mathematical models are developed for torque, thrust, MRR and surface finish in order to predict their values within the range of the drilling parameters, selected for the chosen materials (copper, brass and bronze).
- The experimental and predicted values are very close to each other, which indicate the accuracy of the developed model.
- The adequacy of the developed model is checked using ANOVA at 95% confidence level and found to be adequate.
- From the scatter plot it is understood that experimental and predicted values are close to each other.
- Torque value decreased with increase in spindle speed and increased with increase in spindle feed and drill diameter.
- Thrust force remains constant with spindle speed, where as it increases with spindle feed and decreases with drill diameter.
- MRR increases with increase in spindle speed, spindle feed and drill diameter.
- Surface finish is improved with increase in spindle speed and became worse with increases in spindle feed and drill diameter.
- Out of the chosen materials, better surface finish is obtained in bronze followed by copper and brass.
- MRR is high for bronze followed by brass and copper.
- Torque and thrust forces are high for copper, when compared to brass and bronze.

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Continuous chip is obtained in copper, whereas discontinuous chip is observed in brass and bronze.

- Spindle speed is the most dominating parameter affecting the output responses, followed by spindle feed and drill diameter.
- The models are valid within the specified range of the selected drilling parameters; however the accuracy can be improved by considering more number of factors and their levels.

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