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Machinability Investigations on Al6063+ZnO Metal Matrix Material using Single Point Cutting Tool

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Abstract
This paper summarizes the machinability investigations conducted on Al6063 alloy reinforced with ZnO particles (Al6063+ZnO metal matrix material) using a High-Speed Steel (HSS) single point cutting tool. The study aimed to evaluate the performance of HSS tools in machining this composite material, considering its potential applications in industries where lightweight materials with enhanced mechanical properties are desired. The methodology involved conducting turning experiments on the Al6063+ZnO composite under various cutting conditions such as cutting speeds, feed rates, depths of cut and rake angle. The machinability aspects assessed included material removal rate, cutting force and tool wear. Results indicated that the addition of ZnO particles to the Al6063 alloy affected the machining behavior, influencing tool wear. Specifically, higher cutting speeds led to reduced tool wear. The study provides insights into the challenges and opportunities associated with machining Al6063+ZnO composites using HSS tools, highlighting the importance of selecting appropriate cutting parameters for achieving desired machining outcomes.

Keywords: *Machinability, Al6063+ZnO, Metal Matrix Composites, High-Speed Steel Tool, Flank Wear*

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1. INTRODUCTION

Metal matrix materials have gained significant attention in various industrial applications due to their enhanced mechanical and tribological properties compared to conventional alloys. Among metal matrix materials, Al6063 reinforced with ceramic particles such as ZnO has shown significance in improving hardness, wear resistance. Despite their advantageous properties, the machining of Al6063+ZnO metal matrix materials pose challenges due to the presence of hard ZnO particles, which can lead to rapid tool wear, and increased cutting forces. Machinability, therefore, becomes a critical aspect to understand and optimize to ensure efficient manufacturing processes and acceptable component quality.
In Al6063 aluminum alloy, zinc (Zn) plays several important roles despite being present in relatively small quantities. The typical composition of zinc in Al6063 alloy ranges from 0.10% to 0.20%.

2. LITERATURE REVIEW

According to Sunil Kumar et al. [1], depth of cut has a greater impact on the rate of material removal than feed rate or speed. The rate at which material is removed increases as speed does. As the feed rate rises, so does the material removal rate. As the depth of cut increases, so does the material removal rate. A method for figuring out the ideal machining parameters that result in a minimum of 2^3 surface roughness using the Taguchi method was described by Oussama Zerti et al. [2]. Using L18(21–34), a mixed orthogonal array, the turning operations were carried out in accordance with the Taguchi design of experiment methodology. The optimal levels of the machining parameters were computed using the signal to noise ratio (S/N) based on the "smaller-is-better" approach. The outcomes have demonstrated the high reliability of the Taguchi approach in maximizing machining parameters for increased surface roughness. The machining of hardened steel using an advanced cutting tool has several advantages over a conventional method, according to research by Nithin M. Mali et al. [3]. These advantages include a shorter cycle time, process flexibility, compatible surface roughness, a higher material removal rate, and fewer environmental issues due to the lack of cutting fluid. However, because of the increased mechanical stress and heat generation, it resulted in significant tool wear and altered the product's quality and performance. To create nine conditions for turning operations, the Design of Experiment (DOE) with Taguchi L9 Orthogonal Array (OA) has been investigated. Additionally, the performance of multilayer coated (Al_2O_3+TiC+TiNAlCrN) ceramic tool in dry machining of hardened AISI 4340 steel (46 HRC) has been studied and compared with that of uncoated ceramic tool on CNC machine. Using a CVD (TiN/TiCN/Al_2O_3/TiN) multilayer coated carbide tool, Sudhansu Ranjan Das, et al. [4] addressed surface roughness, flank wear, and chip morphology during dry hard turning of AISI 4340 steel (49 HRC). To find out how cutting parameters affected flank wear and surface roughness on the tool and workpiece, three factors (cutting speed, feed, and depth of cut) and three-level factorial experiment designs using Taguchi's L9 Orthogonal array (OA) and statistical analysis of variance (ANOVA) were used. Sharma, Vishal S. et al., [5] This paper reports on studies done on cutting tool wear and a methodology for tool wear estimate. We recode and analyse the variations in cutting force, vibration, and acoustic emission values with cutting tool wear.

3. OBJECTIVES OF THE STUDY

This present work aims to address these identified gaps by conducting an experimental investigation.

For the current study the following conclusions were made

- To Prepare the work material Al6063+ZnO by die-casting process
- To calculate material removal rate (MRR) and resultant force (RF)
- To find out the flank wear of selected tools
- To develop a mathematical model (regression equation)

4. EXPERIMENTATION

Preparing the work material Al 6063+ZnO using die-casting process by varying ZnO with 4% and 12% percentage. Al6063 alloy of the following composition is used for the experimentation which is the optimum composition of Al6063 alloy having highest tensile strength. The experimentation is carried on lathe machine with dynamometer setup.

Table 1: Weight percentage of metals in Al6063+ZnO (4%)

Metal	Mg	Si	Fe	Cu	Zn	Ti	Mn	Cr	Al	ZnO
Weight %	0.45	0.2	0.3	0.1	0.1	0.05	0.05	0.1	98.65	4

Table 2: Weight percentage of metals in Al6063+ZnO (12%)

Metal	Mg	Si	Fe	Cu	Zn	Ti	Mn	Cr	Al	ZnO
Weight %	0.45	0.2	0.3	0.1	0.1	0.05	0.05	0.1	98.65	12

Fig 1: workpiece after machining and grooving

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Fig 2: Experimental Setup

4.1 Factors and Levels:
The following table shows the input parameters considered for carrying experiment and the levels of each parameter along with designation.

Table 3: Experimentation table

Factors	Units	Designation	Test levels	
			Low	High
Cutting speed	rpm	v	150	445
Feed	mm/rev	f	0.21	0.421
Depth of cut	mm	d	0.2	0.5
Rake angle	degrees (°)	r	15	20

4.2 Design of Experiments
Using full factorial design of experiments the following table of trials have been developed

which is used for both the specimens (Al6063+4% ZnO and Al6063+12% ZnO). The number factors considered are four with two levels.

Total number. of trials = $2^4 = 16$

Table 4: Design Matrix

Trial No.	v (rpm)	f (mm/rev)	d (mm)	r (°)
1	150	0.21	0.2	15
2	445	0.21	0.2	15
3	150	0.421	0.2	15
4	445	0.421	0.2	15
5	150	0.21	0.5	15
6	445	0.21	0.5	15
7	150	0.421	0.5	15
8	445	0.421	0.5	15
9	150	0.21	0.2	20
10	445	0.21	0.2	20
11	150	0.421	0.2	20
12	445	0.421	0.2	20
13	150	0.21	0.5	20
14	445	0.21	0.5	20
15	150	0.421	0.5	20
16	445	0.421	0.5	20

In the analysis of the experimental results the effect of each factor can be determined with the same accuracy as if only one factor has been varied at a time and the interaction effects between the factors can also be evaluated.

4.3 Images of Flank Wear

- **For Al6063+ 4% ZnO**

Fig 3: Tool 1 geometry before and after experiment

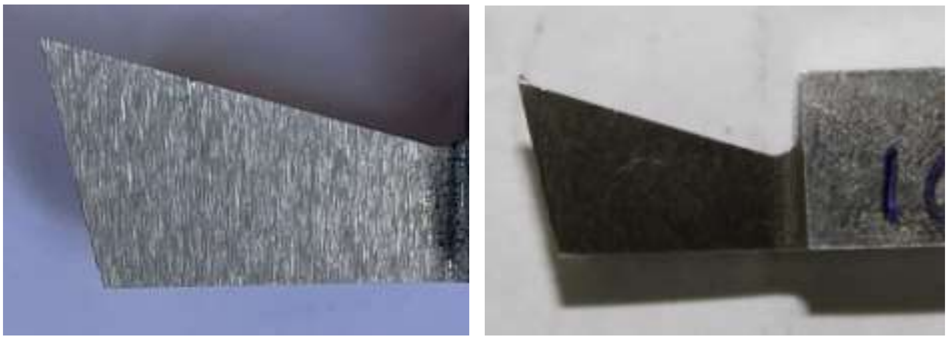


Fig 4: Tool 2 geometry before and after experiment

Fig 5: Tool 3 geometry before and after experiment

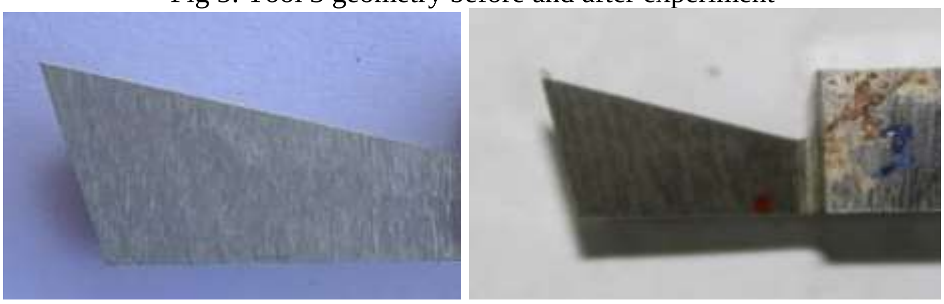


Fig 6: Tool 4 geometry before and after experiment

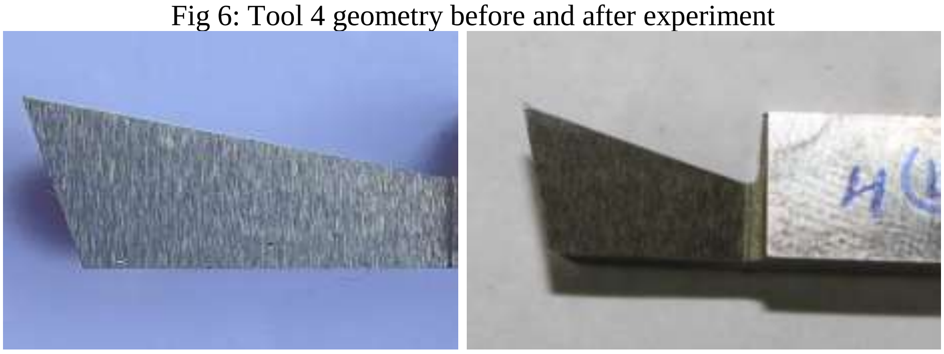


Fig 7: Tool 5 geometry before and after experiment

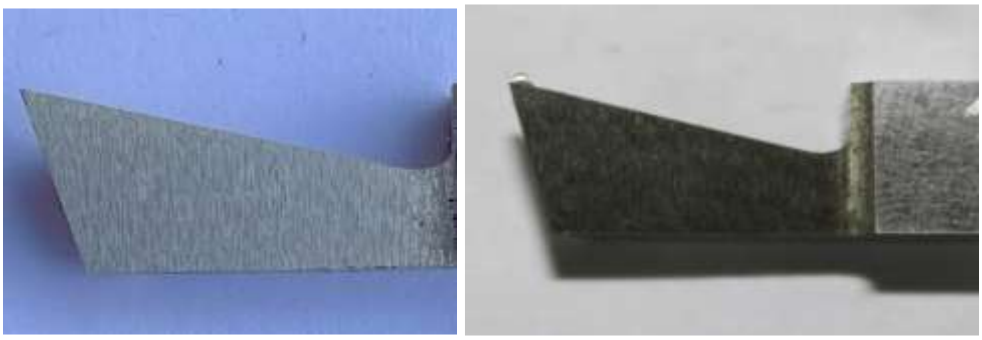


Fig 8: Tool 6 geometry before and after experiment

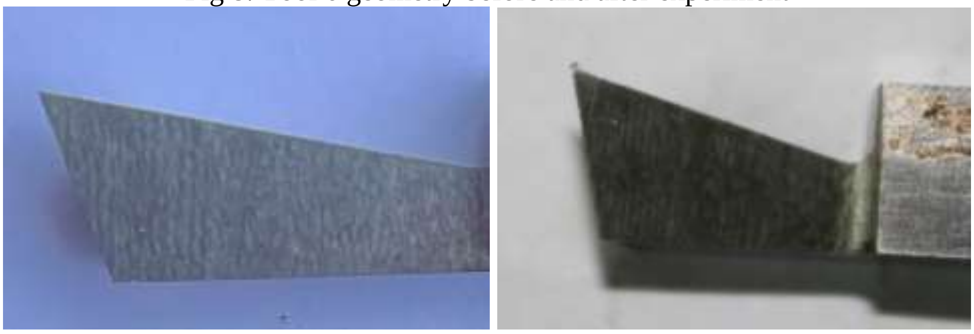


Fig 9: Tool 7 geometry before and after experiment

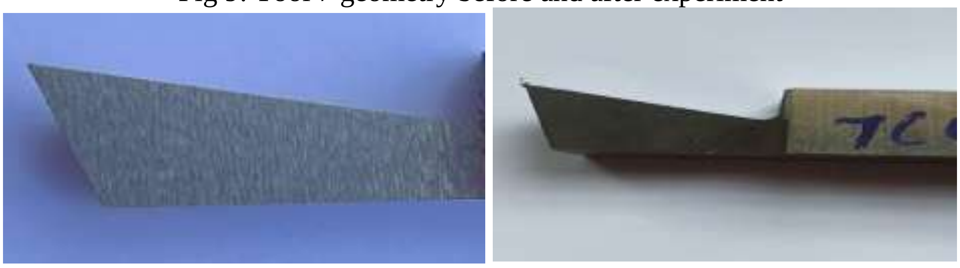


Fig 10: Tool 8 geometry before and after experiment

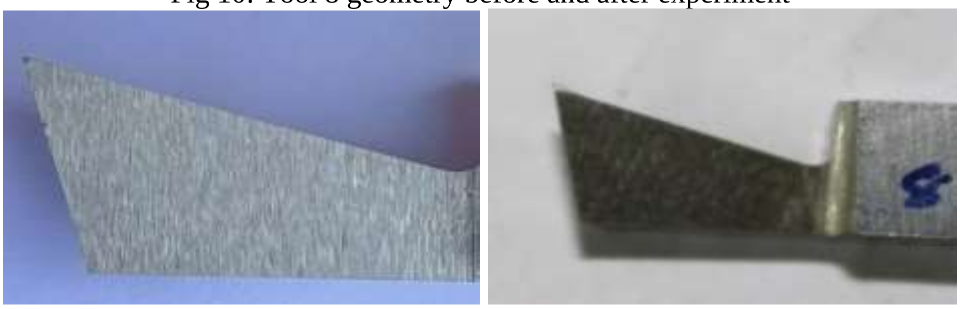


Fig 11: Tool 9 geometry before and after experiment

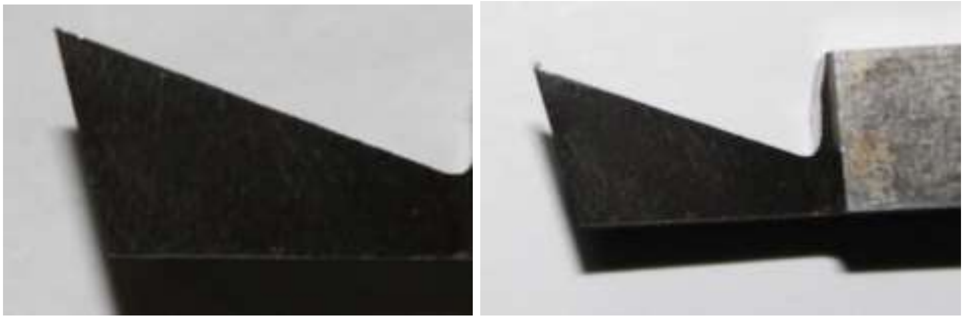


Fig 12: Tool 10 geometry before and after experiment

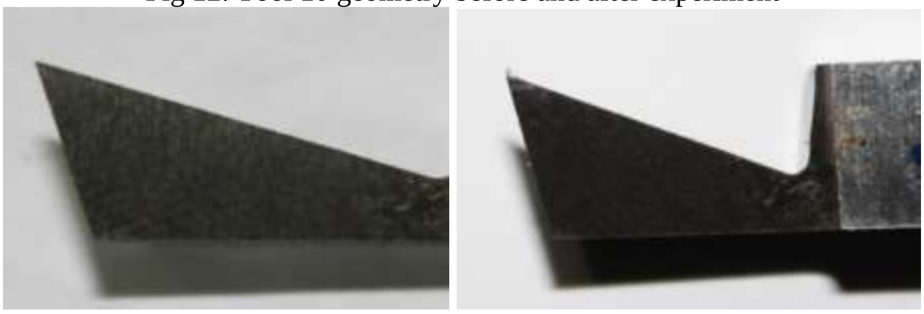


Fig 13: Tool 11 geometry before and after experiment

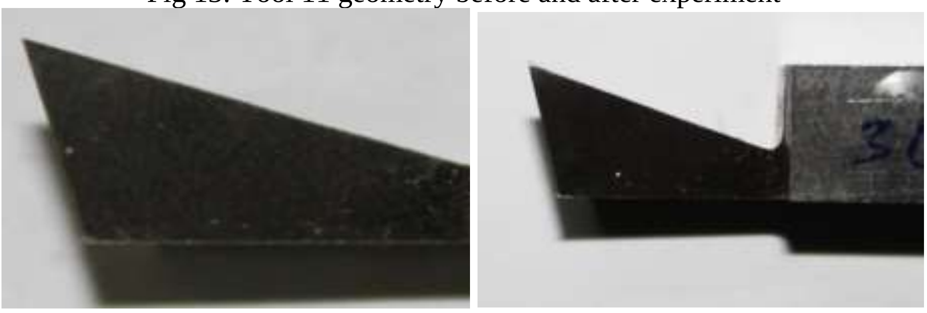


Fig 14: Tool 12 geometry before and after experiment

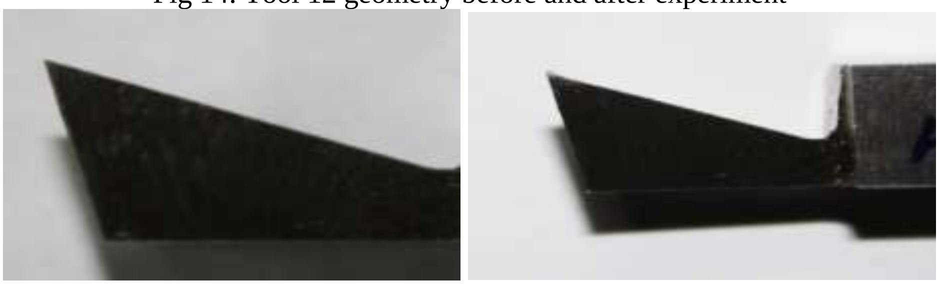


Fig 15: Tool 13 geometry before and after experiment

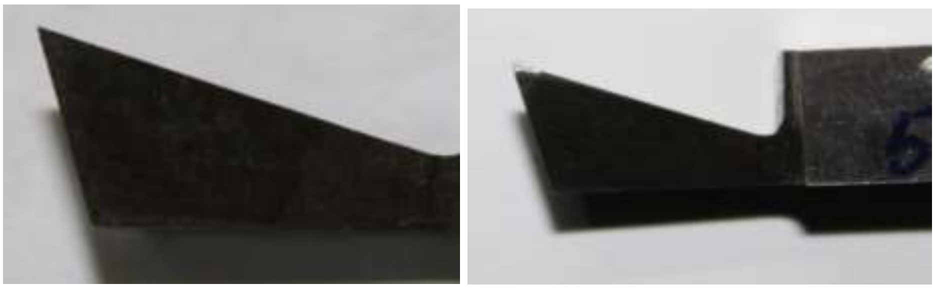


Fig 16: Tool 14 geometry before and after experiment

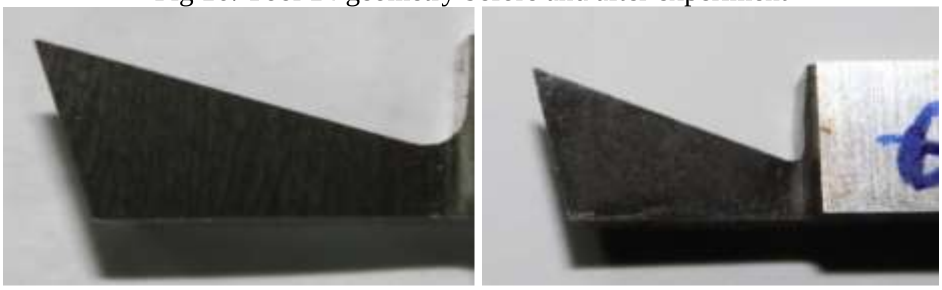


Fig 17: Tool 15 geometry before and after experiment

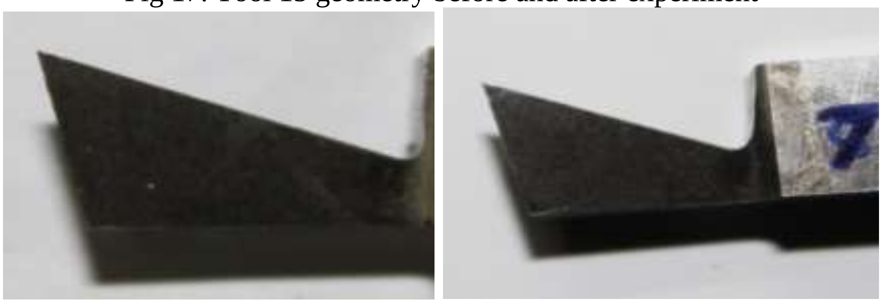
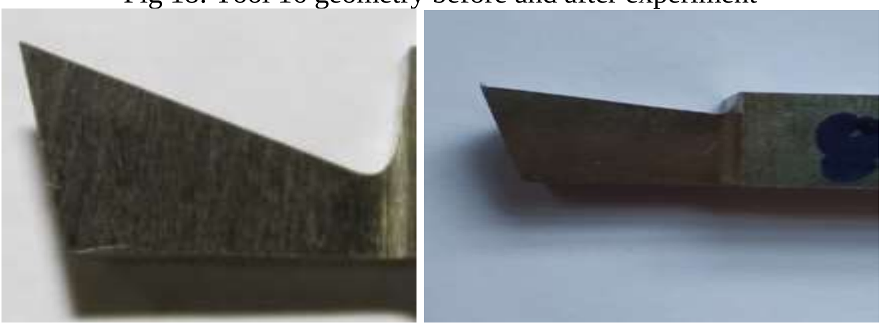


Fig 18: Tool 16 geometry before and after experiment



- **For Al6063+ 12% ZnO**

Fig 19: Tool 1 geometry before and after experiment

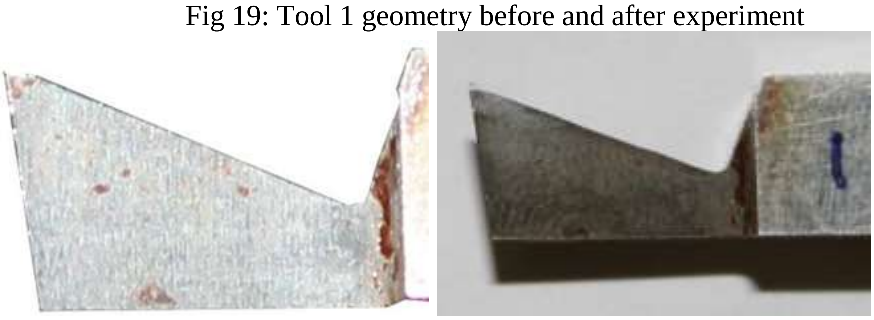


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Fig 20: Tool 2 geometry before and after experiment

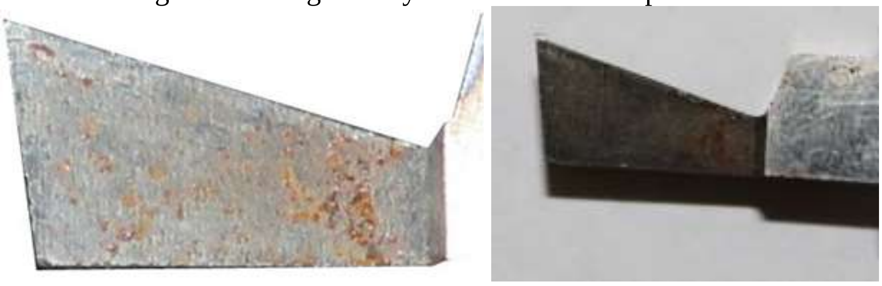

Fig 21: Tool 3 geometry before and after experiment

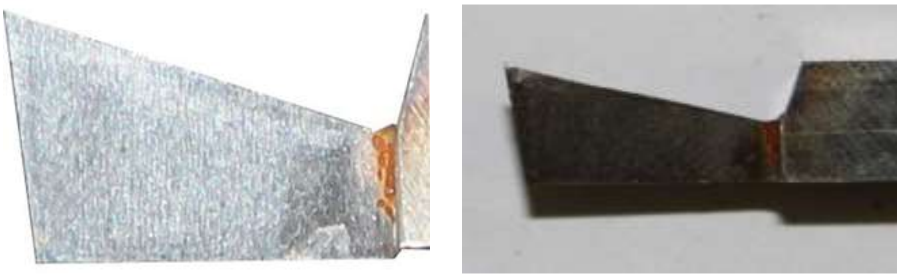

Fig 22: Tool 4 geometry before and after experiment

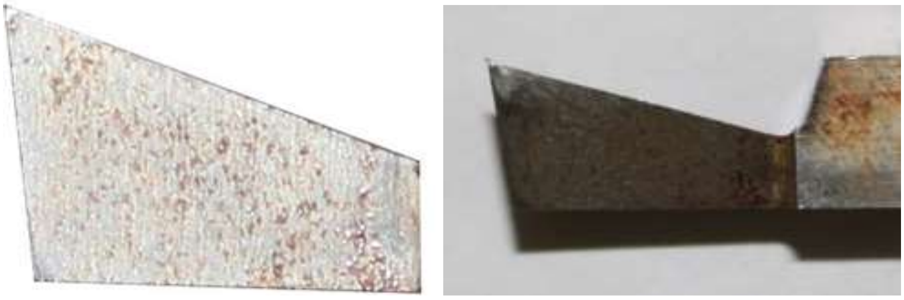

Fig 23: Tool 5 geometry before and after experiment

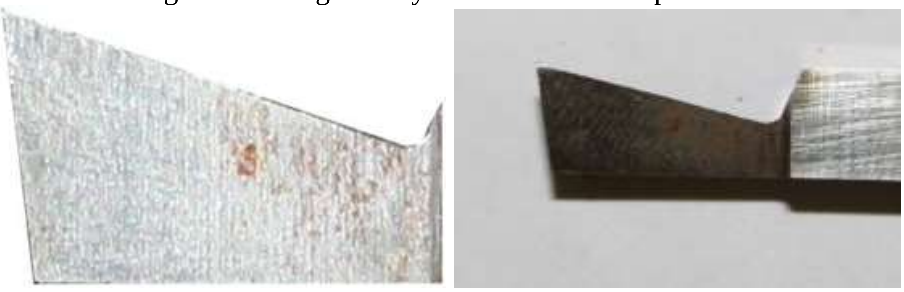

Fig 24: Tool 6 geometry before and after experiment

Fig 25: Tool 7 geometry before and after experiment

Fig 26: Tool 8 geometry before and after experiment

Fig 27: Tool 9 geometry before and after experiment

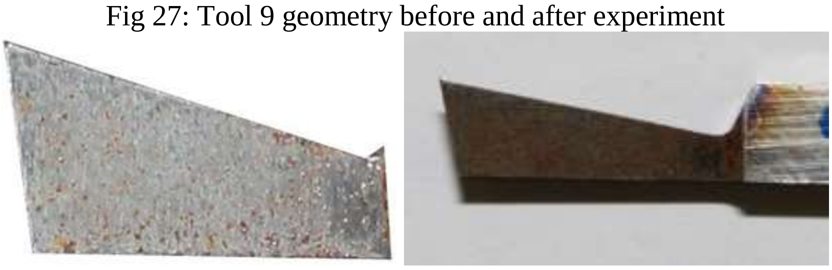

Fig 28: Tool 10 geometry before and after experiment

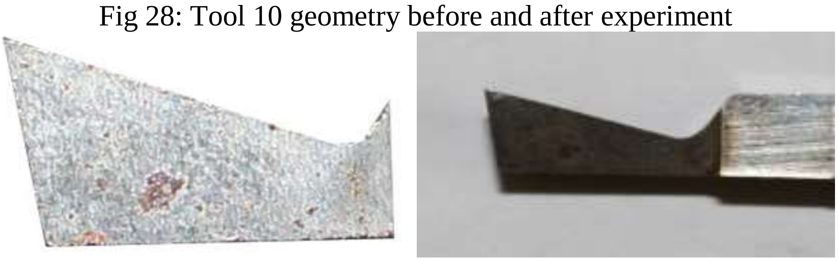

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Fig 29: Tool 11 geometry before and after experiment

Fig 30: Tool 12 geometry before and after experiment

Fig 31: Tool 13 geometry before and after experiment

Fig 32: Tool 14 geometry before and after experiment

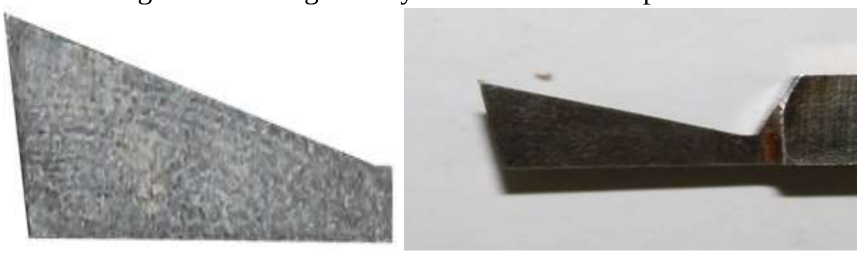

Fig 33: Tool 15 geometry before and after experiment

Fig 34: Tool 16 geometry before and after experiment


5. RESULTS AND DISCUSSIONS

Following tables shows the results of the experiment for all the trials and MRR is calculate using the formula

$$MRR = \frac{w_1 - w_2}{t}$$

Where w_1 is the weight of the workpiece before machining (gm) w_2 is the weight of the workpiece after machining (gm) t is the machining time (min)

Resultant Force (RF) = $\sqrt{{F_x}^2 + {F_y}^2}$; where F_x and F_y are the dynamometer readings

Flank wear (VB) is observed from image processing.

Table 5: Result table of Al6063+4% ZnO

Trial No.	v (rpm)	f (mm/rev)	d (mm)	r (°)	MRR (gm/min)	RF (kgf)	Flank Wear VB (mm)
1	150	0.21	0.2	15	2.263	8.276	0.16
2	445	0.21	0.2	15	6.897	14.77	0.14
3	150	0.421	0.2	15	6.579	27.07	0.13
4	445	0.421	0.2	15	4.461	38.58	0.16
5	150	0.21	0.5	15	3.942	27.65	0.18
6	445	0.21	0.5	15	5.636	8.32	0.16
7	150	0.421	0.5	15	2.826	22.42	0.12
8	445	0.421	0.5	15	7.07	44	0.12
9	150	0.21	0.2	20	2.315	35	0.15
10	445	0.21	0.2	20	4.127	6.80	0.12
11	150	0.421	0.2	20	6.004	16.8	0.12
12	445	0.421	0.2	20	11.269	16.8	0.13
13	150	0.21	0.5	20	2.721	33.05	0.15
14	445	0.21	0.5	20	7.169	20.21	0.15
15	150	0.421	0.5	20	5.413	35.02	0.11
16	445	0.421	0.5	20	6.509	8.20	0.13

Table 6: Result table of Al6063+12% ZnO

Trial No.	v (rpm)	f (mm/rev)	d (mm)	r (°)	MRR (gm/min)	RF (kgf)	Flank Wear

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							VB (mm)
1	150	0.21	0.2	15	2.056	21.77	0.14
2	445	0.21	0.2	15	6.69	23.85	0.16
3	150	0.421	0.2	15	3.236	8.77	0.13
4	445	0.421	0.2	15	2.590	23.25	0.16
5	150	0.21	0.5	15	3.684	25.44	0.17
6	445	0.21	0.5	15	11.929	12.80	0.12
7	150	0.421	0.5	15	2.336	33.62	0.13
8	445	0.421	0.5	15	2.631	30.24	0.12
9	150	0.21	0.2	20	2.449	17.22	0.14
10	445	0.21	0.2	20	2.321	14.22	0.10
11	150	0.421	0.2	20	6.454	23.38	0.15
12	445	0.421	0.2	20	5.027	13.43	0.12
13	150	0.21	0.5	20	2.246	5.40	0.12
14	445	0.21	0.5	20	6.072	14.71	0.15
15	150	0.421	0.5	20	7.042	7.10	0.12
16	445	0.421	0.5	20	2.833	21.80	0.13

5.1 Development of Mathematical model for Al6063+4%ZnO

Full Factorial Design of Al6063+4% ZnO

Factors: 4 Base Design: 4, 16
Runs: 16 Replicates: 1
Blocks: 1 Center pts (total): 0

Regression Equations for MRR

MRR = -71.84 + 0.3445 v + 271.2 f + 211.0 d + 3.678 r - 1.217 v*f - 0.8703 v*d - 0.01856 v*r - 758.9 f*d - 13.49 f*r - 11.12 d*r + 3.086 v*f*d + 0.06729 v*f*r + 0.04883 v*d*r + 39.89 f*d*r - 0.1725 v*f*d*r

Regression Equations for RF

RF = -591.2 + 1.538 v + 1699 f + 1506 d + 35.35 r - 3.930 v*f - 4.726 v*d - 0.09290 v*r - 4644 f*d - 99.25 f*r - 83.84 d*r + 14.47 v*f*d + 0.2417 v*f*r + 0.2687 v*d*r + 265.1 f*d*r - 0.8362 v*f*d*r

5.2 Development of Mathematical model for Al6063+12%ZnO

Full Factorial Design of Al6063+12%ZnO

Regression Equation for MRR

MRR = -25.57 + 0.1378 v + 61.69 f + 76.85 d + 1.386 r - 0.3787 v*f - 0.07798 v*d - 0.007899 v*r - 273.8 f*d - 2.645 f*r - 4.911 d*r + 0.5102 v*f*d + 0.02150 v*f*r + 0.009920 v*d*r + 17.02 f*d*r - 0.04355 v*f*d*r

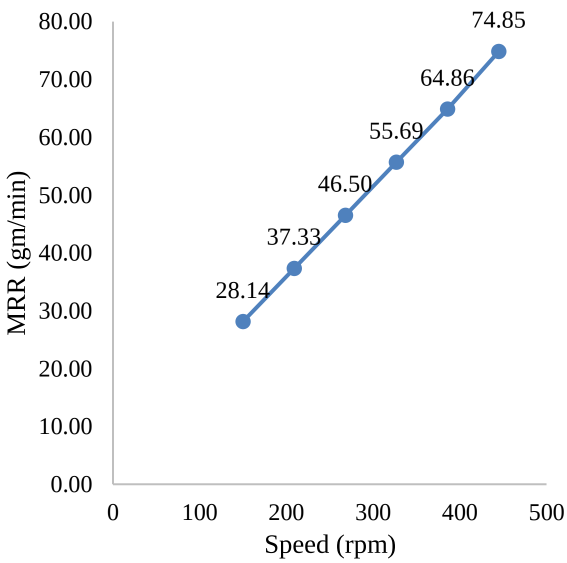
Regression Equations for RF

RF = 148.3 - 0.07396 v - 893.4 f - 79.56 d - 6.715 r + 1.663 v*f - 0.5250 v*d + 0.004359 v*r + 1948 f*d + 48.66 f*r + 2.746 d*r - 2.655 v*f*d -0.09533 v*f*r + 0.02627 v*d*r - 105.9 f*d*r + 0.1658 v*f*d*r

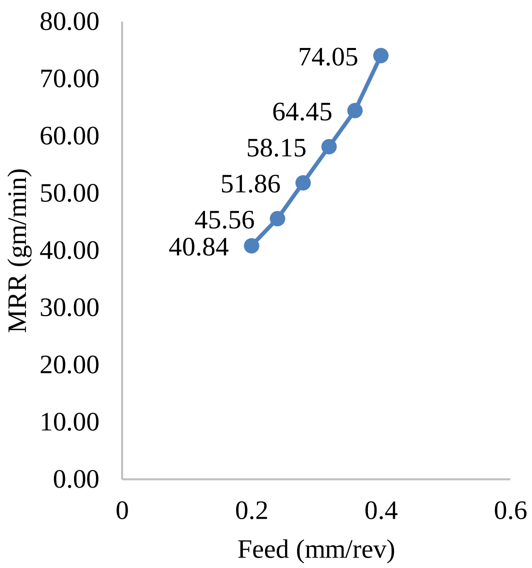
6. GRAPHICAL REPRESENTATION

Graphs for Al6063+4%ZnO

Graph 1: Speed Vs MRR

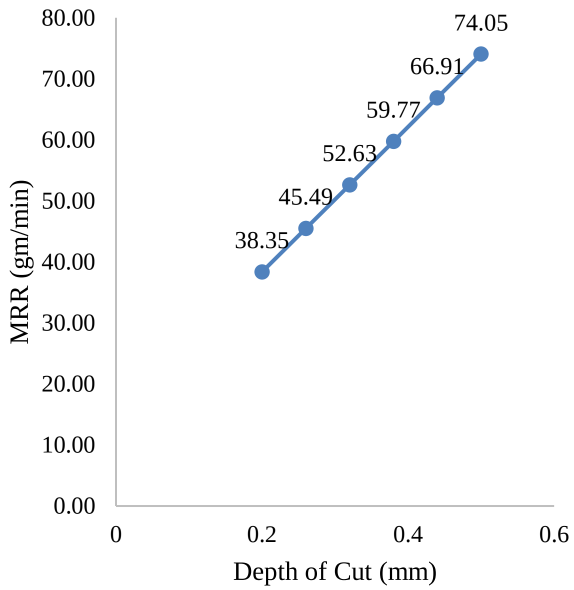


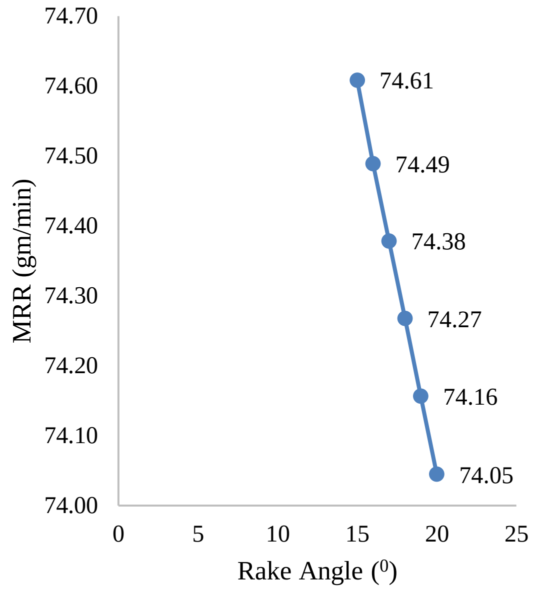
Graph 2: Feed Vs MRR



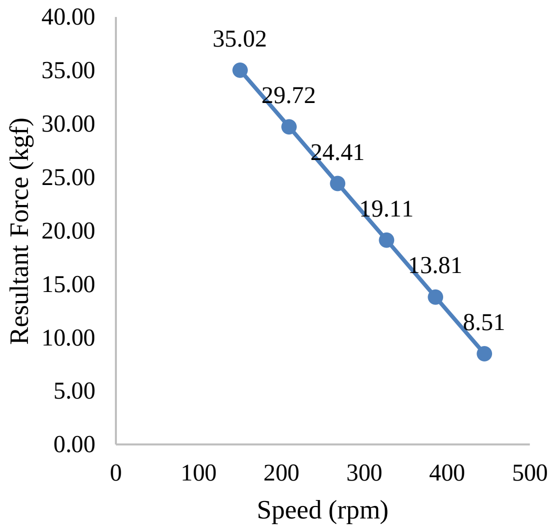
Graph 3: Depth of Cut Vs MRR

Graph 4: Rake Angle Vs MRR

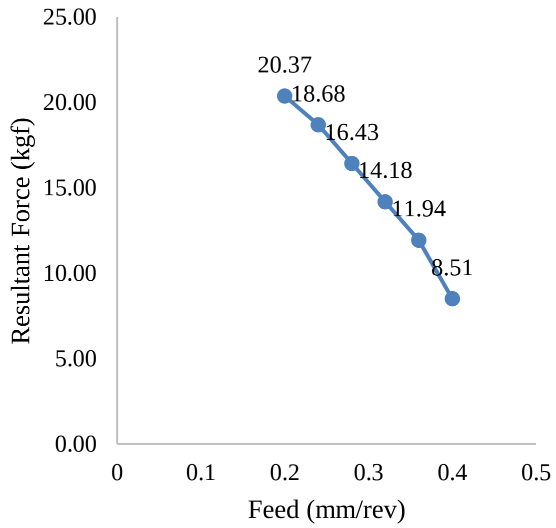




Graph 5: Speed Vs Resultant Force



Graph 6: Feed Vs Resultant Force



Graph 7: Depth of Cut Vs Resultant Force

Graph 8: Rake Angle Vs Resultant Force

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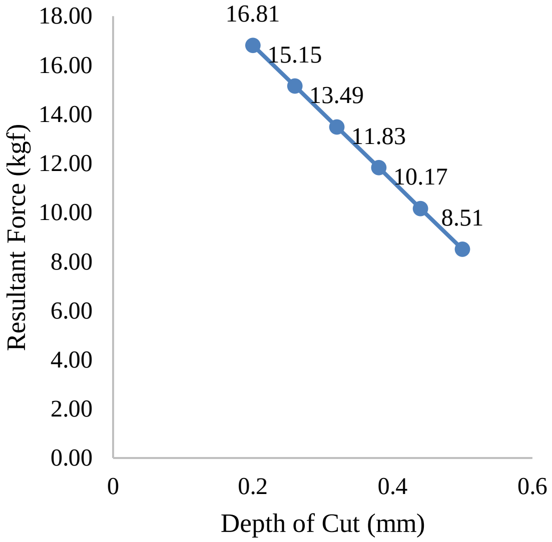
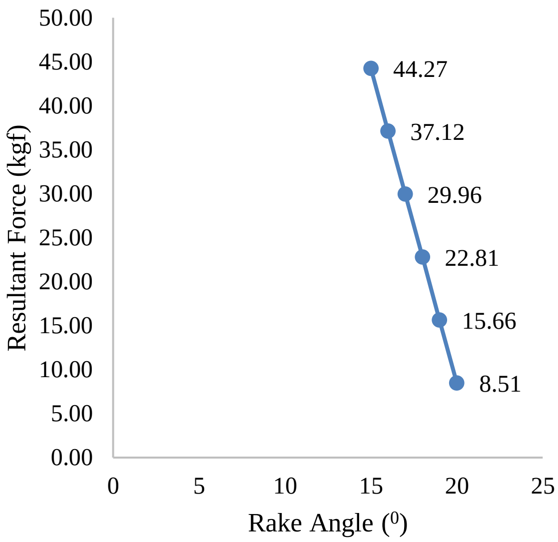
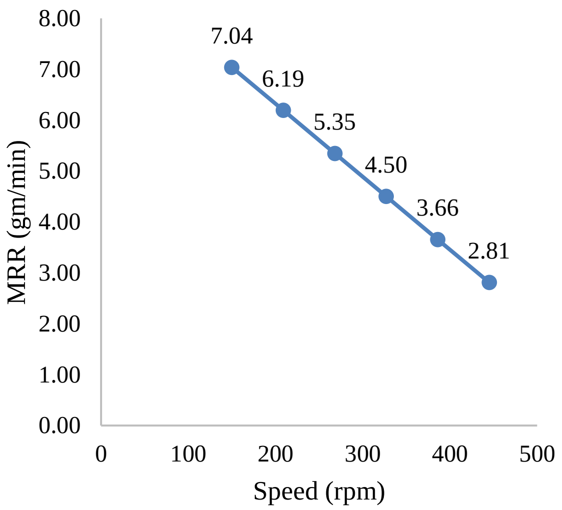
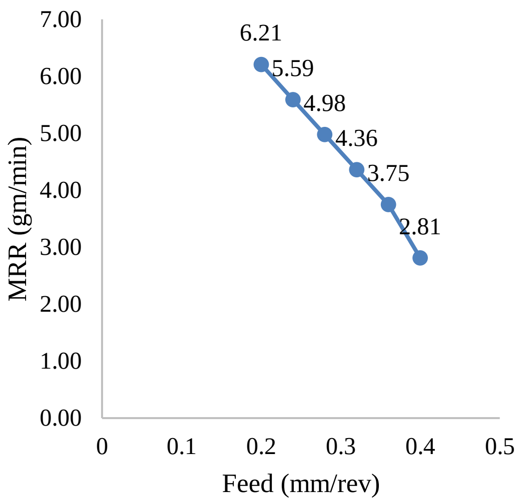




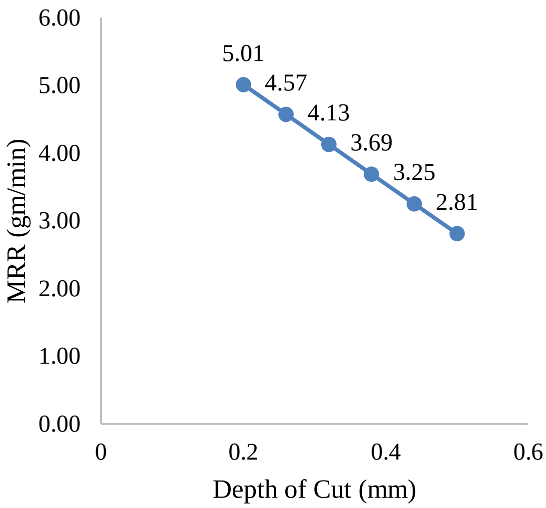
Graphs for Al6063+12%ZnO

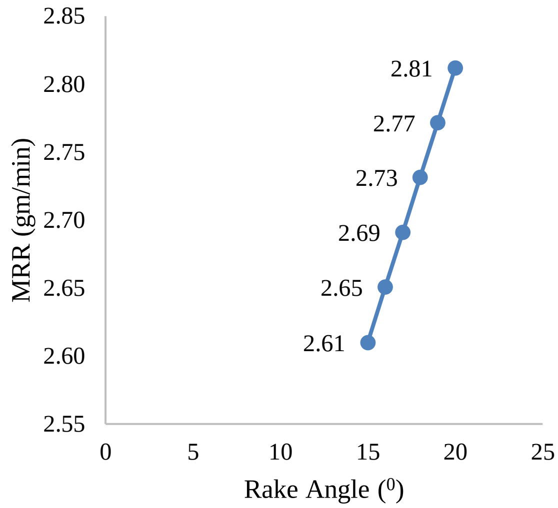
Graph 9: Speed Vs MRR **Graph 10: Feed Vs MRR**





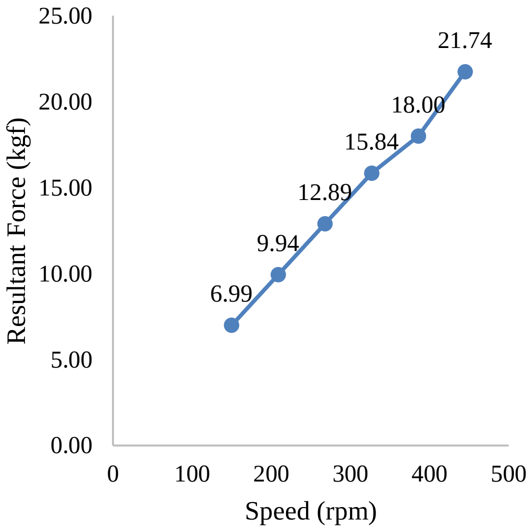
Graph 11: Depth of Cut Vs MRR **Graph 12: Rake Angle Vs MRR**

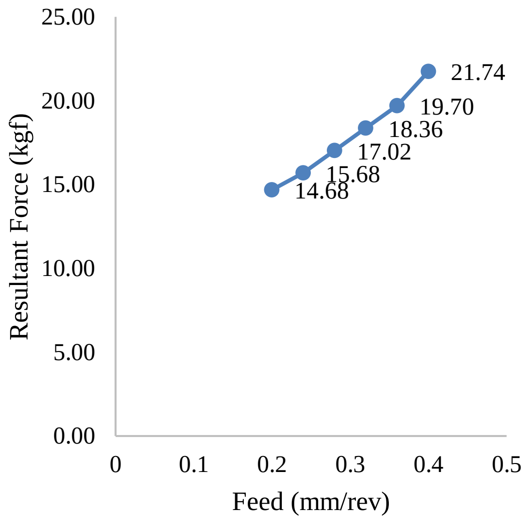




Graph 13: Speed Vs Resultant Force

Graph 14: Feed Vs Resultant Force





Graph 15: Depth of Cut Vs Resultant Force

Graph 16: Rake Angle Vs Resultant Force

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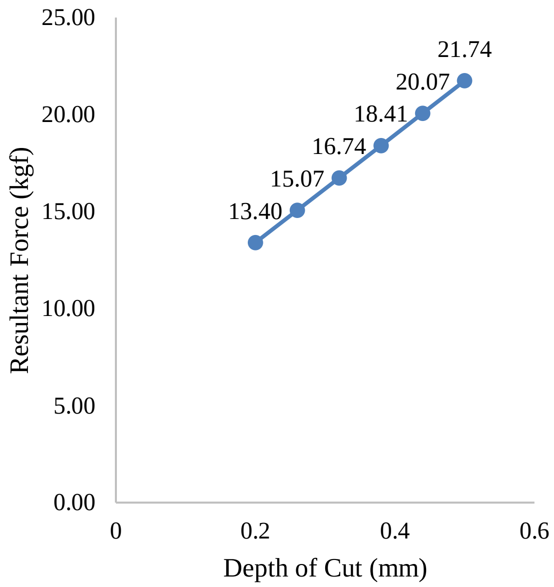

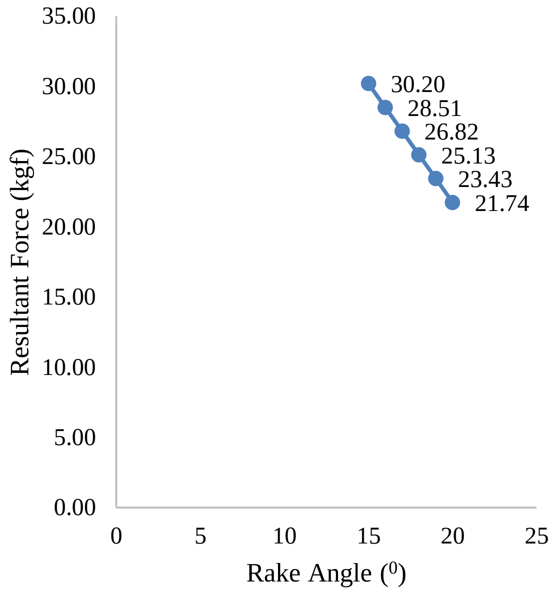

CONCLUSIONS

- From the above observations, for Al6063+4%ZnO the highest MRR observed is 11.269gm/min for trial-12, for which machining parameters are v = 445rpm, f = 0.421 mm/rev, d = 0.2 mm at rake angle 20^0 at cutting force is 16.8 kgf.
- For Al6063+12%ZnO the highest MRR observed is 11.929gm/min for trial-6, for which machining parameters are v = 445rpm, f = 0.21 mm/rev, d = 0.5 mm at rake angle 15^0 at cutting force is 12.8 kgf.
- Both models (Al6063 + 4% ZnO and Al6063 + 12% ZnO) show significant interaction effects between various factors (v,f,d,r). These interactions indicate that the combined effect of factors can influence MRR and RF beyond their individual effects.
- From the obtained VB values, it is concluded that the minimum MRR and minimum cutting force is required for the tool to be more reliable.

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