Reliability Analysis of Single Point Cutting Tool on Al6063+Zno Metal Matrix Composites

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The reliability of single point cutting tools in machining Al6063 aluminium alloy reinforced with zinc oxide (ZnO) particles is critically evaluated in this study. Al6063+ZnO metal matrix composites (MMCs) are increasingly used in high-performance applications due to their enhanced mechanical properties and wear resistance. However, the challenging nature of these materials necessitates a thorough examination of tool performance and durability. This research investigates the impact of various machining parameters—such as cutting speed, feed rate, and depth of cut—on tool wear and performance. Advanced analytical techniques, including wear measurement and statistical reliability modeling, are employed to assess tool longevity and operational stability. Results indicate that the incorporation of ZnO particles significantly affects tool wear patterns, with a notable increase in tool life under optimized cutting conditions. The study provides insights into optimizing machining parameters to improve tool reliability and efficiency when working with Al6063+ZnO MMCs. These findings offer valuable guidelines for manufacturing processes involving similar composite materials, aiming to enhance the performance and cost-effectiveness of machining operations.

Keywords: DOE, HSS single point cutting tool, Process parameters, Reliability, Resultant Force.

1. Introduction

Aluminium, silicon, and magnesium are the alloying ingredients that make up Al 6063. Its mechanical properties are good, and it might be heat treated and welded. The machinability and material characterisation of Al6063 have been the subject of numerous investigations. Tool wear can have a detrimental effect on the surface quality of produced components and need expensive rework. Examples of this wear include crater development, built-up edges, and flank and nose wear.

Many life studies by J.G. Wager et al. [1] utilizing HSS tools for low carbon steel machining reveal that tool life values follow a statistical distribution that deviates from the normal distribution by about 0.3 of a coefficient of variation. The distribution patterns of normal and accelerated exams are similar, indicating a potential wider use for accelerated exams. It is important to remember that the commonly accepted concepts of "constant" and "exponent" tool life are merely statistical mean values and cannot be used to predict the life of any specific tool used in the field. Estimates of the probabilistic tool life are proposed, and the planned direction for further work is emphasized. The study by K Hitomi et al. [2] concentrated on the tool life's dependability analysis. Moreover, based on machining parameters and tool-wear limitations, it was shown that the reliability function may be utilized to swiftly compute the reliability of cutting tools in specific time. W.S. Lin [3] conducted multiple trials to evaluate the dependability variance of the cutting tool. Along with tool life and wear distribution, the trial data yields the dependability function and tool wear distribution of cutting tools. In addition, the reliability of the cutting tools at any given moment and the tool wear limit and cutting parameters for high-speed machining (HSM) may be easily ascertained with the help of the derived reliability function. A stochastic model is presented by El Wardany et al. [4] to forecast the tool failure rate while using ceramic tools to convert hardened steel. This model is predicated on the idea that the primary causes of the toot life ending are chemical wear, progressive wear, and early failure (such as chipping and breaking). Each reason for "tool failure" is believed to have a statistical distribution. The failure rate, reliability function, and toot-life distribution are then represented by general equations. Next, an experimental verification of the assumed distributions is made. The coefficients of these equations are found using the experimental data. Researchers Konstantinos Salonitisa et al. [5] looked at how the overall manufacturing efficiency is affected by the dependability of cutting tools. It is challenging to determine a cutting tool's exact remaining life as, in most circumstances, it can be utilized for several operations with various processing conditions. Based on sophisticated approximation techniques, the current study suggests a novel approach to cutting tool dependability estimate. A widely used technique for structural reliability issues is reliability-based design/operation, which evaluates essential infrastructure performance under stochastic design parameters. The life of the cutting tools used in the machining processes has a significant impact on the components' quality. Chipping from tool damage may lead to the component being machined being trashed. As Carmen Elena Patino Rodriguez et al. [6] showed, it was expected that a normal distribution might be utilized to represent tool's life. Finding the machining technique's operations sequence will allow you to determine how long each tool will run during the procedure. An algorithm is provided to determine when the cutting tool should be replaced. The proposed method is used to evaluate a turning and drilling manufacturing process's reliability. S. Ajmal Hussain et al. conducted an experimental analysis and comparison between silicon carbide and aluminum (6063) [7]. Aluminum and its component parts are a great alternative to steel because of their low weight and resistance to corrosion, making them useful in both commercial and domestic contexts. Steel is a well-known commodity that is used extensively in industries, and its price is always rising, which has an impact on manufacturing costs for both the home and automotive sectors. Because of this, it is imperative to swap out steel with a material that maintains the right weight ratio while being extremely robust and lightweight. Al6063 is therefore utilized in this situation due to its strong tensile properties, good toughness, medium strength, moderate ductility, and resistance to corrosion. Siva Bhaskar et al.'s [8] approach for calculating the optimal time for replacement of tool is based on the tool performance determined by the dependability function. Oussama Zerti et al. [9] provided a method for determining the optimal machining parameters that yield a minimum of 23 surface roughness using the Taguchi approach. The mechanical properties of the heat-treated 6063 aluminum alloy were examined by researchers Montasser S. Tahat et al. [10]. Aluminum alloy is appropriate for a variety of industrial applications due to its stable mechanical properties and structural integrity. In addition to summarizing current patents, the study focused on the mechanical properties of the alloy in question following age hardening treatment. Abdalla Hassan Mihdy Jassim, et al. [11] looked into the effects of heat treatments on the aluminum alloy 6063's tensile behavior and toughness. After two hours of homogenization at 560°C, the alloy samples underwent a one-hour solution heat treatment at 500, 530, and 560°C, and then they were quickly quenched in room-temperature water. The yield stress and tensile strength maximum values are 288.6 and 264.5 MPa, respectively. U. Lakshminarayana, et al. [12] used the dependability function to calculate a tool's performance in order to identify when it should be replaced. The results of the study by Nithin M. Mali et al. [13] include shorter cycle times, adaptable procedures, compatible surface roughness, higher rates of material removal, and less environmental issues because cutting fluid is not required. However, it significantly increased tool wear and changed the quality and performance of the product due to the increased mechanical stress and heat generation. Additionally, utilizing a CNC machine for dry machining, an examination and comparison of the performance of uncoated and multilayer coated (Al2O3+TiC+TiNAlCrN) ceramic tools have been carried out. A model for estimating tool wear and an experimental study on cutting tool wear were published by Vishal S. Sharma et al. [14]. We recode and analyze the variations in cutting force, vibration, and acoustic emission values with cutting tool wear. Adaptive Neuro fuzzy Inference system (ANFIS) is used to construct a model for tool wear estimation in turning operations based on experimental data. The model has been developed using acoustic emission (Ring down count), vibrations (acceleration), and cutting forces in conjunction with time. The cutting tool's wear rate can be estimated by this model. The model's wear estimation findings are compared with the actual outcomes and displayed. When comparing the actual and anticipated tool wear values, the model produced results that were quite excellent. The model can also be used to estimate tool wear online, although its accuracy is dependent on appropriate training and data point selection. The addition of WC and group IV carbides to Ti(C,N)–was examined by Kwon et al. in [15].Ni Cermet alters the microstructure, which modifies the material's properties.

2. EXPERIMENTATION

2.1 Work material preparation

- To Prepare the work material Al 6063+ZnO by using Die-casting process
- To find out the Flank wear of selected Tools
- To perform reliability analysis on selected Tools

The dimensions of the work piece after machining are 140 mm length and 22 mm diameter.

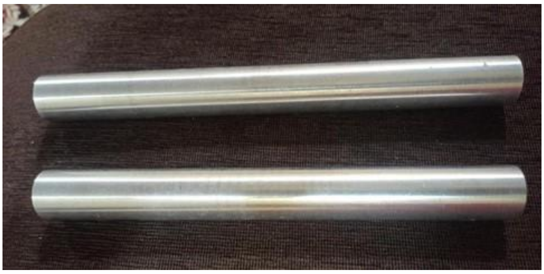


Figure 1. Workpiece after machining

2.2Optimum composition of Al6063

Al6063 material of the following composition were used based on strength criteria, and the same material is used for this experimentation. This is the optimum composition of Al6063 alloy having highest tensile strength to which ZnO in varying percentages i.e., 4% and 12% is reinforced and prepare.

Table 1: Weight percentage of metals in Al6063

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

All the machining parameters considered and the levels of each parameter are represented in table 2 along with the units considered.

Table 2: Input parameters with test levels

Factors	Units	Designation		Test levels	
		Actual form	Coded form	Low	High
Cutting speed	rpm	v	X_1	150	445
Feed	mm/rev	f	X_2	0.21	0.421
Depth of cut	mm	d	X_3	0.2	0.5
Rake angle	degrees (°)	r	X_4	15	20

2.3Selection of tool material

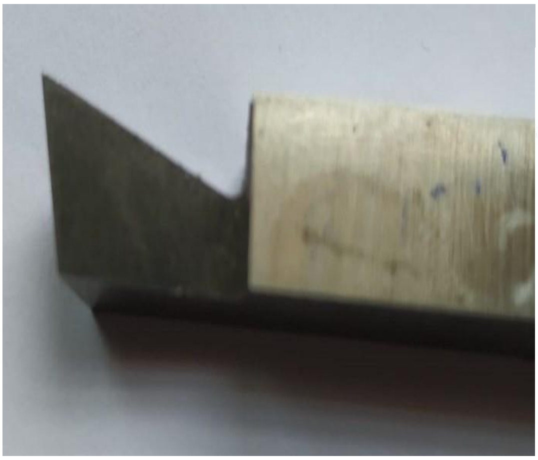
Tool material used is HSS tool (High Speed Steel) for the machining purpose.

Table 3: Chemical composition of Miranda HSS ZEDD Tool

Tool Grade	Material Grade	Approximate % of metals					
		C	Cr	Mo	W	Co	V
ZEDD	M2	0.9	4.1	5.0	6.4	-	1.8

❖ Tool Angles for HSS tool on Al6063+ZnO

➢ Back Rake angle - 20°, 15°, Side Rake angle - 15°, End Relief angle - 12°, Side Relief angle - 10°, Side Cutting Edge angle - 5°, End Cutting Edge angle - 5°



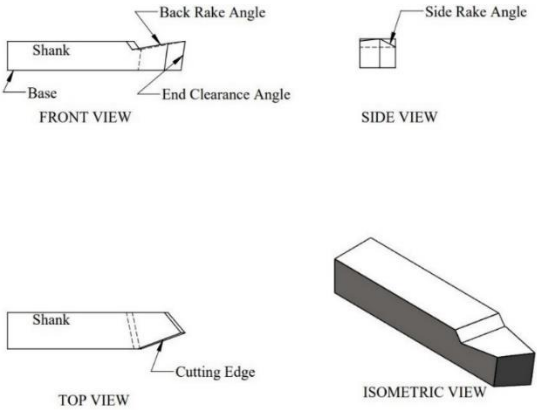


Figure 2: HSS tool after grinding

Figure 3: Tool Angles

2.4 Design of Experiments (DOE):

To solve the problem with the necessary precision, as indicated in Table 4, the DOE involves choosing the appropriate number of trials and conditions under which to conduct them.

No. of Trials (2 levels 4 factors) = 2^4 = 16 for each set of metal matrix composite

Among the below mentioned 32 trials, 1 to 16 trials represent set of Al6063+4%ZnO and 17 to 32 trials represent set of Al6063+12%ZnO

Table 4: Experiment table

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
17	150	0.21	0.2	15
18	445	0.21	0.2	15
19	150	0.421	0.2	15
20	445	0.421	0.2	15
21	150	0.21	0.5	15
22	445	0.21	0.5	15

23	150	0.421	0.5	15
24	445	0.421	0.5	15
25	150	0.21	0.2	20
26	445	0.21	0.2	20
27	150	0.421	0.2	20
28	445	0.421	0.2	20
29	150	0.21	0.5	20
30	445	0.21	0.5	20
31	150	0.421	0.5	20
32	445	0.421	0.5	20

3. OBSERVATION OF FLANK WEAR (VB)

For all the 32 trials flank wear is observed after each trial and are shown below in Figures 4 to 35

- For Al6063+ 4% ZnO

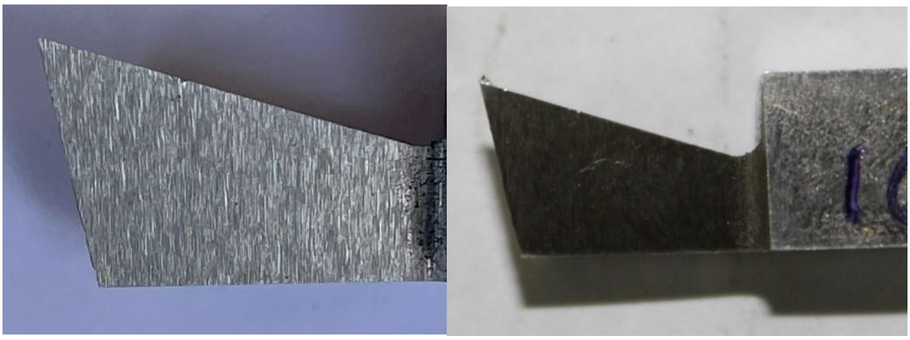


Figure 4: Tool-1 geometry before and after experiment

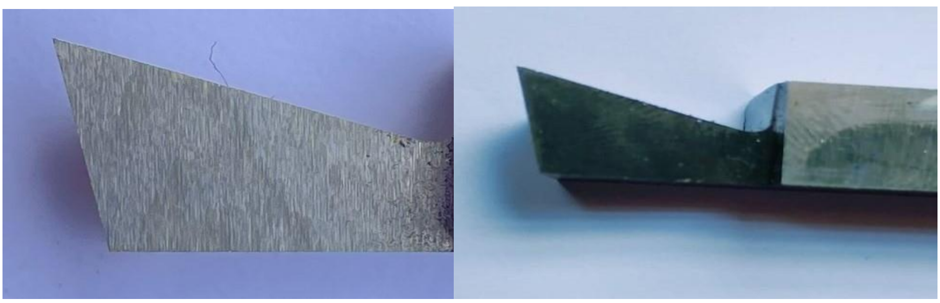


Figure 5: Tool-2 geometry before and after experiment

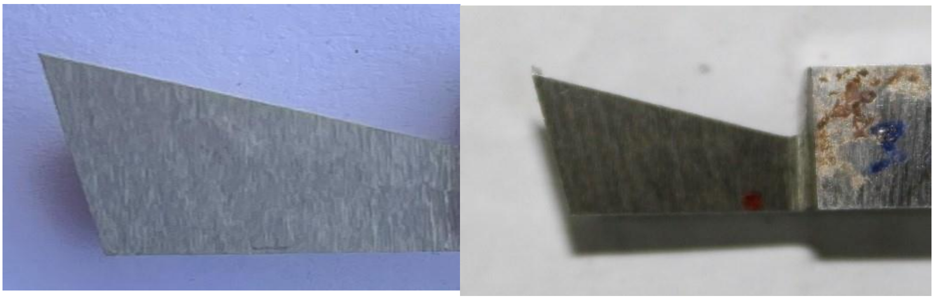


Figure 6: Tool-3 geometry before and after experiment

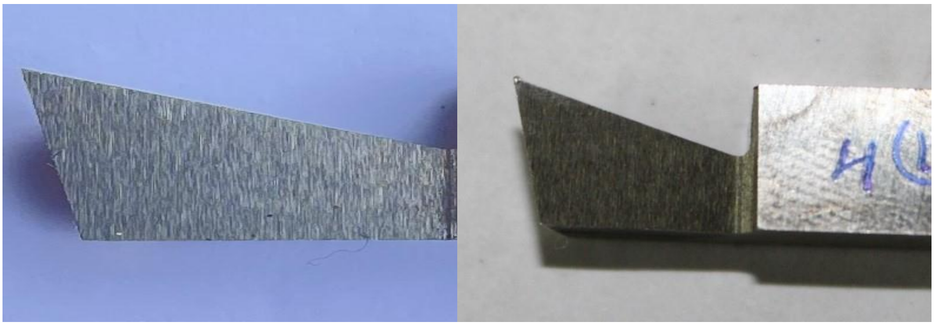


Figure 7: Tool-4 geometry before and after experiment

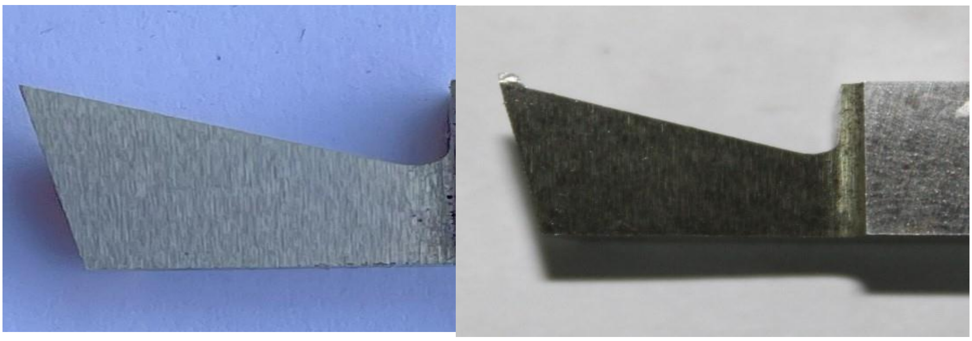


Figure 8: Tool-5 geometry before and after experiment

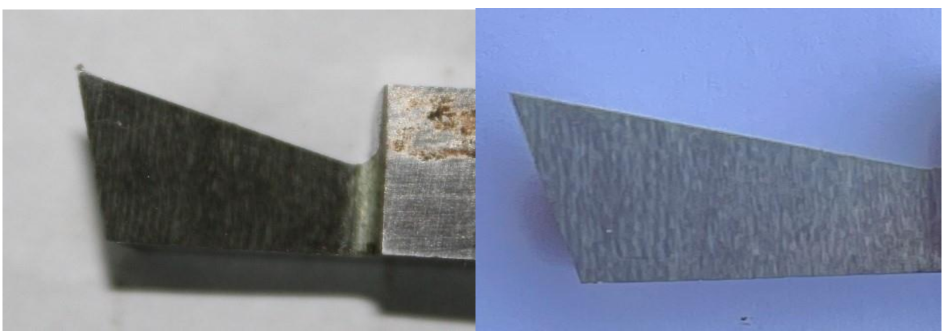


Figure 9: Tool-6 geometry before and after experiment

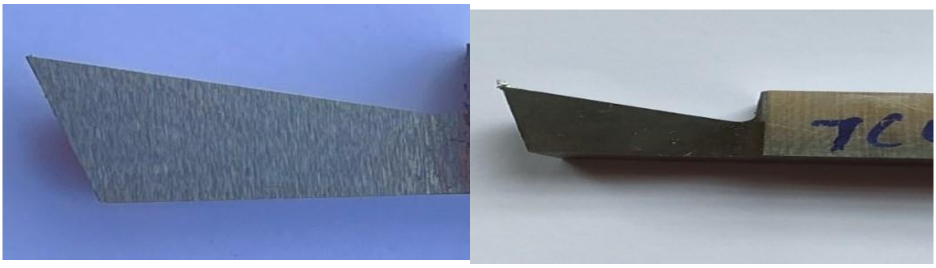


Figure 10: Tool-7 geometry before and after experiment

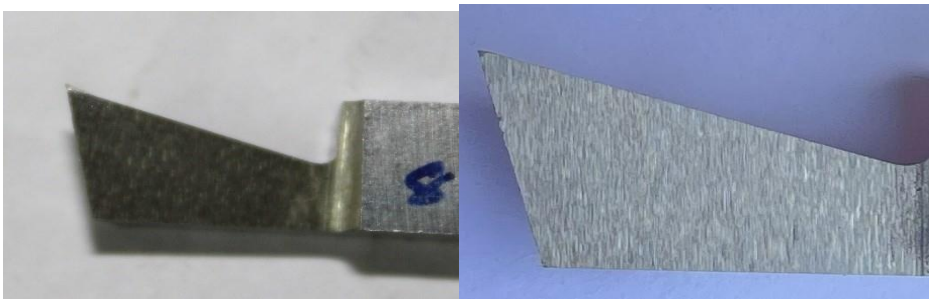


Figure 11: Tool-8 geometry before and after experiment

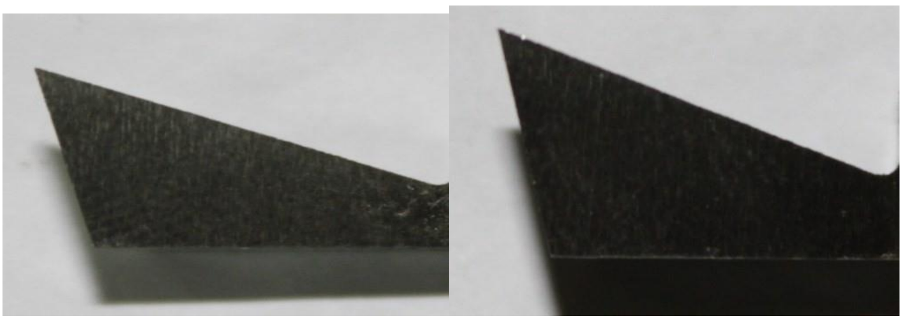


Figure 12: Tool-9 geometry before and after experiment

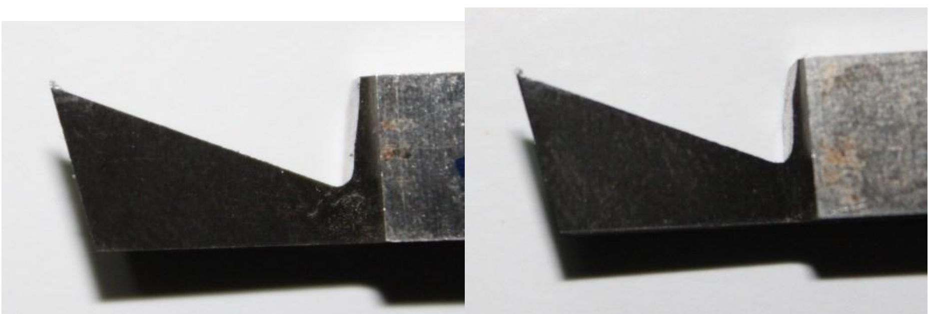


Figure 13: Tool-10 geometry before and after Experiment

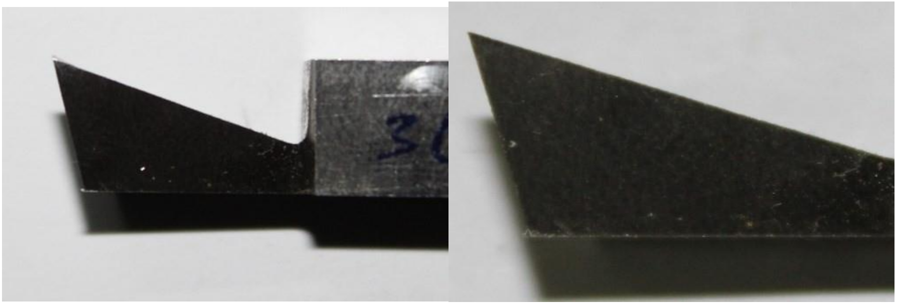


Figure 14: Tool-11 geometry before and after experiment

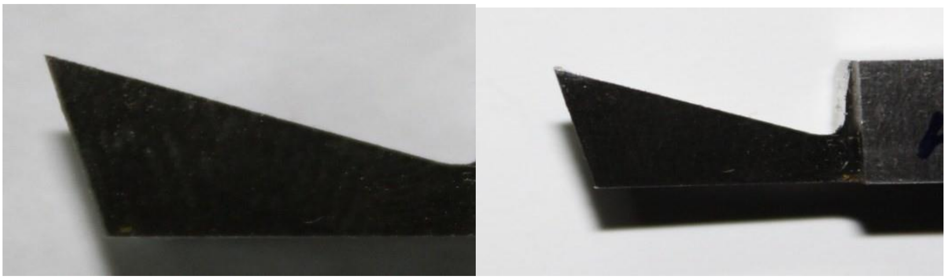


Figure 15: Tool-12 geometry before and after experiment

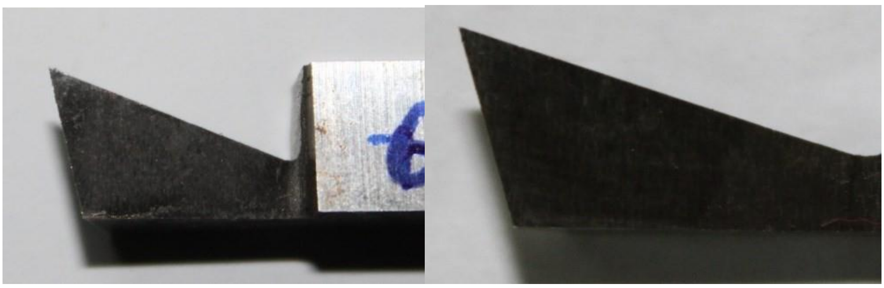


Figure 16: Tool-13 geometry before and after experiment

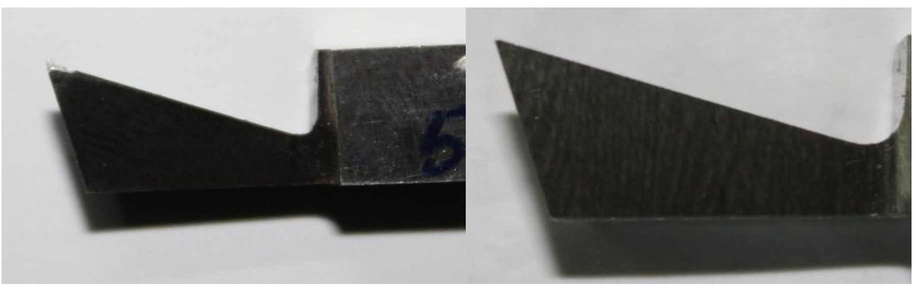


Figure 17: Tool-14 geometry before and after experiment

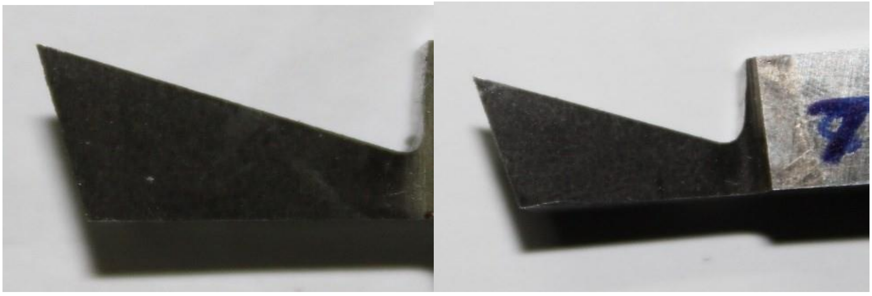


Figure 18: Tool-15 geometry before and after experiment

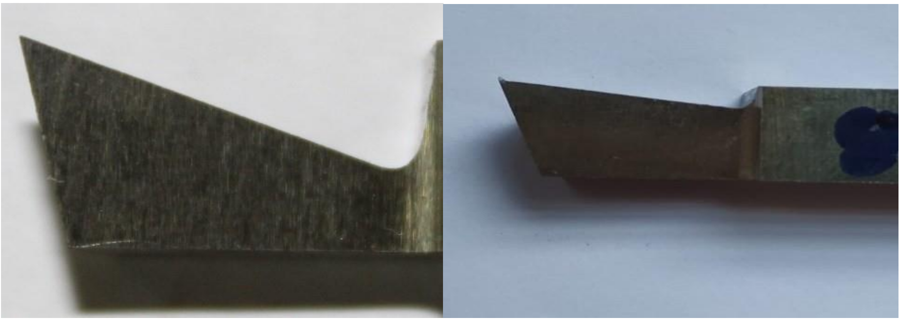


Figure 19: Tool-16 geometry before and after experiment

- ❖ For Al6063+ 12% ZnO

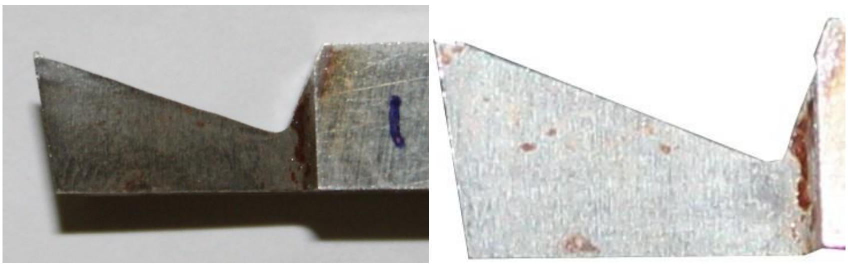


Figure 20: Tool-17 geometry before and after experiment

Figure 21: Tool-18 geometry before and after experiment

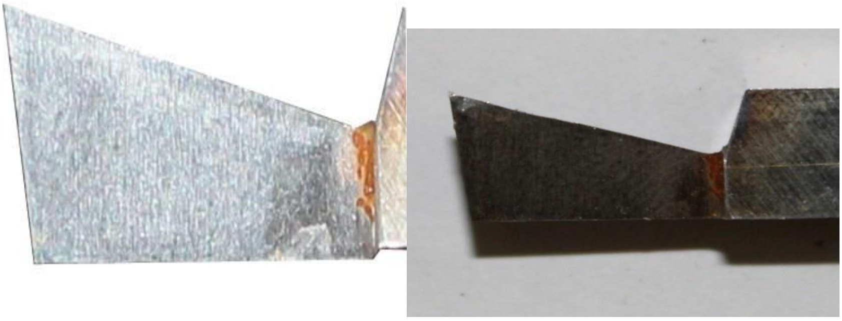


Figure 22: Tool-19 geometry before and after experiment

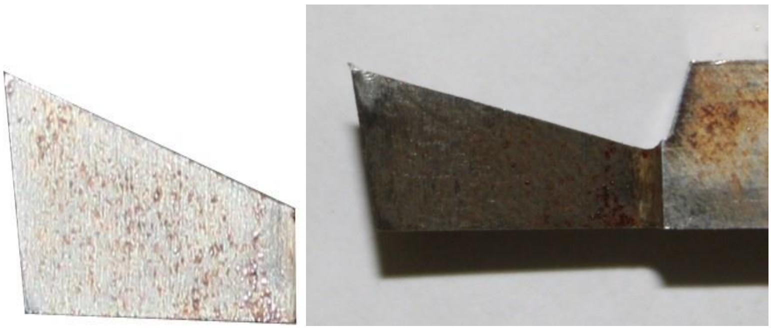


Figure 23: Tool-20 geometry before and after experiment

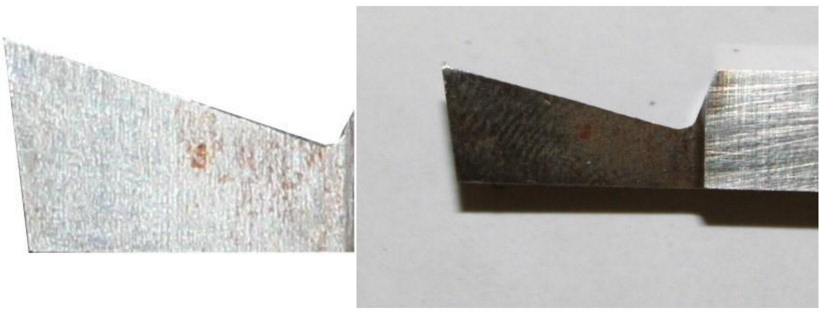


Figure 24: Tool-21 geometry before and after experiment

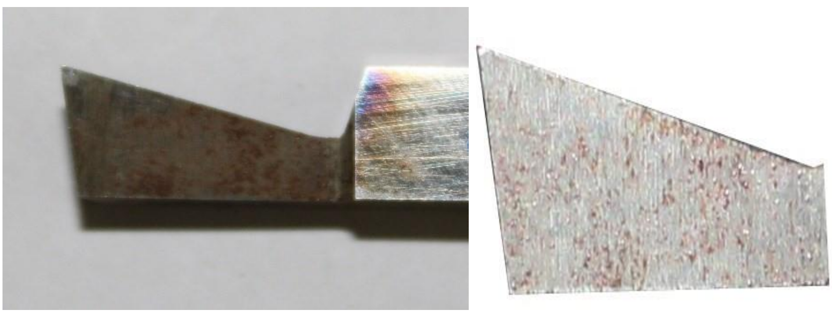


Figure 25: Tool-22 geometry before and after experiment

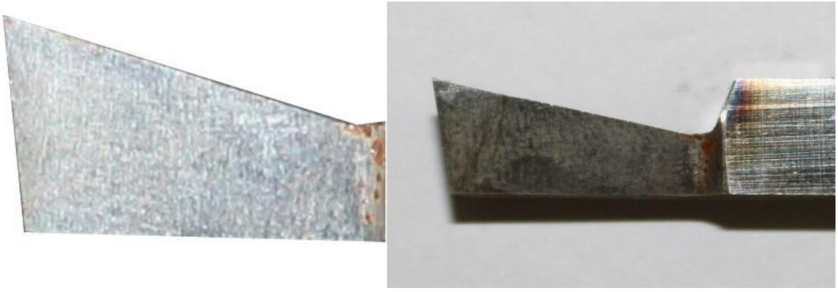


Figure 26: Tool-23 geometry before and after experiment

Figure 27: Tool-24 geometry before and after experiment

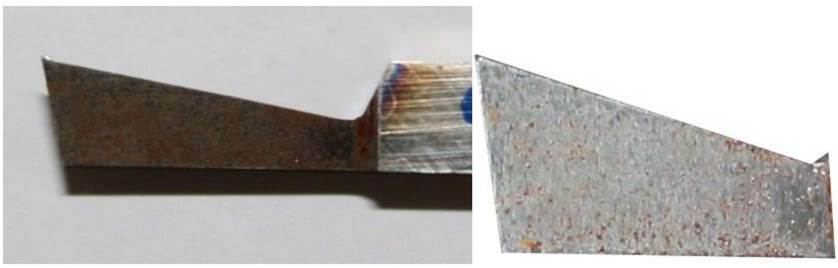


Figure 28: Tool-25 geometry before and after experiment

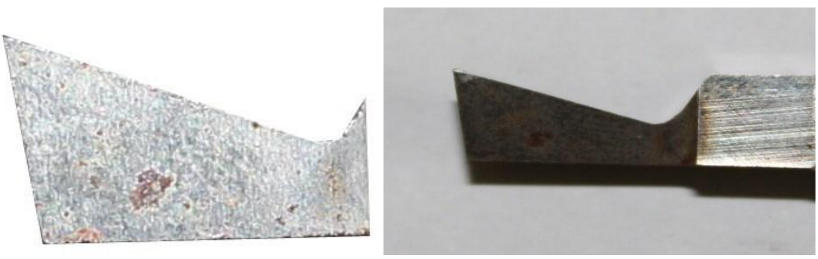


Figure 29: Tool-26 geometry before and after experiment

Figure 30: Tool-27 geometry before and after experiment

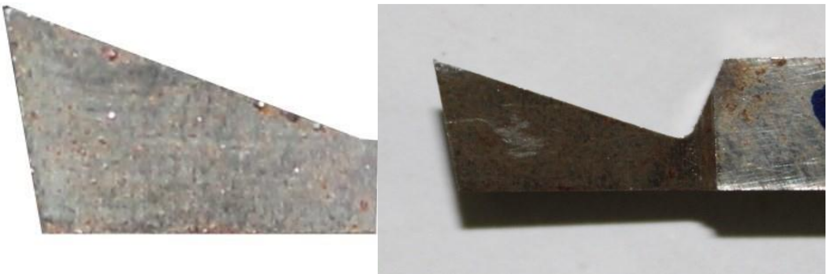


Figure 31: Tool-28 geometry before and after experiment

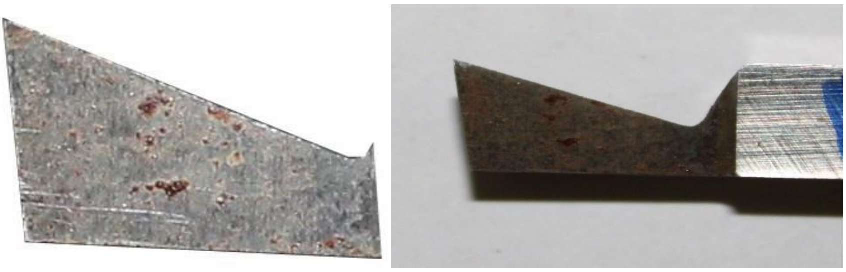


Figure 32: Tool-29 geometry before and after experiment

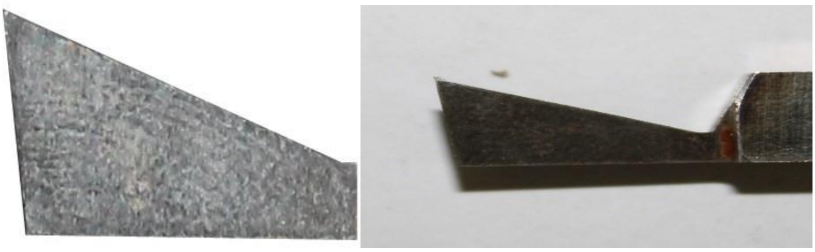


Figure 33: Tool-30 geometry before and after experiment

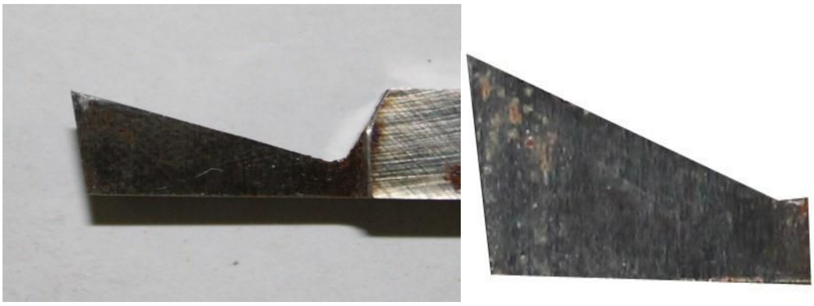


Figure 34: Tool-31 geometry before and after experiment

Figure 35: Tool-32 geometry before and after experiment

Flank wear detection using MATLAB is shown in below Figure 36.

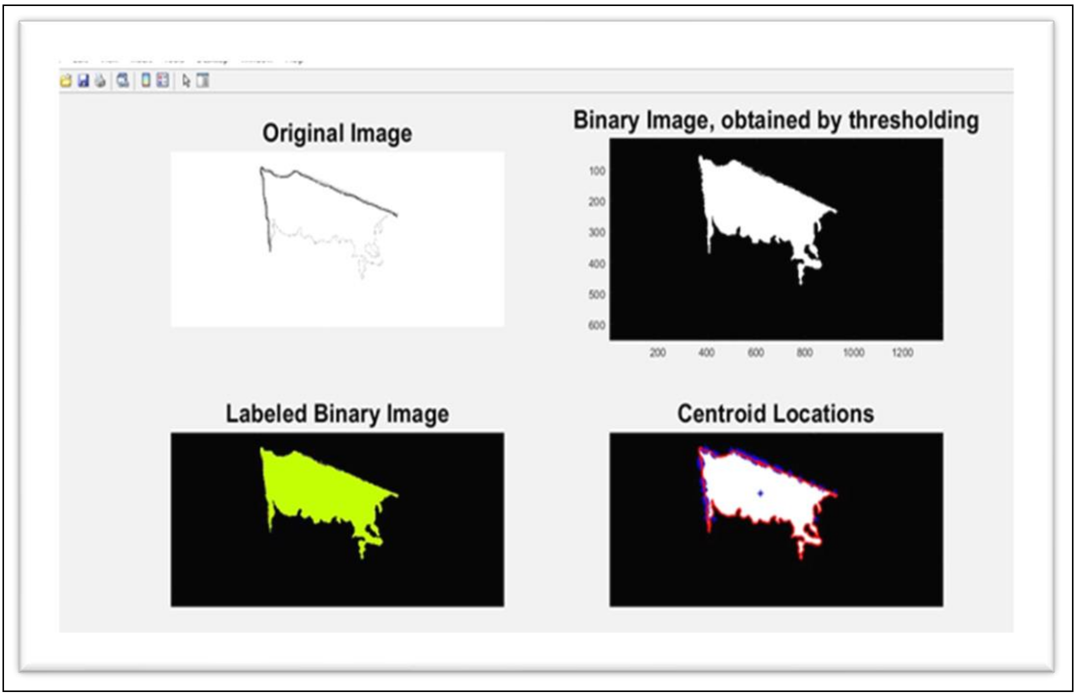


Figure 36: Flank Wear detection in MATLAB

3.2Calculation of Reliability

The tool life model assumes that flank wear follows a normal distribution.

Based on the extrapolation of Wager and Barash [1971], Hitomi et al. [1979], and W.S. Lin [2008], the flank wear distribution's probability density function (f(VB)) can be expressed by the following formula:

$$\boldsymbol{f(VB) = \frac{1}{[\sqrt{2\Pi}]\sigma} exp\left(-\frac{(VB - \mu)^2}{2\sigma^2}\right)} \quad (1)$$

If the average VB is the function of (f), (d), (v) and (r) then,

VB = Ø (v, f, d, r)

μ = E[VB] = E [Ø (v, f, d, r)]

σ = Var [VB] = E [(VB - μ)^2]

There is an exponential relationship between VB and cutting parameters, thus the flank wear is expressed by

VB = C v^{b1} f^{b2} d^{b3} r^{b4}

where C, b1, b2, b3 are constants which can be obtained from experimentation. Now, the probability function of flank wear is given by,

$$\boldsymbol{f(VB) = \frac{1}{[\sqrt{2\Pi}]\sigma} exp\left(-\frac{\left(VB - C\, v^{b1}\, f^{b2}\, d^{b3} r^{b4}\right)^2}{2\sigma^2}\right)} \quad (2)$$

Damage probability of turning tool occurred before time t:

$$P\ (\tau < t) = \left[\int_0^t f(\tau)d\tau\right] \quad (3)$$

If the flank wear when the tool life end is VB*, then, the probability of flank wear reach life limit at time t is:

$$P\ (VB \geq VB^*) = 1-\left[\int_0^{VB*} f(VB)dVB\right] \quad (4)$$

Then,

$$\left[\int_0^t f(\tau)d\tau\right] = \left[\int_0^{VB*} f(VB)dVB\right] \quad (5)$$

On substituting f(VB), into equation (5), rearranging and differentiating with respect to t, probability density function of tool life f(t) is

$$\boldsymbol{f(t) = \frac{1}{[\sqrt{2\Pi}]\sigma} exp[-\left(\frac{Tv - t}{\sqrt{2}\sigma}\right)^2]}$$

The time Tv is reached when the average value of flank wear reaches VB*. The following equation can be used to get the reliability function R(t).

R(t) = 1 – P (τ < t)

$$= 1- \int_{-\infty}^{t} \frac{1}{[\sqrt{2\Pi}]\sigma} exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]dx$$

However, there is no closed form of solution to this integral, then the transformation Z is given by,

$$Z = \frac{Tv - \mu}{\sigma}$$

As a result, the general cutting tool reliability equation based on the failure event is provided by,

$$R(t) = 1 - Ø\left[\frac{Tv-\mu}{\sigma}\right]$$

Thus, R(t) = 1- Ø(Z)

Where Ø(Z) is the probability of failure of the tool, Hence, R(t) =1-P(t)

Value of Z is chosen from normal distribution table.

From the experimental investigation, the following table 5 has been developed.

Table 5: Dynamometer readings

Trial No.	F_X	F_Y	F_Z	F_R (kgf)
1	0	7.5	3.5	8.276
2	0	6	13.5	14.77
3	3	20	18	27.07
4	3	34	18	38.58
5	5.5	16.5	21.5	27.65
6	0	4.5	7	8.32
7	4.5	14.5	16.5	22.42
8	11.5	31.5	28.5	44
9	10	33	6	35
10	0	4	5.5	6.80
11	3	15	7	16.8
12	3	15	7	16.8
13	14.5	21.5	20.5	33.05
14	3.5	9.5	17.5	20.21
15	8.5	28.5	18.5	35.02
16	0	5	6.5	8.20
17	8	11	17	21.77
18	8	12	19	23.85
19	4	5	6	8.77
20	6	12	19	23.25.
21	8	11	21.5	25.44
22	6	8	8	12.80
23	10.5	24.5	20.5	33.62
24	7.5	17.5	23.5	30.24
25	8.5	13.5	6.5	17.22
26	5	11	7.5	14.22
27	6.5	21.5	6.5	23.38
28	0	9.5	9.5	13.43

29	0	3	4.5	5.40
30	4	10.5	9.5	14.71
31	0	5.5	4.5	7.10
32	0	13	17.5	21.80

Table 6: Result table

Trial No.	v (rpm)	f (mm/rev)	d (mm)	r (°)	Machining time t (min)	Flank Wear VB (mm)	Resultant Force F_R (kgf)
1	150	0.21	0.2	15	13.7	0.16	8.276
2	445	0.21	0.2	15	4.68	0.14	14.77
3	150	0.421	0.2	15	8.07	0.13	27.07
4	445	0.421	0.2	15	1.17	0.16	38.58
5	150	0.21	0.5	15	29.08	0.18	27.65
6	445	0.21	0.5	15	8.62	0.16	8.32
7	150	0.421	0.5	15	13.18	0.12	22.42
8	445	0.421	0.5	15	4.94	0.12	44
9	150	0.21	0.2	20	14.47	0.15	35
10	445	0.21	0.2	20	9.38	0.12	6.80
11	150	0.421	0.2	20	12.42	0.12	16.8
12	445	0.421	0.2	20	4.39	0.13	16.8
13	150	0.21	0.5	20	28.06	0.15	33.05
14	445	0.21	0.5	20	9.75	0.15	20.21
15	150	0.421	0.5	20	13.50	0.11	35.02
16	445	0.421	0.5	20	4.60	0.13	8.20
17	150	0.21	0.2	15	28.82	0.14	21.77
18	445	0.21	0.2	15	10.61	0.16	23.85
19	150	0.421	0.2	15	14.71	0.13	8.77
20	445	0.421	0.2	15	4.43	0.16	23.25.
21	150	0.21	0.5	15	28.58	0.17	25.44
22	445	0.21	0.5	15	9.32	0.12	12.80
23	150	0.421	0.5	15	13.75	0.13	33.62
24	445	0.421	0.5	15	5.70	0.12	30.24
25	150	0.21	0.2	20	28.07	0.14	17.22
26	445	0.21	0.2	20	11.42	0.10	14.22
27	150	0.421	0.2	20	15.10	0.15	23.38
28	445	0.421	0.2	20	5.49	0.12	13.43
29	150	0.21	0.5	20	27.53	0.12	5.40
30	445	0.21	0.5	20	9.11	0.15	14.71
31	150	0.421	0.5	20	12.63	0.12	7.10
32	445	0.421	0.5	20	5.09	0.13	21.80

- Mean of flank wear (μ) = 0.137
- Standard deviation of flank wear (σ) = 0.02

Table 7: Calculation of normal variate(Z)

Trial No	Flank wear VB (mm)	Machining time t(min)	T_V	Z
1	0.16	13.7	7.94	0.79
2	0.14	4.68	3.97	0.39
3	0.13	8.07	3	0.29
4	0.16	1.17	0.17	0.003
5	0.18	29.08	5.81	0.57
6	0.16	8.62	7.32	0.73

7	0.12	13.18	4.08	0.40
8	0.12	4.94	1.13	0.10
9	0.15	14.47	0.14	6.36
10	0.12	9.38	2.34	0.22
11	0.12	12.42	1.49	0.13
12	0.13	4.39	4.39	0.43
13	0.15	28.06	5.61	0.55
14	0.15	9.75	5.75	0.57
15	0.11	13.50	4.45	0.43
16	0.13	4.60	1.05	0.09
17	0.14	28.82	15.82	8.04
18	0.16	10.61	9.01	4.55
19	0.13	14.71	5.58	2.79
20	0.16	4.43	0.66	0.26
21	0.17	28.58	5.71	2.85
22	0.12	9.32	7.92	3.99
23	0.13	13.75	4.26	2.11
24	0.12	5.70	1.31	0.60
25	0.14	28.07	0.28	0.07
26	0.10	11.42	2.85	1.39
27	0.15	15.10	1.81	0.85
28	0.12	5.49	5.49	2.74
29	0.12	27.53	5.50	2.75
30	0.15	9.11	5.37	2.68
31	0.12	12.63	4.16	2.06
32	0.13	5.09	1.17	0.53

Table 8: Calculation of Reliability

Trial No.	Normal Variate (Z)	Probability of failure (%)	Reliability (%)
1	0.79	78.5	21.5
2	0.39	65.1	34.9
3	0.29	61.4	38.6
4	0.003	30.1	69.9
5	0.57	71.5	28.5
6	0.73	76.4	23.6
7	0.40	65.5	34.5
8	0.10	53.9	46.1
9	6.36	98.2	1.8
10	0.22	58.3	41.7
11	0.13	55.1	4.9
12	0.43	66.27	33.73
13	0.55	70.88	29.12
14	0.57	71.5	28.5
15	0.43	66.64	33.36
16	0.09	53.5	46.5
17	8.04	99.18	0.82
18	4.55	98.9	0.10
19	2.79	99.7	0.3
20	0.26	60.25	39.75
21	2.85	99.7	0.3
22	3.99	99.9	0.1
23	2.11	98.21	2.79
24	0.60	74.5	25.5

25	0.07	52.49	47.21
26	1.39	91.77	8.23
27	0.85	80.23	9.77
28	2.74	99.69	0.31
29	2.75	99.70	0.30
30	2.68	99.63	0.37
31	2.06	98.06	1.97
32	0.53	70.19	29.81

4. CONCLUSIONS

From the observations, the highest reliability observed is 69.9% for trial-4 (Al6063+4%ZnO), for which machining parameters are speed = 445rpm, feed = 0.421 mm/rev, depth of cut = 0.2 mm at rake angle 15^0 and cutting force is 38.58 kgf. This conclude that the minimum MRR and minimum cutting force is required for the tool to be more reliable.

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