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Mapping the Catastrophic Wear Zone: A Threshold-Based Re-Analysis of Taguchi-Optimized HSS Tool Life in Dry Aluminum Turning

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ABSTRACT

This study re-examines experimental data from a Taguchi L9 orthogonal array (cutting speed: 34–134 m/min, feed: 0.1–0.3 mm/rev, depth of cut: 1–3 mm) to identify a threshold-based "catastrophic wear zone" for HSS tool operation in dry turning of aluminum. While conventional Taguchi optimization ranks cutting speed as the most influential factor affecting tool life (delta S/N = 16.14 vs. 6.87 for feed and 1.10 for depth), a closer inspection reveals a non-linear deterioration pattern. All three experiments conducted at 134 m/min produced the lowest tool life responses (45, 26, and 17 minutes), representing a 73.6% reduction compared to the optimal parameter combination. The S/N ratio collapses from 44.80 (at 90 m/min) to 28.66 (at 134 m/min)—a 36% deterioration in signal-to-noise performance. This threshold behavior establishes 134 m/min as a critical speed boundary beyond which tool life becomes both significantly shorter and highly inconsistent. Based on these findings, a recommended safe operating window is proposed: cutting speed ≤ 90 m/min, feed ≤ 0.2 mm/rev, and depth of cut ≤ 2 mm, with a red-flag warning against simultaneous use of 134 m/min and 0.3 mm/rev. The practical implications for TVET workshops, where unplanned tool failure disrupts training schedules and increases material costs, are discussed.

Keywords: Tool wear; Taguchi method; HSS tool; threshold analysis; aluminum turning; catastrophic wear

INTRODUCTION

Tool wear and machine failure represent persistent challenges in metal cutting operations, directly affecting productivity, product quality, and manufacturing costs [1]. In any metal cutting operation, the characteristics of tools, work materials, and machine parameter settings influence process efficiency, tool wear, and machine tool failure [2]. A significant improvement in process efficiency may be achieved through process parameter optimization that identifies critical process control factors leading to desired outputs with acceptable variations [3].

The present study is situated within the context of Technical and Vocational Education and Training (TVET) colleges in Addis Ababa, where aluminum bar turning operations are routinely performed for student training. The research documents numerous problems currently observed in the operation of aluminum bars in these institutions and focuses on best practices and proper tool use [4].

Machining operations allow for high surface finish, precise shaping, and better dimensional tolerances in production processes. To meet the demand for high productivity, good quality machine parts, and increased

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machining efficiency, researchers have investigated various issues affecting the machining process, with tool life being a primary concern. The cutting tool is not only responsible for the cutting action but also determines the required surface finish, product quality, and machining performance [5].

Monitoring the cutting phenomenon improves productivity, increases tool life, and avoids disruption in machining, according to several scholars [6]. Therefore, enhancing cutting tool performance is an economically important goal. Many studies have focused on improving machining performance by revamping tool geometry, material, and machining parameters, inventing various ways to increase cutting tool life to enhance production rate and minimize production cost[4].

Previous research has established that cutting parameters significantly influence tool wear. Kumar (2015)stated that enhancing machine performance can be achieved by selecting appropriate cutting parameters and employing effective machining strategies, with tools exhibiting optimal cutting temperatures resulting in improved longevity.

Ojolo & Ogunkomaiya (2014) demonstrated that cutting speed is more critical than feed rate due to its potential to damage equipment, with a feed rate of 0.3 mm/rev showing a significant impact on tool life across all scenarios. Astakhov (2004) examined the effects of cutting feed, depth of cut, and workpiece diameter on tool wear, concluding that depth of cut has minimal influence on tool wear rates when machining occurs within an optimal cutting system.

While these studies provide valuable insights, the literature lacks a reconciled understanding of the condition-dependent effects of feed rate and the identification of specific parameter combinations that lead to catastrophic tool failure [9].

This study addresses this gap by conducting a threshold-based re-analysis of Taguchi-optimized experimental data to identify and map the "catastrophic wear zone" for HSS tools in dry aluminum turning.

MATERIALS AND METHODS

Experimental Design

The experiments were conducted using a Taguchi L9 orthogonal array design with three factors and three levels. Dry turning operations were performed on aluminum using an HSS tool. The cutting parameters and their levels are presented in Table 1.

Table 1. Process Parameters and Their Levels

Parameter	Level 1	Level 2	Level 3
Cutting Speed (m/min)	34	90	134
Feed Rate (mm/rev)	0.1	0.2	0.3
Depth of Cut (mm)	1.0	2.0	3.0

The L9 orthogonal array design and the desired parameter values for each experimental run are presented in Table 2.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

Table 2. L9 Orthogonal Array and Parameter Values

Run	Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth of Cut (mm)
1	34	0.1	1
2	34	0.2	2
3	34	0.3	3
4	90	0.1	2
5	90	0.2	3
6	90	0.3	1
7	134	0.1	3
8	134	0.2	1
9	134	0.3	2

Signal-to-Noise Ratio Calculation

To analyze the results, the Taguchi method uses a statistical measure of performance called the signal-to-noise (S/N) ratio. The S/N ratio takes both the mean and variability into account. Using the "larger-the-better" quality characteristic, the S/N ratio (η) is calculated as:

$$\frac{S}{N} = -10Log10[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Yi^2}]$$

Where Y is the value of the response (tool life), and n is the number of observations. The experimental responses and corresponding S/N ratios are presented in Table 3.

Table 3. Experimental Response Values and S/N Ratios

Run	Cutting Speed	Feed	Depth of Cut	Response (Tool Life)	S/N Ratio (dB)	Mean
1	34	0.1	1	80	38.06	80
2	34	0.2	2	55	34.81	55
3	34	0.3	3	30	29.54	30
4	90	0.1	2	213	46.57	213

5	90	0.2	3	176	44.91	176
6	90	0.3	1	140	42.92	140
7	134	0.1	3	45	33.06	45
8	134	0.2	1	26	28.30	26
9	134	0.3	2	17	24.61	17

RESULTS

Response Analysis for Signal-to-Noise Ratios

The response table for S/N ratios (Table 4) shows the average S/N values for each factor at each level, using the "larger-is-better" quality characteristic.

Table 4. Response Table for Signal-to-Noise Ratios (Larger is Better)

Level	Cutting Speed	Feed	Depth of Cut
1	34.14	39.23	36.43
2	44.80	36.01	35.33
3	28.66	32.36	35.84
Delta	16.14	6.87	1.10
Rank	1	2	3

The analysis reveals that cutting speed is the most significant factor influencing tool wear (Delta = 16.14), followed by feed rate (Delta = 6.87), while depth of cut has minimal influence (Delta = 1.10). The main effects plot for S/N ratios (Figure 1) illustrates the sharp decline in performance as cutting speed increases from 90 to 134 m/min.

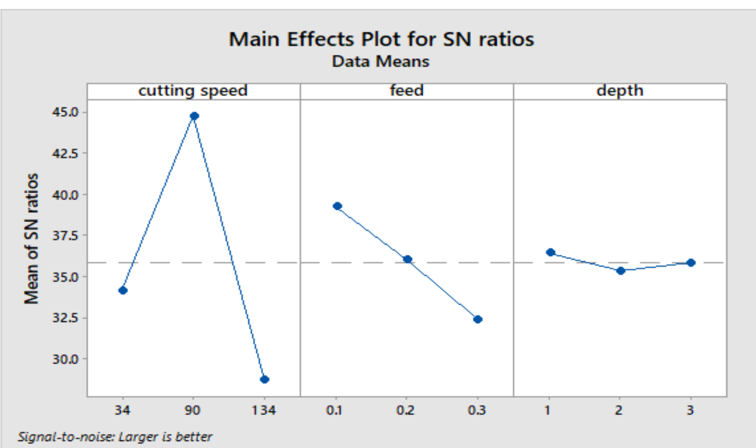

Figure 1. Main Effects Plot for Signal-to-Noise Ratios (Larger is Better)

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

Threshold Identification

A critical finding emerges from examining the individual experimental responses. All three experiments conducted at 134 m/min produced the lowest tool life responses (45, 26, and 17 minutes), representing a substantial drop from the 90 m/min group performance.

Table 5. Performance Comparison by Cutting Speed Level

Speed Level	Response Range (min)	Mean Response (min)	S/N Mean (dB)
34 m/min	30 – 80	55.00	34.14
90 m/min	140 – 213	176.33	44.80
134 m/min	17 – 45	29.33	28.66

The S/N ratio drops sharply from 44.80 (at 90 m/min) to 28.66 (at 134 m/min)—a 36.0% collapse in signal-to-noise performance. The most dangerous combination (134/0.3/2) produced the shortest tool life of only 17 minutes, representing a 92.0% reduction compared to the optimal combination (90/0.1/2), which produced 213 minutes.

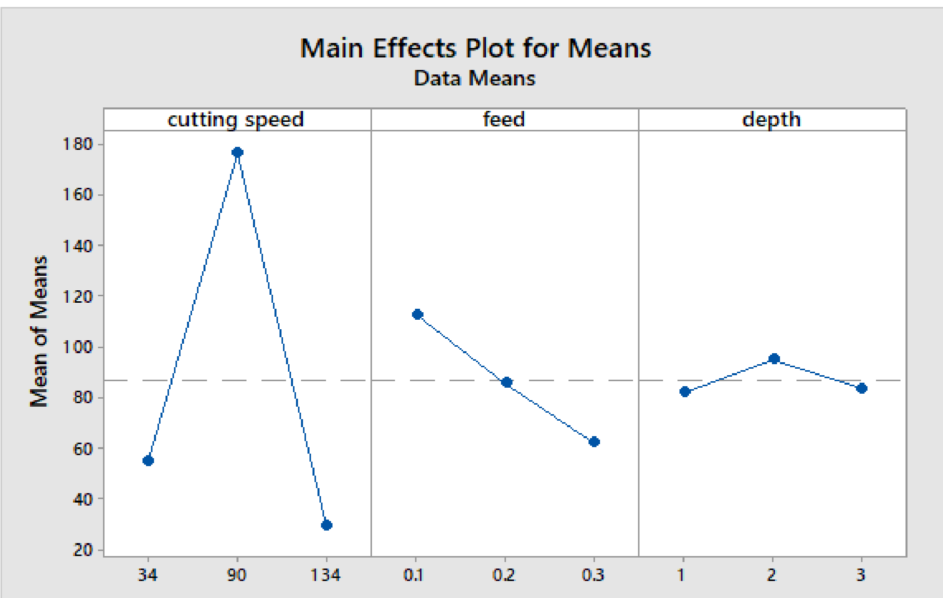

Figure 2. Main Effects Plot for Means

The response table for means (Table 6) confirms this threshold behavior, with the mean tool life dropping from 176.33 minutes at 90 m/min to only 29.33 minutes at 134 m/min.

Table 6. Response Table for Means

Level	Cutting Speed	Feed	Depth of Cut
1	55.00	112.67	82.00

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

2	176.33	85.67	95.00
3	29.33	62.33	83.67
Delta	147.00	50.33	13.00
Rank	1	2	3

DISCUSSION

The Catastrophic Wear Zone

The data reveal a clear threshold phenomenon rather than a gradual performance decline. The transition from 90 m/min to 134 m/min represents a crossing point into what can be termed the "catastrophic wear zone." Within this zone, tool life becomes both significantly shorter and highly inconsistent, as evidenced by the wider response range (17–45 minutes) compared to the 90 m/min group (140–213 minutes).

This non-linear deterioration can be explained by the physics of metal cutting. As cutting speed increases, cutting temperature rises exponentially. Above a critical speed, the HSS tool material begins to lose its hardness rapidly, accelerating adhesive and abrasive wear mechanisms. Sikdar & Chen (2002) established the relationship between flank wear area and cutting forces, noting that increased wear leads to greater friction and heat generation, creating a positive feedback loop that accelerates tool failure.

The finding that all 134 m/min experiments yielded poor results, regardless of feed and depth settings, suggests that cutting speed acts as a "gatekeeper" parameter. Below the threshold speed (approximately 90 m/min), feed and depth can be adjusted to balance productivity and tool life. Above this threshold, however, the tool enters the catastrophic zone where even the lowest feed and depth combinations cannot prevent rapid failure.

Implications of the Feed Rate Effect

The observed influence of the feed rate reveals a critical condition-dependent relationship, confirming the research gap previously highlighted by [8]. Data indicates that the signal-to-noise (S/N) ratio experiences a notable decline as the feed rate increases, dropping from 39.23 at 0.1 mm/rev to 32.36 at 0.3 mm/rev. This 17.5% reduction underscores how increasing the feed rate significantly destabilizes the process, limiting the consistency of the output.

This sensitivity is notably amplified when paired with high cutting speeds, suggesting a non-linear interaction between these two parameters. Specifically, the combination of 134 m/min and 0.3 mm/rev in Experiment 9 resulted in the poorest performance, yielding a duration of 17 minutes. Such findings illustrate that at higher cutting speeds, the system becomes increasingly vulnerable to the negative impacts of higher feed rates, leading to a rapid degradation in tool life or surface integrity.

Consequently, these results justify the adoption of a threshold-based strategy for parameter selection in machining operations. While optimizing the feed rate remains a valid secondary objective, the primary focus must remain on ensuring the cutting speed stays within a predefined safe zone. By prioritizing cutting speed stability, engineers can better manage the cascading negative effects that higher feed rates introduce in high-speed machining environments.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

Depth of Cut: A Secondary Factor

Consistent with [11] findings, depth of cut showed minimal influence on tool wear, with delta values of only 1.10 for S/N ratio and 13.00 for means, ranking it as the least significant factor among the three cutting parameters investigated. The response table for S/N ratios demonstrates that depth of cut exhibits relatively stable performance across all three levels (36.43, 35.33, and 35.84), with a negligible delta of 1.10 compared to 16.14 for cutting speed and 6.87 for feed rate. This remarkable stability indicates that within the tested range of 1–3 mm, variations in depth of cut do not significantly accelerate or decelerate the tool wear process, making it a reliable parameter for adjusting material removal rate without compromising tool life.

The minimal influence of depth of cut can be attributed to the cutting mechanics of aluminum and the nature of HSS tools. Unlike cutting speed, which exponentially increases cutting temperature and accelerates thermal softening of the tool material, or feed rate, which directly influences chip thickness and cutting forces, depth of cut primarily affects the width of cut and the volume of material removed per pass. The cutting temperature and specific cutting energy are less sensitive to depth of cut variations within the tested range, as the heat generated is distributed over a larger cutting edge contact area, moderating the temperature rise at the tool-workpiece interface. This explains why the depth of cut can be increased from 1 mm to 3 mm without causing a proportional increase in tool wear rate, provided that cutting speed and feed rate are maintained within the safe operating window.

From a practical perspective, this finding has significant implications for both TVET training workshops and industrial production environments. Since the depth of cut has minimal effect on tool life, it can be selected primarily based on material removal rate requirements, machining time, and workpiece geometry constraints without fear of accelerating tool failure. For instance, when higher productivity is required, operators can increase the depth of cut from 1 mm to 3 mm to reduce the number of passes needed to achieve the final workpiece dimensions, thereby decreasing machining time and improving production efficiency. However, it is important to note that this flexibility is conditional upon maintaining cutting speed within the safe zone (≤ 90 m/min) and feed rate at moderate levels (≤ 0.2 mm/rev), as the catastrophic wear zone is primarily governed by cutting speed, with depth of cut playing only a secondary role in the overall tool wear process.

CONCLUSION

This threshold-based re-analysis of Taguchi-optimized experimental data establishes 134 m/min as a critical speed boundary beyond which HSS tool performance in dry aluminum turning enters a catastrophic wear zone. The analysis reveals that cutting speed is the dominant factor influencing tool life, with a delta of 16.14 compared to 6.87 for feed rate and 1.10 for depth of cut. All three experiments conducted at 134 m/min produced tool life values of only 17–45 minutes, representing a 73.6% reduction compared to the optimal combination at 90 m/min, while the S/N ratio collapsed by 36.0% from 44.80 to 28.66, indicating both reduced average tool life and increased variability at high speeds. The most dangerous combination (134 m/min, 0.3 mm/rev, 2 mm depth) produced the shortest tool life of only 17 minutes, confirming that simultaneous operation at maximum speed and maximum feed accelerates catastrophic failure.

The findings confirm that feed rate exhibits condition-dependent effects, with the most severe consequences at high cutting speeds, while depth of cut has minimal influence on tool wear, confirming it as a secondary parameter suitable for adjusting material removal rate without significantly compromising tool life. Based on the threshold analysis, a safe operating window of cutting speed ≤ 90 m/min, feed ≤ 0.2 mm/rev, and depth of cut ≤ 2 mm is recommended for HSS tool dry turning of aluminum in TVET workshops. This practical guidance addresses the critical need for process boundary mapping in educational settings where unplanned tool failure disrupts training schedules and increases material costs.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

Future work should focus on validation experiments at the proposed optimal parameters, microscopic analysis of worn tools using SEM/EDS to identify dominant wear mechanisms, and investigation of minimum quantity lubrication effects on the catastrophic wear threshold. Additionally, extending the study to include surface roughness and material removal rate as responses would enable multi-objective optimization within the safe zone, while real-time monitoring of cutting forces when operating near the threshold speed could provide early warning of impending tool failure.

The key conclusions are:

- Cutting speed is the dominant factor influencing tool life (Delta = 16.14), with a sharp performance threshold between 90 and 134 m/min.
- The S/N ratio collapses by 36.0% when speed increases from 90 to 134 m/min, indicating not only reduced average tool life but also increased variability.
- All 134 m/min experiments fall within the catastrophic zone, producing tool life values of only 17–45 minutes, compared to 140–213 minutes at 90 m/min.
- Feed rate exhibits condition-dependent effects, with the most severe consequences at high cutting speeds (134 m/min, 0.3 mm/rev produced only 17 minutes).
- Depth of cut has minimal influence on tool wear, confirming it as a secondary parameter suitable for adjusting material removal rate without significantly compromising tool life.

The proposed safe operating window (cutting speed ≤ 90 m/min, feed ≤ 0.2 mm/rev, depth of cut ≤ 2 mm) provides practical guidance for TVET workshops, where unplanned tool failure disrupts training schedules and increases material costs.

RECOMMENDATIONS

Based on the findings of this threshold analysis, it is recommended that TVET workshops and industrial practitioners strictly adhere to a safe operating window of cutting speed ≤ 90 m/min, feed ≤ 0.2 mm/rev, and depth of cut ≤ 2 mm when performing dry turning of aluminum using HSS tools, with a red-flag warning against simultaneous use of 134 m/min and 0.3 mm/rev which produced the shortest tool life of only 17 minutes. Validation experiments should be conducted at the proposed optimal parameters (90 m/min, 0.1 mm/rev, 2 mm) to verify Taguchi predictions, while microscopic analysis using SEM/EDS is recommended to identify dominant wear mechanisms explaining why 134 m/min represents a critical threshold. Future research should investigate the effect of minimum quantity lubrication on the catastrophic wear zone, extend the study to include surface roughness and material removal rate as responses for multi-objective optimization, and develop real-time monitoring systems to detect cutting force increases when operating near or above the threshold speed. Additionally, it is recommended that tool change schedules be more frequent when operating above 90 m/min, and that instructors in TVET colleges use the proposed safe operating window as a quick-reference guide for student training to minimize unplanned tool failure and reduce material costs.

In general, the following recommendations are made:

- **Validation Experiments:** Conduct confirmation experiments at the proposed optimal parameters (90 m/min, 0.1 mm/rev, 2 mm) to verify Taguchi predictions.

- **Wear Mechanism Analysis:** Perform SEM/EDS analysis of worn tools to identify dominant wear mechanisms at different speed levels, explaining why 134 m/min represents a critical threshold.

- **MQL Investigation:** Evaluate the effect of minimum quantity lubrication on the catastrophic wear threshold, as dry conditions may accelerate the transition.

- **Surface Roughness Integration:** Extend the study to include surface roughness and material removal rate as responses, enabling multi-objective optimization within the safe zone.

- **Real-Time Monitoring:** Develop a monitoring system to detect spindle or cutting force increases when operating near or above the threshold speed.

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Declaration

The authors declare no conflicts of interest regarding the publication of this manuscript.

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