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TAGUCHI-BASED COMPARATIVE EVALUATION OF BORIC ACID AND MOS2 SOLID LUBRICANTS IN TURNING OF ALUMINIUM ALLOY 6061-T6

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Abstract-Aluminium alloy 6061-T6 is widely used in aerospace, automotive and structural applications due to its high strength-to-weight ratio and favourable machinability, however heat build-up and tool-chip adhesion during turning still limit surface finish and dimensional accuracy at higher cutting speeds. Flood cooling helps to some extent, but the disposal, health and environmental costs encourage interest in powdered solid lubricants as a cleaner alternative. The present study is an experimental comparison of dry, wet (flood-coolant), boric acid and molybdenum disulphide (MoS2) machining environments on the tool temperature, cutting force and surface roughness during turning of Al 6061-T6. A Taguchi L9 orthogonal array was considered with spindle speed (600, 900, 1200 rpm) and feed rate (0.05, 0.07, 0.10 mm/rev) as control factors. Thus, thirty-six trials were carried out in the four environments. Each response was analysed by signal to noise ratio analysis and ANOVA. Results show that feed rate contributes most of the cutting force and surface roughness (76-83%) and spindle speed contributes most of the tool temperature (68-73%) in all tested environments. The lowest cutting force and the smoothest surface finish were obtained with MoS2 lubrication among all conditions, which were about 12.9% and 17.7% better than that of dry machining, respectively, while wet machining gave the largest drop in tool temperature (about 30% below dry machining) but the poorest surface finish. A confirmation trial at the optimal parameter combination (1200 rpm, 0.05 mm/rev, MoS2) improved surface roughness by 50.3% and cutting force by 6.2% compared to a mid-range baseline, confirming the Taguchi predictions. The results indicate that MoS2-assisted machining is a feasible and low-impact substitute to flood coolant when turning Al 6061-T6.

Keywords: Aluminium 6061-T6; Turning; Solid Lubricant; Boric Acid; Molybdenum Disulphide; Taguchi Method; ANOVA; Surface Roughness.

1. INTRODUCTION

Turning is the most common machining process in the manufacture of rotationally symmetric components. Al 6061-T6 is one of the most common turned aluminium alloys due to its combination of light weight, good corrosion resistance and reasonable strength. The alloy is often described as free-machining but has practical difficulties; its ductility encourages chip sticking and built-up edge formation and heat generated at the tool-chip and tool-workpiece interfaces can degrade surface finish and dimensional control once cutting speed or feed is pushed too high. The conventional solution to these problems is flood cooling, using mineral-oil-based cutting fluid. This is effective in reducing both temperature and force. However, it poses disposal problems, risk of exposure to the operator and questionable biodegradability, which has led to research interest in minimum quantity lubrication and solid-lubricant machining as more sustainable options.

Two powdered solid lubricants that have been extensively studied for steel and hardened-alloy turning are boric acid and molybdenum disulphide, which have layered crystal structures and low shear strength that reduce friction and adhesion at the cutting interface. Data for aluminum alloys, and Al 6061-T6 in particular, are much more limited, even though the alloy is widely used in industry. This paper presents an experimental comparison of dry, wet, boric acid and MoS2 machining environments for Al 6061-T6 turning and evaluation of their effects on tool temperature, cutting force and surface roughness in a common Taguchi-based experimental design and determination of the combination of parameters that minimises these responses.

2. LITERATURE REVIEW

Taguchi-based optimisation of Al 6061 turning gained momentum through the early-to-mid 2010s. Camposeco-Negrete [1] applied Taguchi methodology with ANOVA to minimise energy consumption while turning Al 6061-T6, while Jayaraman and Mahesh Kumar [2] used an L9 array to study the influence of spindle speed, feed rate and depth of cut on surface roughness and material removal rate, reporting feed rate as the dominant factor for roughness. Subsequent work paired Taguchi design with genetic algorithms and Grey relational analysis to optimise several quality characteristics together, consistently confirming feed rate and spindle speed as the parameters most worth controlling for surface finish in Al 6061 turning.

A separate and larger body of literature examined powdered solid lubricants, chiefly boric acid, MoS2 and graphite, mostly on steels and hardened alloys. Vamsi Krishna et al. [10] and Damera and Pasam [11] documented the friction- and force-reducing effect of boric acid in machining, while Deshmukh et al. [13] characterised its tribological behaviour under extended operation. Reddy and Rao [12] reported reduced cutting force and improved surface quality with solid lubricants in end milling. da Silva et al. [20] and related studies extended MoS2

lubrication to hardened steel turning with coated tools, and minimum-quantity-lubrication studies combining boric acid and MoS2 [21] reported gains over dry cutting on steel alloys.
Despite this volume of work on steels, direct comparative data on boric acid and MoS2 solid lubricants for Al 6061-T6 turning, benchmarked against both dry and wet machining within a single experimental framework, remains scarce. The present study addresses this gap using a controlled Taguchi L9 design across all four lubrication conditions.

3. MATERIALS AND METHODS

3.1 Workpiece Material

The workpiece of Al 6061-T6 round bar stock was selected for its industrial use and the relative scarcity of solid-lubricant machining data specific to this alloy. Table 3.1 and Table 3.2 summarise its mechanical properties and chemical composition respectively.

Table-3.1 Mechanical properties of Al 6061-T6

Property	Value
Hardness	95 HB (Brinell)
Tensile Strength	310 MPa
Yield Strength	276 MPa
Density	2.70 g/cm³
Thermal Conductivity	167 W/m·K

Table-3.2 Chemical composition of Al 6061-T6

Element	Percentage (%)
Aluminium (Al)	95.8 - 98.6
Magnesium (Mg)	0.8 - 1.2
Silicon (Si)	0.4 - 0.8
Iron (Fe)	Max 0.7
Copper (Cu)	0.15 - 0.40
Zinc (Zn)	Max 0.25

3.2 Equipment and Experimental Design

All trials were carried out on a centre lathe fitted with a tool-post dynamometer and an air-assisted powder delivery attachment for feeding boric acid and MoS2 into the cutting zone. A CCMT 120404-AL cemented carbide insert (grade LT10-ALU), designed specifically for aluminium turning, was used throughout to minimise built-up edge formation. Tool temperature was measured with a K-type thermocouple mounted close to the cutting edge and linked to a digital readout; cutting force was measured with a calibrated lathe tool dynamometer; and average surface roughness (Ra) was measured with a Mitutoyo Surftest SJ-210 stylus profilometer, with three readings averaged per specimen.
Four lubrication conditions were tested: dry machining, wet (flood-coolant) machining with a water-soluble cutting fluid, and powdered boric acid and MoS2, each delivered through the same metered, air-assisted attachment aimed at the tool-chip interface. Spindle speed and feed rate were varied across three levels each, as listed in Table 3.3, while depth of cut was held constant. A Taguchi L9 orthogonal array was used to plan nine trials per lubrication condition, giving thirty-six experimental runs in total. Each response was converted to a signal-to-noise ratio using the smaller-the-better criterion, and ANOVA was applied to quantify the percentage contribution of each parameter at a 95% confidence level. Minitab software was used for the design layout, S/N ratio calculation and ANOVA.

Table-3.3 Experimental levels of independent parameters

Cutting Parameter	Level 1	Level 2	Level 3
Spindle Speed (rpm)	600	900	1200
Feed Rate (mm/rev)	0.05	0.07	0.10

4. RESULTS AND DISCUSSION

The following subsections summarise the ANOVA-based percentage contribution of spindle speed and feed rate to each response, the grand-average comparison across the four machining environments, and the optimal parameter combination confirmed experimentally.

4.1 ANOVA Percentage Contribution

Table 4.1 lists the ANOVA percentage contribution of spindle speed and feed rate to each response, averaged from the individual analyses carried out for each of the four machining environments. The pattern is consistent across all environments: feed rate dominates cutting force (76.1-78.1%) and surface roughness (81.1-83.2%), since it directly sets the uncut chip cross-section and the resulting feed marks, while spindle speed dominates tool temperature (68.2-72.5%), consistent with higher cutting speeds generating more frictional heat at the tool-chip interface.

Table-4.1 ANOVA percentage contribution of spindle speed and feed rate to each response

Environment	Tool Temperature (%)		Cutting Force (%)		Surface Roughness (%)	
	Spindle	Feed	Feed	Spindle	Feed	Spindle
Dry	68.2	30.1	76.1	20.2	83.2	14.5
Wet	70.2	27.4	76.5	19.8	81.1	16.2
Boric Acid	72.5	24.5	78.1	18.2	81.8	15.1
MoS2	71.8	25.2	77.8	18.5	81.1	15.6

4.2 Grand-Average Comparison Across Environments

Table 4.2 gives the grand average of each response across all nine trials within every environment, together with the resulting rank (1 = best). No single environment wins on every count: wet machining gives the lowest average tool temperature but the highest (worst) surface roughness, while MoS2 ranks first for both cutting force and surface roughness and a close second for temperature. Relative to dry machining, MoS2 reduced tool temperature by about 26.1%, cutting force by about 12.9% and surface roughness by about 17.7%, while boric acid gave smaller but still consistent improvements on all three responses.

Table 4.2 Grand average of responses and overall ranking by machining environment

Environment	Avg. Tool Temp. (°C)	Rank	Avg. Cutting Force (N)	Rank	Avg. Surface Roughness (µm)	Rank
Dry	78.23	4	332.67	4	2.09	3
Wet	54.50	1	322.89	3	2.89	4
Boric Acid	60.84	3	299.51	2	1.89	2
MoS2	57.79	2	289.89	1	1.72	1

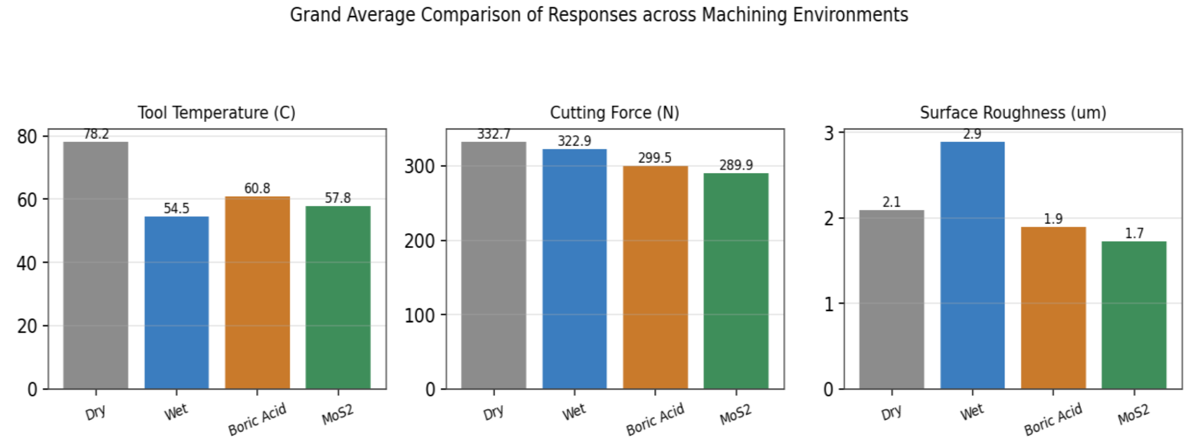

Fig. 4.1 Grand average comparison of tool temperature, cutting force and surface roughness across the four machining environments

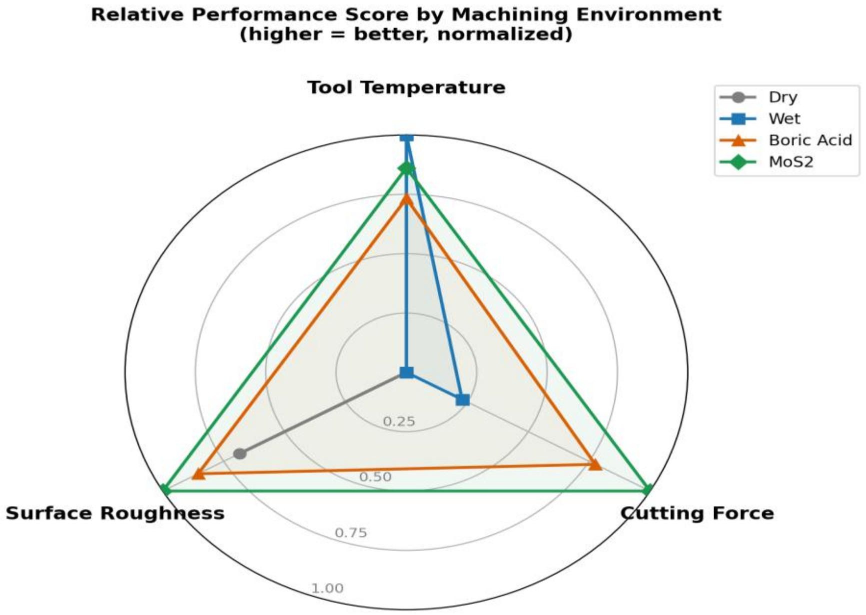

Fig. 4.2 Normalised relative-performance radar comparison of the four machining environments (higher = better)

Figure 4.2 rescales each response so that the best-performing environment scores 1 and the worst scores 0, making the trade-offs easier to visualise. MoS2 traces the largest enclosed area of the four environments, indicating the most balanced performance across all three responses simultaneously, with boric acid close behind. Dry machining is outperformed by the other three conditions on cutting force and tool temperature, while wet machining stands out only on tool temperature.

4.3 Optimal Parameters and Confirmation Test

Table 4.3 lists the parameter combination identified as optimal for each response individually, and the subsequent confirmation trial conducted at 1200 rpm and 0.05 mm/rev feed under MoS2 lubrication, benchmarked against a mid-range baseline setting (900 rpm, 0.07 mm/rev).

Table 4.3 Optimal parameter combination by response

Response	Best Environment	Optimal Speed (rpm)	Optimal Feed (mm/rev)
Tool Temperature	Wet Machining	600	0.05
Cutting Force	MoS2	600	0.05
Surface Roughness	MoS2	1200	0.05

Table 4.4 Confirmation experiment results (MoS2 environment)

Response	Baseline (900 rpm, 0.07 mm/rev)	Optimum	% Improvement
Surface Roughness (µm)	1.65	0.82	50.3%
Cutting Force (N)	288.6	270.8	6.2%

The confirmation trial supports the Taguchi predictions: surface roughness improved by 50.3% and cutting force by 6.2% relative to the mid-range baseline, confirming 1200 rpm with a 0.05 mm/rev feed under MoS2 lubrication as the combination giving the best surface finish for Al 6061-T6 turning within the range studied.

CONCLUSION

Turning trials on Al 6061-T6 across dry, wet, boric acid and MoS2 lubrication conditions, planned using a Taguchi L9 orthogonal array, show that feed rate is the dominant parameter for cutting force and surface roughness in every environment (76-83% ANOVA contribution), while spindle speed dominates tool temperature (68-73% contribution). This pattern held regardless of the lubrication condition used.

Among the four environments, wet machining gave the lowest tool temperature but the poorest surface finish, while MoS2 powder lubrication delivered the lowest cutting force and the smoothest surface finish, improving on dry machining by about 12.9% and 17.7% respectively, and outperforming boric acid on both counts. A confirmation trial at the predicted optimum (1200 rpm, 0.05 mm/rev, MoS2) improved surface roughness by 50.3% and cutting force by 6.2% over a mid-range baseline, validating the Taguchi-based optimisation.

Overall, the results support MoS2-assisted machining as a practical, lower-impact alternative to flood coolant for turning Al 6061-T6, offering the best combined surface finish and force performance of the conditions tested, with boric acid as a viable and cheaper intermediate option. Future work could extend this comparison to tool wear, chip morphology and residual stress, and to a wider range of cutting speeds and feed rates.

Nomenclature

Symbol / Abbreviation	Meaning
Ra	Average surface roughness (µm)
S/N	Signal-to-Noise ratio
ANOVA	Analysis of Variance
DF	Degrees of Freedom
MoS2	Molybdenum Disulphide
MQL	Minimum Quantity Lubrication
rpm	Revolutions per Minute
mm/rev	Millimetre per Revolution

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REFERENCES

[1] Camposeco-Negrete, C. (2013). Optimization of cutting parameters for minimizing energy consumption in turning of AISI 6061 T6 using Taguchi methodology and ANOVA. Journal of Cleaner Production, 53, 195-203.

[2] Jayaraman, P. and Mahesh Kumar, L. (2014). Optimization of machining parameters in turning of aluminium alloy 6061 using Taguchi method. Proc. 2nd Int. Conf. on Advances in Industrial Engineering Applications.

[3] Chowdary, B.V. et al. Optimisation of surface roughness when CNC turning of Al 6061: Application of Taguchi design of experiments and genetic algorithm.

[4] Deepak, D. and Rajendra, B. (2015). Investigations on the surface roughness produced in turning of Al6061 (as-cast) by Taguchi method. International Journal of Research in Engineering and Technology, 4(8).

[5] Multi-response optimization of machining parameters in turning 6061 aluminium alloy using Grey-Taguchi approach.

[6] Vamsi Krishna, P., Srikant, R.R. and Nageswara Rao, D. (2011). Solid lubricants in machining. Proc. IMechE Part J: Journal of Engineering Tribology, 225, 213-227.

[7] Damera, N.R. and Pasam, V.K. (2008). Performance profiling of boric acid as lubricant in machining. International Journal of Machine Tools & Manufacture, 3, 239-244.

[8] Reddy, N.S. and Rao, P.V. (2005). Experimental investigation to study the effect of solid lubricants on cutting forces and surface quality in end milling. International Journal of Machine Tools and Manufacture, 46, 189-198.
[9] Deshmukh, P., Lovell, M., Sawyer, W.G. and Mobley, A. (2006). On the friction and wear performance of boric acid lubricant combinations in extended duration operations. Wear, 260, 1295-1304.
[10] Kılıçay, K. and Ulutan, M. (2016). Investigation of the solid lubrication effect of commercial boron-based compounds in end milling. International Journal of Precision Engineering and Manufacturing, 17, 517-524.
[11] Mahadi, M.A., Choudhury, I.A., Azuddin, M. and Nukman, Y. (2017). Use of boric acid powder aided vegetable oil lubricant in turning AISI 431 steel. Procedia Engineering, 184, 128-136.
[12] da Silva, R.B. et al. MoS2 solid lubricant application in turning of AISI D6 hardened steel with PCBN tools. Journal of Manufacturing Processes.
[13] Performance evaluation of boric acid and MoS2 based minimum quantity lubricants in turning of En-31 steel alloy. Advances in Production Engineering & Management (2012), 7(1), 39-50.
[14] Abhang, L.B. and Hameedullah, M. (2010). Experimental investigation on the performance of solid lubricant assisted MQL in metal cutting.
[15] Sharma, P., Sidhu, B.S. and Sharma, J. (2015). Investigation of effects of MQL and solid lubricants on machining performance.