

Evaluation of the Influence of Optimized End-Milling Parameters on the Surface Roughness and Surface Microstructure of AZ61 Magnesium Alloy: Taguchi L9, ANOVA and SEM Evidence

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Abstract

The surface finish and microstructure just below it of a magnesium part are affected by the way the part is milled, which in turn affects the fatigue and corrosion behavior of the part. For AZ61, however, there are few studies that relate milling parameters to the surface produced. The spindle speed (235 rpm, 542 rpm and 1000 rpm), the table feed (12.1 mm/min, 16.2 mm/min, and 21.5 mm/min), and the depth of cut (0.5 mm, 1.0 mm and 1.5 mm) were varied in a Taguchi L9 experimental design and the arithmetic mean roughness (Ra) of the milled surface of AZ61 was measured for both high-speed steel (HSS) and carbide cutting tools. The results were analyzed using signal-to-noise (S/N) ratios and analysis of variance (ANOVA), with the surface condition of three machined surfaces being described by scanning electron microscopy (SEM). Ra fell between 0.45 and 0.81 μm with HSS and between 0.30 and 0.60 μm with carbide; carbide gave a mean Ra 28% lower (paired t-test, $p = 0.027$). The two tools ranked first in terms of depth of cut. The predicted optimum was 1000 rpm and 21.5 mm/min, with 1.0 mm depth for HSS or 0.5 mm for carbide (Ra 0.55 and 0.33 μm). None of these factors proved to be significant at 95% level, as the residual error contained 79% and 68% of the variation; and measured runs had previously excelled the predicted optima, which necessitates experimental confirmation. The SEM images showed that the surface with 1000 rpm and 0.5 mm feed marks had the most distinct feed marks, while the surface with 542 rpm had the smeared and mottled appearance. Based on published research on magnesium alloys, the thermo-mechanical mechanisms that might explain the features are discussed.

Keywords: AZ61 magnesium alloy, end milling, Taguchi L9; ANOVA, surface microstructure

1. Introduction

Because of the need for moderate strength and low mass, magnesium alloys are the lightest structural metals used in common application, and AZ61 (nominally 6 wt% Al and 1 wt% Zn) is selected. Typical finishing process is machining. The cutting force is small, the chip is short, but fine chip in dry cutting can be ignited, the alloy is prone to adhesion to the cutting tool, the selection of cutting tools and parameters has a direct impact on the resulting surface [2].

Surface quality: Surface integrity doesn't only include Ra, but also the sub-surface microstructure, hardness and residual stress. At room temperature, there are relatively few easy slip systems in hexagonal close-packed lattice of Mg and cutting deformation takes place mainly by twinning and shear banding. Asgari et al. [3] reported that, in the case of AZ91, surface defects occurred .

predominantly around secondary phases, and twinning and shear bands were the most significant near surface changes, with plastic deformation of approximately 180 μm . Zakaria et al. [2] found a thin layer with no significant features in turned AZ31, which increased from 7 to 12 μm when the cutting speed was increased from 120 to 240 m/min in dry cutting. Magnesium alloys of the Mg–Al–Zn (AZ) family are widely used where weight reduction matters, such as automotive, aerospace and defence components. AZ61 combines good strength with reasonable formability, and it machines easily compared with most structural metals. Even so, surface finish, tool wear, built-up edge formation and the condition of the machined sub-surface remain practical concerns in milling [8,9]. Surface roughness (Ra) is the most commonly reported quality indicator, while the machined layer's

microstructure (grain size, twinning, secondary phases) governs hardness, residual stress and, indirectly, corrosion and fatigue behaviour [10,11].

The effect of speed is less uniform. Mostafapour et al. observed that R_a rose by about 85–90% as speed doubled from 62.83 to 125.66 m/min, which they attributed to tool vibration with their single-edge cutter, while cryogenic or lubricated conditions lowered roughness, particularly at the shallower depth of cut [5]. Marakini et al. found that high-speed dry face milling of AZ91 with uncoated carbide could improve overall surface integrity, evaluating roughness, hardness, microstructure and residual stress together [10]. Results therefore depend on tool, machine rigidity and cooling, and should not be transferred between setups without checking.

Both play a role in fatigue. Grzesik [6] summarizes the effects of machining on fatigue life, and considers the initiation of cracks at surface notches as the major contributor to the life. In fact, Chen et al. [4] milled the surfaces of ZK61M under the same conditions in terms of R_a , residual stress and microstructure but with different texture directions, and found that lives ranged between 32 k and 145 k cycles when used with the same R_a and an image of the surface. The L9 array of Taguchi designs combined with ANOVA is a common approach to ranking milling parameters for cost effectiveness, and Marakini et al. [5] used grey relational analysis for analysis of the L9 array of the face milling of the AZ91 alloy. In plain L9 study,

Muniraj et al. [1] reported the results of using HSS and carbide cutters for AZ61, and Alshibi et al. [7] investigated the chip morphology and tool wear in the high-speed cutting of AZ61. None of the sources used here provides an L9 roughness analysis of machined surface for both the different cutters used to mill the surface and observations of the surface using SEM. Across the literature, feed is the dominant driver of roughness. Shi et al. used Taguchi design with grey relational analysis (GRA) for dry milling of a magnesium alloy and found feed rate to be the most influential factor on the combined surface-quality grade [12].

Alharthi et al. built regression and artificial neural network (ANN) models for R_a in face milling of AZ61. The best ANN (six hidden neurons) and the regression model reached coefficients of determination of 94.93% and 93.63% against thirteen validation tests [13]. Optical microscopy of two surfaces showed that a higher feed produced thick, widely spaced feed marks, whereas a lower feed gave thin, closely spaced marks and better finish [13]. This supports the geometric view that roughness scales with feed per tooth

The objectives are as follows (i) rank the influence of spindle speed, feed rate and depth of cut on R_a for each cutter, (ii) predict the optimum and test the extent to which this data support it, (iii) visualise the response in three dimensions, and (iv) interpret the SEM appearance of three machined surfaces through mechanisms reported for magnesium alloys.



Fig.1 Carbide Cutter.
Fig.3 Milling Process



Fig2. Specimen



2. Materials and Methods

2.1 Workpiece, tools and measurements

The workpiece was AZ61 magnesium alloy supplied as hot rolled, circular blank of 30 mm and 300 long with tensile strength of 310 MPa, 230 MPa in yield and 68 VH in hardness with the density 1.80 g/cm^3 and its composition are Mg-92%, Al-5.82%, Zn-0.4-1.5%, Mn-0.15%, Si-0.1%, Cu-0.05%, Ni & Fe- 0.005 %each. . Milling was carried out on BD_PEDERSEN-BPU-1 173/71, 3Hp capacity vertical milling machine tool(German made) with HSS and carbide cutters 25 mm in diameter, number of flutes-4, , and base oil coolant intermittent spraying on tool and work piece contact during milling. Each of the nine L9 runs was made once per cutter. Ra was recorded with Mitutoyo Surf Test (Make-Japan Model SJ-301) _ Model ES2 surface tester with 25 mm cut-off length, 15 mm in traverse direction and 5 number of traces were recorded for Average Ra.. Because the cutter diameter is not stated here, spindle speed is reported in rpm and not as cutting speed in m/min. The feed per spindle revolution, $f_r = F/N$, was calculated from the table feed F (mm/min) and spindle speed N (rpm).

2.2 Experimental design

Three factors were assigned to a L9 orthogonal array at three levels shown in Table 1. The factors are carried in three columns, so six of the eight degrees of freedom (DOF) are used by the main effects and two are left for error. Each combination of levels appears exactly once in each pair of factor columns . The main effects are thus separable . Table 2 shows the nine runs and the measured Ra.

Table 1. Factors and levels.

Code	Factor	Level 1	Level 2	Level 3
A	Spindle speed (rpm)	235	542	1000
B	Depth of cut (mm)	0.5	1.0	1.5
C	Feed rate (mm/min)	12.1	16.2	21.5

2.3 Signal-to-noise ratio and analysis of variance

Roughness is a smaller-the-better characteristic. With one measurement per run ($n = 1$), the S/N ratio of run i reduces to $-20 \log_{10} y_i$:

$$SN_i = -10 \log_{10} \left(\frac{1}{n} \sum_{j=1}^n y_{ij}^2 \right) \quad (1)$$

where y_{ij} is the j th Ra measurement of run i . The level that gives the highest mean S/N is the predicted best level of that factor. For ANOVA, the total sum of squares and the sum of squares of a factor F with three levels and $r = 3$ runs per level are

$$SS_T = \sum_{i=1}^N (y_i - \bar{y})^2 \quad (2)$$

$$SS_F = r \sum_{j=1}^3 (\bar{y}_{Fj} - \bar{y})^2 \quad (3)$$

where $\bar{y}$ is the grand mean and $\bar{y}_{Fj}$ the mean Ra at level j of factor F . The error sum of squares is $SS_e = SS_T - \sum SS_F$, with $v_e = N - 1 - \sum v_F = 8 - 6 = 2$ degrees of freedom. The mean square, the F ratio and the percentage contribution are

$$MS_F = \frac{SS_F}{v_F}, F_F = \frac{MS_F}{MS_e}, P_F = \frac{SS_F}{SS_T} \times 100 \% \quad (4)$$

A factor is significant at the 95% level when its F ratio exceeds $F_{0.05;2,v_e}$, which equals 19.00 for two error degrees of freedom and 6.94 when the smallest factor is pooled into the error (four degrees of freedom). The p values were taken from the F distribution. The Ra values of the two tools were also compared with a paired t -test across the nine runs, since both cutters were used under identical settings.

The predicted Ra at the optimum combination, and the confidence interval of a confirmation run, were calculated from

$$Ra_{pred} = \bar{y} + \sum_{i=A,B,C} (\bar{y}_{i, opt} - \bar{y}) \quad (5)$$

$$CI_{CE} = \pm \sqrt{F_{0.05;1,v_e} MS_e \left(\frac{1}{n_{eff}} + \frac{1}{R} \right)}, n_{eff} = \frac{N}{1 + v_{used}} \quad (6)$$

where R is the number of confirmation runs and $v_{used} = 6$ is the number of degrees of freedom spent on the three factors [5].

2.4 Response surfaces

The three-dimensional surfaces were built from an additive model in which each factor contributes a quadratic function $g_i(x_i)$ passing through its three level means:

$$Ra(x_A, x_B, x_C) = \bar{y} + \sum_{i=A,B,C} (g_i(x_i) - \bar{y}) \quad (7)$$

This reproduces the level means exactly and interpolates smoothly in between. It has no interaction terms so the surfaces are descriptive summaries of the main effects. The two parameters shown on the horizontal axes were varied, while the third was held unchanged at its predicted optimum value.

2.5 Scanning electron microscopy

The machined surfaces were imaged with a Zeiss scanning electron microscope in secondary-electron mode (SE1) at 20 kV and 200 pA probe current, at working distances of 14.4 to 16.7 mm (images dated 20 May 2022). Three conditions were imaged at 500× to 15 000×: 542 rpm with 0.5 mm depth,

1000 rpm with 0.5 mm, and 1000 rpm with 1.0 mm. Each speed–depth pair occurs once in the L9 array, so these surfaces are runs 6, 8 and 9, with feeds of 12.1, 16.2 and 12.1 mm/min. The cutter used for the imaged specimens was carbide\], and the surfaces were examined as machined and the surface cleaning was done as per standard procedure. Scale bars are those printed on the micrographs. Grey-level surface plots were made from the 5 kX micrographs after removing the data bar and applying a one-pixel Gaussian filter; they show relative signal and are not height maps.

3. Results

3.1 Surface roughness

The measured roughness is provided in table 2, and all of the values are less than 1 μm . With HSS, Ra ranged from 0.45 μm (run 4) to 0.81 μm (run 7), with a mean of 0.628 μm (SD 0.132 μm). With carbide it ranged from 0.30 μm (run 7) to 0.60 μm (run 5), with a mean of 0.450 μm (SD 0.102 μm). Therefore, the HSS run is the roughest HSS run and the carbide run is the smoothest carbide run, revealing the interaction between the tool and the parameter set. In seven out of 9 runs, the lower Ra was achieved by carbide (with the exception of run 4 (0.06 μm higher) and run 9 (0.02 μm higher). The mean difference of 0.178 μm , a 28% reduction, was significant in the paired test ($t_8 = 2.71$, $p = 0.027$).

Table 2. L9 layout, measured Ra and S/N ratio (smaller-the-better).

Run	Speed (rpm)	Depth (mm)	Feed (mm/min)	Ra HSS (μm)	Ra carbide (μm)	S/N HSS (dB)	S/N carbide (dB)
1	235	0.5	21.5	0.58	0.47	4.73	6.56
2	235	1.0	16.2	0.74	0.41	2.62	7.74
3	235	1.5	12.1	0.53	0.49	5.51	6.20
4	542	1.0	21.5	0.45	0.51	6.94	5.85
5	542	1.5	16.2	0.74	0.60	2.62	4.44
6	542	0.5	12.1	0.75	0.34	2.50	9.37
7	1000	1.5	21.5	0.81	0.30	1.83	10.46
8	1000	0.5	16.2	0.51	0.37	5.85	8.64
9	1000	1.0	12.1	0.54	0.56	5.35	5.04

3.2 Signal-to-noise response

The measured roughness is provided in table 2, and all of the values are less than 1 μm . With HSS, Ra ranged from 0.45 μm (run 4) to 0.81 μm (run 7), with a mean of 0.628 μm (SD 0.132 μm). With carbide it ranged from 0.30 μm (run 7) to 0.60 μm (run 5), with a mean of 0.450 μm (SD 0.102 μm). Therefore, the HSS run is the roughest HSS run and the carbide run is the smoothest carbide run, revealing the interaction between the tool and the parameter set. In seven out of 9 runs, the lower Ra was achieved by carbide (with the exception of run 4 (0.06 μm higher) and run 9 (0.02 μm higher). The mean difference of 0.178 μm , a 28% reduction, was significant in the paired test ($t_8 = 2.71$, $p = 0.027$).

Table 3. Response table: mean S/N (dB) and mean Ra (μm) by factor level.

Cutter	Factor	L1 S/N	L2 S/N	L3 S/N	Δ (dB)	Rank	Best level	Ra at L1 / L2 / L3 (μm)
HSS	Speed	4.29	4.02	4.34	0.33	3	1000 rpm	0.617 / 0.647 /
	Depth	4.36	4.97	3.32	1.65	1	1.0 mm	0.613 / 0.577 /
	Feed	4.46	3.69	4.50	0.81	2	21.5	0.607 / 0.663 /
Carbide	Speed	6.83	6.55	8.04	1.49	2	1000 rpm	0.457 / 0.483 / 0.410
	Depth	8.19	6.21	7.03	1.98	1	0.5 mm	0.393 / 0.493 /
	Feed	6.87	6.94	7.62	0.75	3	21.5	0.463 / 0.460 /

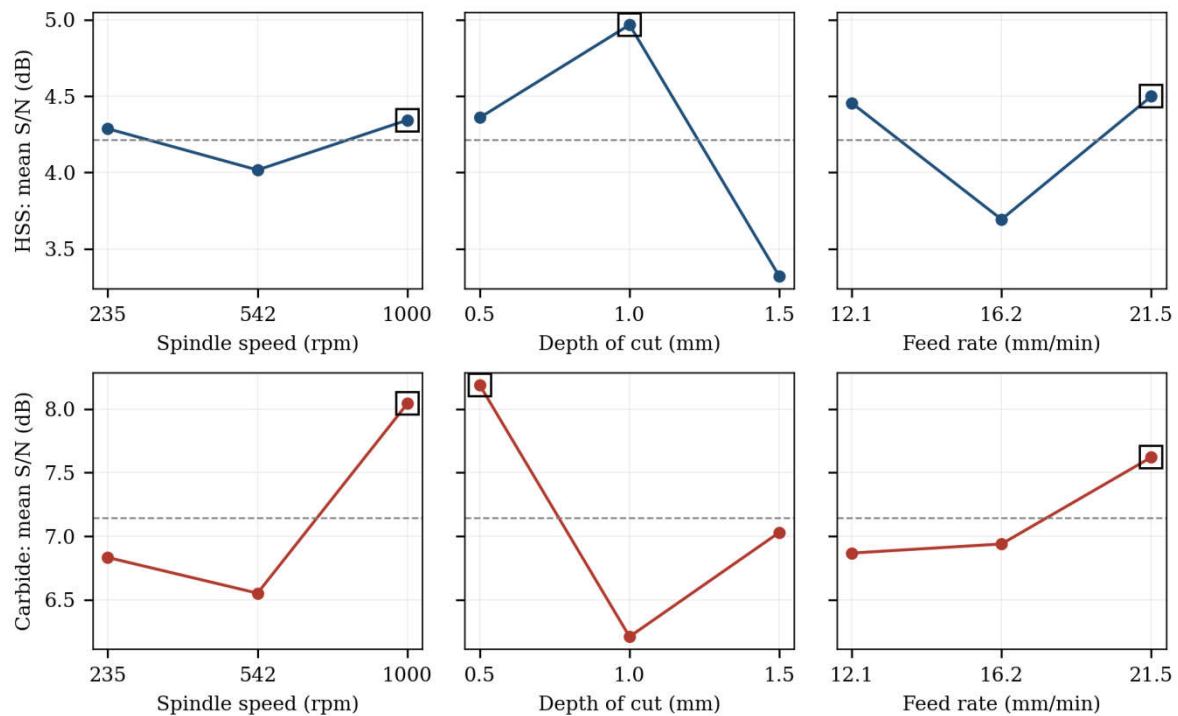


Figure 1. Main-effect plots of the mean S/N ratio for HSS (top row) and carbide (bottom row). Dashed lines show the overall mean S/N and open squares mark the best level of each factor.

3.3 Analysis of variance

The ANOVA is provided as tables 4 and 5. In both cases, most of the variation is due to the residual error (79.2% in the case of HSS, and 68.0% in the case of carbide), and no factor has a value larger than the critical value of 19.00. The most important factor contributions are the depth of cut (15.4% for HSS tools and 19.1% for carbide tools), but the corresponding F ratios are low (0.19 and 0.28). The smallest factor is pooled in the error, thus the error degrees of freedom becomes four, and the critical value drops to 6.94, however, the largest factor F value is then 0.54 (carbide, depth of cut). The model is additive and explains 21% of the total variance (HSS) and 32% (carbide).

Table 4. ANOVA for Ra, HSS cutter (critical $F_{0.05;2,2} = 19.00$).

Source	DOF	SS (μm^2)	MS (μm^2)	F	p	P (%)
Spindle speed	2	0.00162	0.00081	0.01	0.985	1.2
Depth of cut	2	0.02136	0.01068	0.19	0.837	15.4
Feed rate	2	0.00576	0.00288	0.05	0.950	4.2
Error	2	0.10962	0.05481	—	—	79.2
Total	8	0.13836				100

Table 5. ANOVA for Ra, carbide cutter (critical $F_{0.05;2,2} = 19.00$).

Source	DOF	SS (μm^2)	MS (μm^2)	F	p	P (%)
Spindle speed	2	0.00827	0.00413	0.15	0.872	10.0
Depth of cut	2	0.01580	0.00790	0.28	0.781	19.1
Feed rate	2	0.00247	0.00123	0.04	0.958	3.0
Error	2	0.05627	0.02813	—	—	68.0
Total	8	0.08280				100

3.4 Predicted optimum and its reliability

The ANOVA is provided as tables 4 and 5. In both cases, most of the variation is due to the residual error (79.2% in the case of HSS, and 68.0% in the case of carbide), and no factor has a value larger than the critical value of 19.00. The most important factor contributions are the depth of cut (15.4% for HSS tools and 19.1% for carbide tools), but the corresponding F ratios are low (0.19 and 0.28). The smallest factor is pooled in the error, thus the error degrees of freedom becomes four, and the critical value drops to 6.94, however, the largest factor F value is then 0.54 (carbide, depth of cut). The model is additive and explains 21% of the total variance (HSS) and 32% (carbide).

Table 6. Predicted optimum compared with the best measured run.

Cutter	Predicted optimum (speed / depth / feed)	Predicted Ra (μm)	Predicted S/N (dB)	CI, R = 1 ($\pm \mu\text{m}$)	Best measured run (Ra, μm)
HSS	1000 rpm / 1.0 mm / 21.5 mm/min	0.554	5.12	1.34	Run 4: 0.45
Carbide	1000 rpm / 0.5 mm / 21.5 mm/min	0.330	9.63	0.96	Run 7: 0.30

3.5 Three-dimensional response surfaces

The surfaces at the optimum level of the predicted parameter can be seen in figure 2. Surface is a ridge for HSS with a minimum depth near 1.0 mm, and a shallow dish for speed and feed with a minimum depth of 0.05 μm . Carbide is the lowest in the high-speed, low-depth, high-feed corner, and the surface becomes higher as you move towards 542 rpm and 1.0 mm. The optimum prediction is marked with dots. The model is additive so each axis is shaped the same throughout the model, with the uncertainty defined in Section 3.3 being represented on the surfaces of the model.

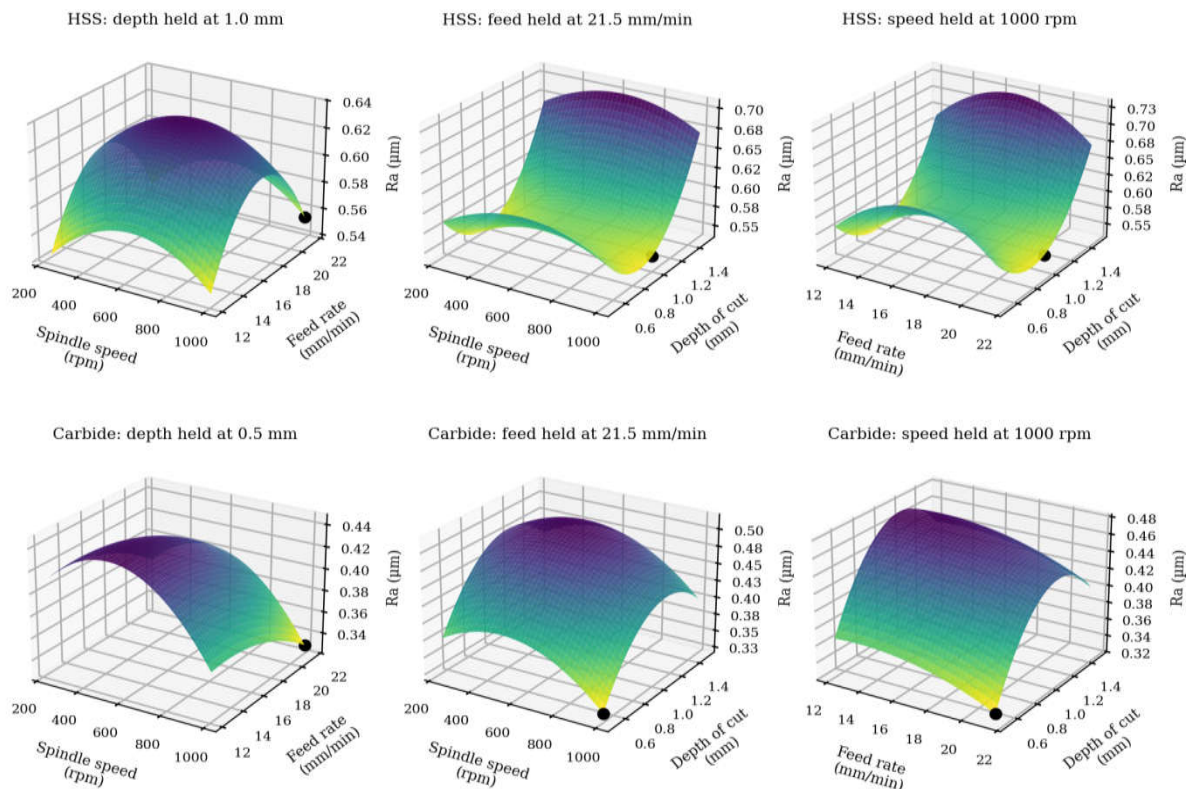


Figure 2. Response surfaces of Ra from the additive quadratic model. Top row: HSS; bottom row: carbide. The third factor is held at its predicted optimum level (stated above each panel) and the black dot marks the predicted optimum.

3.6 Roughness against feed per revolution

However, feed per revolution (F/N) varies widely from 0.0121 to 0.0915 mm/rev over the 9 runs, or by a factor of 7.6. This quantity is plotted in figure 3 against Ra. There is no visible trend, and the Pearson coefficients are -0.06 (HSS, $p = 0.88$) and 0.11 (carbide, $p = 0.78$). There is no difference in the highest feed per revolution (run 1) compared to the lowest (run 9) for either cutter.

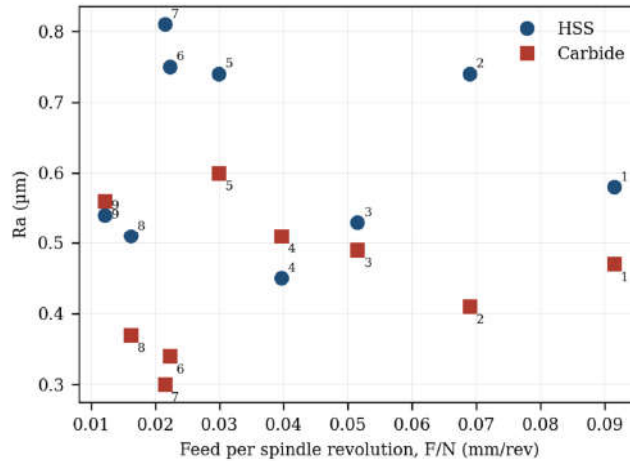


Figure 3. Ra against feed per spindle revolution for both cutters. Numbers beside the symbols are run numbers.

3.7 SEM observations of the machined surfaces

Figure 4 shows the three imaged conditions at 500 $\times$, 5 kX and 15 kX, and Table 7 summarizes them. At 500 $\times$ all surfaces carry feed marks at about the same inclination, but the 1000 rpm surfaces (Figure 4b, c) look smoother and more uniform than the 542 rpm surface (Figure 4a), which has numerous fine scratches and a few bright debris particles. The faint rectangular patch in Figure 4a has the outline of an earlier scan window and is most likely beam-induced contamination.

At 5 kX the 542 rpm surface (Figure 4d) shows fine mottled dark and light contrast across the whole field, overlain by bright smeared ridges. The 1000 rpm, 0.5 mm surface (Figure 4e) is lighter, with one wide feed groove with a bright rim and a scatter of isolated dark features. The 1000 rpm, 1.0 mm surface (Figure 4f) shows dispersed dark mottling and a second set of fine marks crossing the main feed direction. At 15 kX the 542 rpm surface (Figure 4g) displays broad bright bands of smeared material beside sharply bounded dark patches, as if material had been dragged along the feed direction. The 1000 rpm, 0.5 mm surface (Figure 4h) is comparatively featureless between rounded dark pits or blobs of roughly 2 to 5 μm , which sometimes line up along a groove. The 1000 rpm, 1.0 mm surface (Figure 4i) is crossed by a deep continuous groove with bright edges, flanked by speckled light and dark texture.

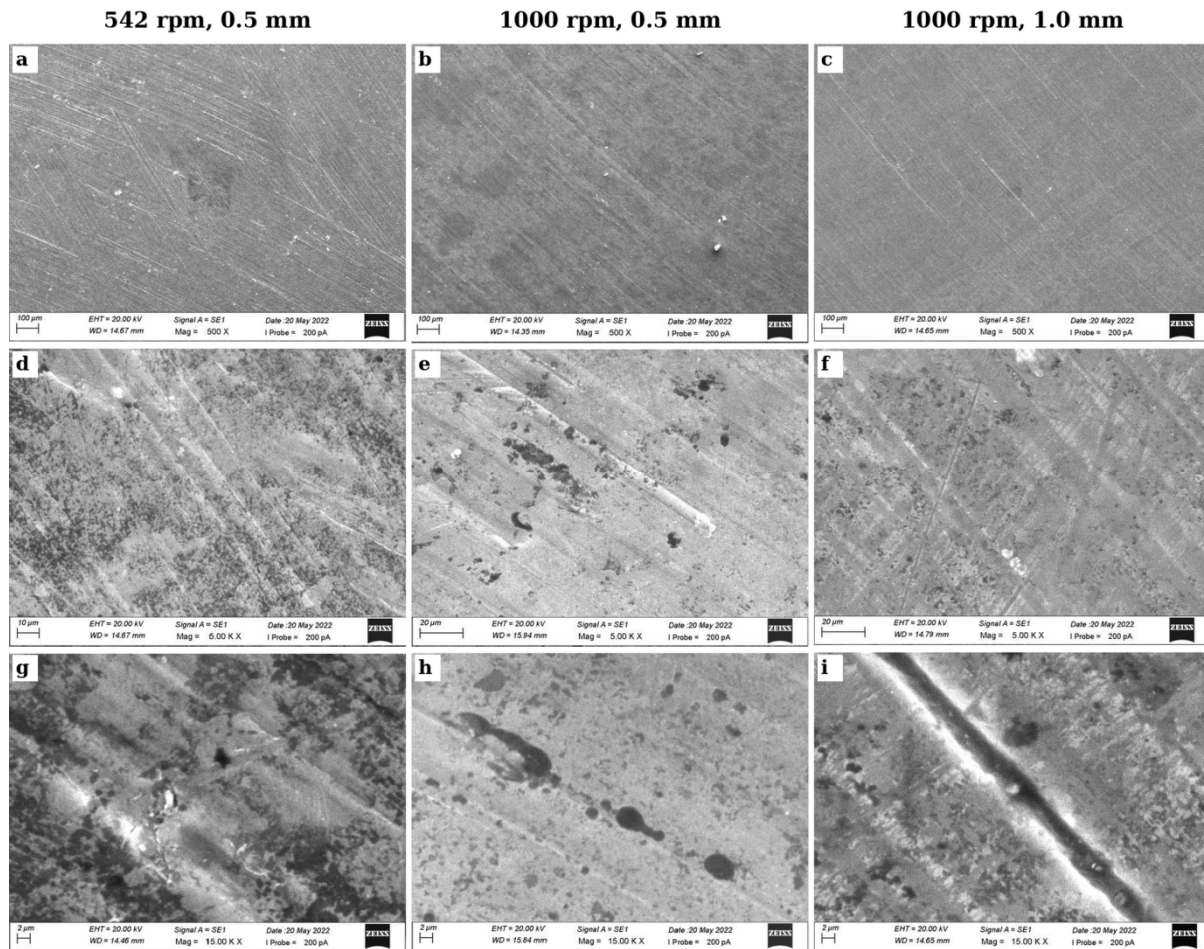


Figure 4. SE micrographs of the machined AZ61 surface. Columns: 542 rpm and 0.5 mm (a, d, g; run 6); 1000 rpm and 0.5 mm (b, e, h; run 8); 1000 rpm and 1.0 mm (c, f, i; run 9). Rows: 500 $\times$ (a–c), 5 kX (d–f), 15 kX (g–i). Scale bars are those printed on each micrograph.

Table 7. Summary of SEM observations and the roughness of the corresponding runs.

Condition	Run (feed)	Ra HSS (μm)	Ra carbide (μm)	Main features
542 rpm, 0.5 mm	6 (12.1)	0.75	0.34	Closely spaced scratches; mottled dark/light contrast; bright smeared bands; sharply bounded dark patches
1000 rpm, 0.5 mm	8 (16.2)	0.51	0.37	Smoothest at low magnification; wide groove with bright rim; isolated rounded dark pits of about 2–5 μm
1000 rpm, 1.0 mm	9 (12.1)	0.54	0.56	Uniform fine marks; crossing second set of marks; deep continuous groove with bright edges; speckled mottling

Figure 5 renders the 5 kX micrographs as grey-level surfaces. The 542 rpm map has broad bands with large light–dark swings, the 1000 rpm, 0.5 mm map has a flatter background with narrow, deep spikes that correspond to the dark pits, and the 1000 rpm, 1.0 mm map has the lowest amplitude. The absolute grey level depends on detector and brightness settings, so only the spatial pattern is comparable between the panels.

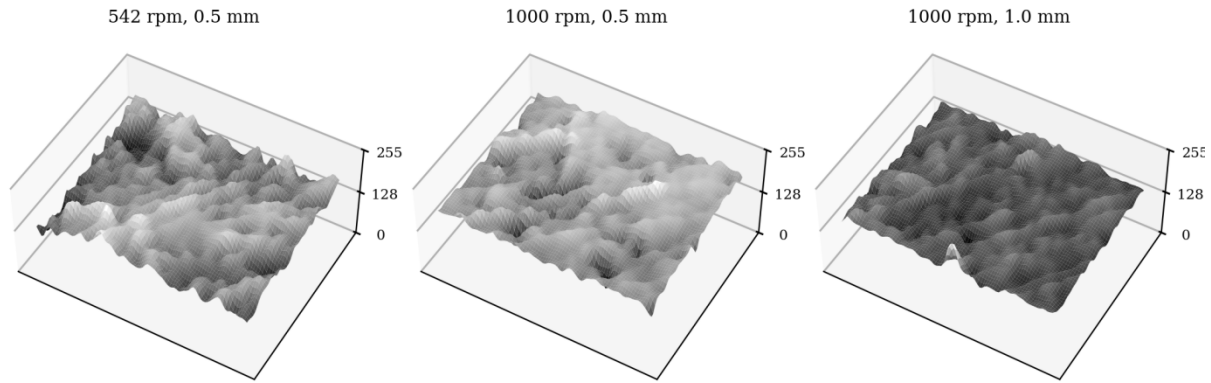


Figure 5. Grey-level surface plots of the 5 kX micrographs of Figure 4d–f (relative secondary-electron signal, 0–255, lightly smoothed). They are visual aids and not measurements of height.

4. Discussion

4.1 Statistics support for the inferences

For significant results an F ratio must be greater than 19 with 2 degrees of error, the data yield ratios of less than 0.3. The nine runs are therefore used for ranking the factors, but cannot be used to isolate the run-to-run scatter among them at this level of Ra. The difference between the cutters is below 5%, but even this carries a message of need for care, since the carbide advantage lies in a range extending from -0.06 to $+0.51 \mu\text{m}$, with an interaction of the tool with the parameter that an L9 array cannot resolve. The abstract of the previous study of this data set indicates that 1 mm is optimal [1] while the S/N ranking here suggests that 0.5 mm is optimal and that 1.0 mm is last. The abstract alone does not reconcile these two results.

4.2 Influence of Feed rate

The roughness left by feed marks scales with the square of the feed per tooth, $f_z = f_r/z$, divided by the effective corner radius r_e :

$$Ra_{th} \approx \frac{f_z^2}{32r_e} \quad (8)$$

As a result of the high variability of f_r , this expression estimates a variation in the kinematic contribution by a factor of 57. None of the measured Ra's exceeds the measured value (Figure 3), and the S/N range of feed is the smallest or second smallest for both cutters, thus there is no restriction on Ra at these low feeds due to the geometric feed marks. Other sources dominate: built-up material on the cutting edge, to which [2] correlated the presence of roughness in dry cutting of AZ31, vibration and run-out, and lateral material flow, which seems to be suggested by the smeared bands in Figure 4g. The S/N ratio is slightly higher at 21.5 mm/min, which could be considered as a thicker uncut chip and less rubbing but it is less than 1 dB and non-stable.

4.3. Influence of Spindle speed

Zakaria and other researchers [2] found that for turned AZ31 Ra decreased as cutting speed increased. They connected this to softening and a smaller built-up edge. At the time near-surface hardness went down and the featureless layer became thicker. The carbide means follow the roughness direction (0.457, 0.483 and $0.410 \mu\text{m}$ at 235, 542 and 1000 rpm). The HSS means (0.617, 0.647 and $0.620 \mu\text{m}$) stay flat. For both cutters 542 rpm is the level. A maximum at speed is the usual sign of a built-up edge. This happens within a window of temperature and contact conditions. The smeared ridges at 542 rpm (Figure 4d g) match this idea. However SEM of the surface cannot confirm it. The speed effect is not significant, in the ANOVA.

4.4 Influence of Depth of cut

Depth of cut has the largest S/N range for both cutters and the largest variance contribution (15.4% and 19.1%), but its preferred level depends on the tool. A larger axial engagement raises force, heat input and vibration tendency, which favours the smaller depth. When depth is small relative to the edge radius, ploughing replaces shearing, which would penalise a rounded HSS edge at 0.5 mm and could explain why HSS performs best at 1.0 mm while carbide, which keeps a sharper edge at higher temperature, performs best at 0.5 mm. This is a hypothesis, since edge radius and cutting force were not measured. In the SEM images, going from 0.5 to 1.0 mm at 1000 rpm coincides with a deeper continuous groove and crossing marks (Figure 4f, i), but feed also changed from 16.2 to 12.1 mm/min, so the two effects cannot be separated.

4.5 Effect of the machining parameters on the microstructure

The parameters act on the microstructure through the strain, strain rate and temperature they impose on the layer being cut. Feed and depth set the uncut chip section and so the force and the volume deformed; spindle speed raises the strain rate and, through friction and plastic work, the temperature. At low temperature hexagonal magnesium deforms by twinning and shear banding, as in the machined AZ91 of [3]; at higher temperature further slip systems and dynamic recrystallisation (DRX) become available and thermal softening raises ductility. The combined effect is expressed by the Zener–Hollomon parameter,

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) \quad (9)$$

where Q is the activation energy, R the gas constant and T the absolute temperature; the recrystallised grain size generally decreases as Z rises ($d_{\text{DRX}} \propto Z^{-n}$, with n a material constant). Because higher spindle speed raises strain rate and temperature together, its net effect on Z can be small while the deformed layer still changes, a plausible reason for the weak, non-monotonic speed response seen here. This also matches [2], where the featureless layer thickened with speed while hardness fell, and where a built-up edge that enlarged the effective edge radius produced a deeper layer by burnishing the surface harder. That link ties the roughness mechanism of Section 4.3 to the microstructure beneath the surface.

Applied to the present results, the predicted optimum (high speed, highest feed, small to moderate depth) shortens the contact time and the engagement per tooth, so less heat should accumulate in the machined layer, with less smearing and a shallower deformed zone. The SEM images agree at the surface: the 1000 rpm surfaces show less smeared, mottled contrast than the 542 rpm surface, and the 1000 rpm, 0.5 mm surface is the cleanest at low and medium magnification. At 15 kX, however, it carries rounded dark pits. In SE images these can be depressions or pores, sites of pulled-out second-phase particles, or oxide and contamination. Asgari et al. [3] report that defects in machined AZ91 concentrate around secondary phases, making particle pull-out a candidate for a Mg–Al alloy that normally contains $\text{Mg}_{17}\text{Al}_{12}$; EDS would show whether the pits are Al-rich. Grain size, twin density and featureless-layer thickness cannot be taken from these images, since they need polished and etched cross-sections or EBSD, so statements about the subsurface remain inferences from the literature and not results of this study.

4.6 Effect on Tool material

In seven out of the nine runs Carbide achieved a lower mean R_a than HSS, in agreement with [1]. The typical explanations are that carbide maintains its hardness and edge sharpness at cutting temperatures, conducts heat away from the edge more efficiently and adheres less to magnesium, all of which help to reduce built-up edge and ploughing. These points are general considerations in machining; in this case tool wear and temperature were not measured. In the two runs in which HSS performed better (runs 4 and 9, by 0.06 and 0.02 μm) the difference lies within a plausible range of variation for a single trace, although this cannot be verified without carrying out further measurements.

4.7 Implications for fatigue life

No fatigue tests were made, so any statement on fatigue is a design hypothesis. Because crack initiation takes up much of fatigue life [6], continuous grooves and pits such as those in Figure 4h and 4i are the features most likely to initiate cracks. The ZK61M work [4] shows that surfaces of equal roughness can differ more than fourfold in life through texture direction alone, so low Ra is a necessary check and not a sufficient one. Of the three imaged conditions, 1000 rpm with 0.5 mm is the most promising finishing condition, provided its dark pits are identified first. Fatigue specimens should be milled at that condition and at the best measured runs, with the feed marks parallel to the loading axis, as in the favourable case of [4].

4.8 Limitations and confirmation plan

Each run was measured only once, which means there is no estimate of either measurement or process scatter, and the ANOVA error is therefore just a model residual. Since the L9 array causes interactions to be confounded with error, the tool-by-parameter interaction seen in the data cannot be estimated. The SEM examines three conditions at each beam setting, and the contrast and scale calibration differ from one image to another. There is no data available on cross-sectional microstructure, hardness, residual stress, force or temperature, and the predicted optima have not been tested. In order to close these gaps it is necessary to take repeated Ra traces, carry out confirmation runs at the two predicted optima as well as at runs 4 and 7, carry out etched cross-sections or EBSD, carry out EDS on the dark pits, obtain micro hardness-depth profiles, measure areal roughness and residual stress, and conduct a response-surface design around 1000 rpm in order to estimate the interactions.

5. Conclusions

In this study, a comparative milling performances of HSS and Carbide cutters are executed to set out the optimal process parameters for the better surface value Ra and the impact of the optimized milling parameter on the microstructure of the AZ61 are studied and following conclusions were made from the statistical and graphical approaches.

1. Ra stayed below 1 μm for both cutters (HSS 0.45–0.81 μm , carbide 0.30–0.60 μm); carbide gave a 28% lower mean Ra (paired t -test, $p = 0.027$).
2. Depth of cut had the largest S/N range (1.65 dB for HSS, 1.98 dB for carbide), but no factor was significant at 95%; residual error carried 79% and 68% of the variation, so the factor ranking is descriptive.
3. The predicted optima are 1000 rpm, 1.0 mm and 21.5 mm/min for HSS (Ra 0.55 μm) and 1000 rpm, 0.5 mm and 21.5 mm/min for carbide (Ra 0.33 μm). Runs 4 (HSS, 0.45 μm) and 7 (carbide, 0.30 μm) already beat them, so confirmation runs are required.
4. Ra was unrelated to feed per revolution ($r = -0.06$ and 0.11) although that quantity varied 7.6-fold, pointing to adhesion, vibration and material flow, not feed-mark geometry, as the controlling mechanisms; the non-monotonic speed response, worst at 542 rpm, is consistent with built-up-edge behavior.
5. SEM showed finer feed marks at 1000 rpm than at 542 rpm, where smeared, mottled contrast prevailed. The 1000 rpm, 0.5 mm surface carried isolated dark pits of about 2–5 μm whose origin needs EDS, and the 1000 rpm, 1.0 mm surface a deep continuous groove. Links to grain refinement, twinning and DRX rest on the literature [2,3], not on these surface images.

Declarations

Author contributions: Dr.S.Muniraj carried out experimental design, analysis, results and discussion and complete drafting of this article. Mr. V.Senthilvelan brought out the literature study and conducted the experimental works and recorded the responses.

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