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High Speed Machining for Enhancing the AZ91 Magnesium Alloy Surface Characteristics: Influence and Optimisation of Machining Parameters

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ABSTRACT

In this study, optimum machining parameters are evaluated for enhancing the surface roughness and hardness of AZ91 alloy using Taguchi design of experiments with Grey Relational Analysis. Dry face milling is performed using cutting conditions determined using Taguchi L9 design and Grey Relational Analysis has been used for the optimisation of multiple objectives. Taguchi's signal-to-noise ratio analysis is also performed individually for both characteristics and grey relational grade to identify the most influential machining parameter affecting them. Further, Analysis of Variance is carried to see the contribution of factors on both surface roughness and hardness. Finally, the predicted trends obtained from the signal-to-noise ratio are validated using confirmation experiments. The study showed the effectiveness of Taguchi design combined with Grey Relational Analysis for the multi-objective problems such as surface characteristics studies.

Keywords: AZ91; Milling; Surface roughness; Microhardness; Taguchi; GRA

1. INTRODUCTION

Lightweight is always better especially in aerospace industries to achieve the green aviation concept, which deals with reducing global warming and environmental pollution. So, over the years many materials have been studied and experimented with to see if they meet the low weight - high strength - economical requirement of the aerospace industries. In detail, aerospace structural material requirements include properties such as great strength-stiffness, thermal, fatigue, corrosion & oxidation resistance, damage proof, low cost - servicing, high manufacturability etc.[1-2]. Magnesium (Mg) is a light metal with a density of 1.74g/cm^3 (2/3rd that of Al, 1/4th that of Iron)[3]. Magnesium is considered the easiest metal to machine with the lowest power consumption. Despite having good properties, several issues need to be identified to explore the full capabilities of Mg and its alloys. Their usage in the aviation industry has decreased tremendously in recent decades. Even though they pass the standards set by the aviation industries, there is always a concern about their flammability. Besides this, the corrosion resistance, high chemical reactivity, strength and difficulty to deform has been the few issues with the application of these alloys[3-4].

Machining is a widely used process in metals and their alloys, yet its application in producing components in aerospace industries has not been very significant, though there have been considerable efforts. Milling is the most widely used machining operation in the industry. Proper selection of machining parameters reduces the number of milling tests resulting in cost reduction. To optimise the cutting conditions, an accurate model of the milling operation is necessary. Improving the material surface characteristics such as roughness and hardness helps the material's overall functionality. In this regard, many researchers have focussed on its individual characteristics. Zeyveli[5]*, et al.* studied the effect of aging, feed rate & cutting speed on surface roughness of AZ91 alloy using dry turning operation. Feed rate was observed to have the highest impact on roughness, as it increased with it, whereas the cutting speed did not cause much impact. The aged samples showed a slight decrease in roughness compared to the roughness of as-cast material. Rubio[6-7]*, et al.* experimented on UNS M11917 alloy using dry face turning with three different types of tool coatings. From ANOVA statistical tool, they observed high surface roughness with high feed rates and other parameters did not matter. Carou[8]*, et al.* during finish intermittent turning of UNS M11917, have observed maximum temperature at high feed and high depth machining, which could be decreased with the increase in slot width. During comparison with the MQL condition, they again observed the feed rate being the only influential factor and concluded that the longer machining times could produce better surface finishes with MQL. Ruslan[9]*, et al.* in their investigation on AZ91D, have analysed the application of milling operation on improving the surface roughness. Uncoated cemented carbide insert was used for a 4-level factorial design and 9 experiments are performed. S/N

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ratio and ANOVA was used to predict the optimal conditions and the study showed significant improvement of surface roughness (0.061µm–0.133µm) for the tested high speed (900rev/min–1400rev/min) machining conditions.

Vishwanathan[10], *et al.* have investigated the AZ91D alloy behaviour under dry turning operations with PCD tools. Taguchi with response surface methodology helped reduce the number of experiments as well as create a standard set of cutting conditions. They observed the feed rate having a greater impact on roughness, whereas speed and cutting depth proved to be insignificant. Eker[11], *et al.* used MQL approach to study the behaviour of AZ91D alloy using turning operations. From the Taguchi design, 9 experiments were conducted for speed (A1 - 230, A2 – 330, A3 – 430 m/min), feed (B1 – 0.2, B2 – 0.35, B3 – 0.5 mm/rev) and cutting depth (C1 – 1, C2 – 2, C3 – 3 mm). They observed better roughness in the cryogenic condition and with the use of S/N ratio, they identified the lowest feed, lowest speed and intermediate depth (A1B1C2) combination as most optimal. Gziut[12], *et al.* investigated AZ91HP alloy behaviour using milling. Among all the tested factors, they found the tool rake angle and feed rate has a great impact in improving the surface roughness. The best surface finish was observed at a high speed run along with lowered feed rate and lowered rake angle. Shi[13], *et al.* evaluated AZ91D alloy surface roughness under dry milling operations using uncoated carbide inserts. Depth & width of cut were kept constant for varying speeds and varying feeds and the results showed the speed being the major factor for roughness alterations. Klonica[14], *et al.* have investigated the AZ91D alloy behaviour using dry milling operations. PCD tools are used and the roughness in terms of R_a and S_a were analysed for a speed range (100m/min - 300m/min) and feed (.05 mm/teeth - .25 mm/teeth). Increased roughness with increased feed was the trend observed in their work. Zagorski[15,16], *et al.* in their investigations on AZ91D using milling with TiAlN-coated carbide cutter and PCD coated cutter, compared the 2D and 3D roughness parameters. The research showed feed increment resulting in increased roughness and the speed increment decreased the roughness values. Sunil[17], *et al.* used drilling operations to study the effect of Al content on AZ31 and AZ91 material hardness. AZ91 showed higher hardness variations than the AZ31 indicating the effect of ($Mg_{17}Al_{12}$) on the machinability of these alloys.

Taguchi model is generally applied in single-objective problems. In cases of multiple quality characteristic measurements, there is a need to use a different approach. Shi[18], *et al.* in their investigation, tried to evaluate the roughness and hardness of AZ91D alloy. Here the conventional Taguchi method was not applicable due to the requirement of combined results with the lowest surface roughness and highest microhardness. They used a statistical model - Grey Relational Analysis (GRA), which is suitable for optimizing multiple characteristics to a single objective. Further, S/N & ANOVA are used to make useful conclusions regarding the most influential factor feed rate. Ramesh[19], *et al.* in their investigations on AZ91D alloy, have compared the GRA with the TOPSIS method for roughness & tool wear. The results from GRA and TOPSIS showed the lowest feed, lowest speed & lowest depth (A1B1C1) as the most optimal condition. During comparison between GRA and TOPSIS, they also observed similar results for the best and the worst conditions. From ANOVA, feed rate and speed are found out to be most influential on roughness & wear rate respectively.

The literature survey showed several studies focused on individual surface characteristics and only a few studies on multiple surface characteristics of AZ91 alloy. It is also identified that most of the work on AZ91 is performed using turning operations and very few studies has been conducted using milling operations. As we know, milling is the most widely used operation in the industry due to its flexibility and high productivity, when compared to other processes such as turning, drilling etc. Further, the application of statistical tools helps in reducing the experimental costs, time and in the decision making process. Literature survey showed a suitable Taguchi design of experiments (DOE) along with either Grey Relational Analysis (GRA) or TOPSIS is the most suitable method for multi-objective problems such as surface characteristic studies. Therefore, the present study aims to improve the multiple surface characteristics of one of the most demanding lightweight alloys in the current aerospace society, using the most widely used machining process in the manufacturing industry. The study focuses on helping the industry needs in terms of improving productivity as well as reducing wastages, by providing the most optimal machining condition for AZ91 alloy. In this regard, a study of AZ91 alloy surface characteristics under high speed dry face milling is performed to identify the important machining parameters in improving the alloy surface characteristics thereby their overall performance. Optimal machining conditions has been identified using Taguchi L9 DOE with GRA, ANOVA & S/N statistical tools, which would help the manufacturers in improving the overall product quality along with reduced production cost and time.

2. MATERIALS AND METHODOLOGY

2.1 Materials

AZ91 is the material tested in this study with blocks of 50 x 50 x 50 mm size. The AZ91 alloy consists of magnesium (89.43 %), aluminium (9.12 %), zinc (0.98 %), manganese (0.47 %) and the minimum quantities (0.00 %) of cadmium, copper, nickel respectively. The cutter used is SECO R220.69-0050-12-5AN and the uncoated carbide insert used in this study is SECO XOEX120404FR-E06 H15.

2.2 Machining Setup

Face milling operation is performed on a CNC milling machine (BFW - BMV 45 T20). A cutting length of 50 mm is fixed and a fresh insert has been used for each experiment, to eliminate the effect of possible wear. Fig. 1 (a) & (b) shows the machining setup & schematic diagram of the setup.

2.3 Design of Experiments (DOE)

High speed machining is performed for the range of process parameters listed in Table 1. Experiments have been conducted for the cutting conditions selected from L_9 Taguchi design, and additional experiments for validation purposes are shown in Table 2. Taguchi type model reduces the money and

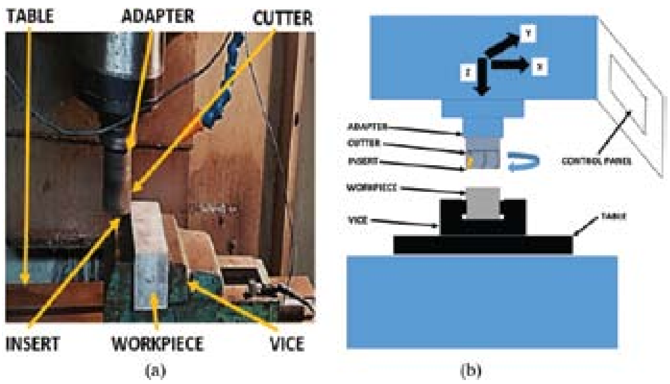


Figure 1. (a) Machining setup (b) Schematic diagram.

Table 1. Experimental conditions

	Process Parameters			
	Variable	**Level 1**	**Level 2**	**Level 3**
A	Cutting speed, *V* (m/min)	500 (3182 RPM)	700 (4456 RPM)	900 (5729 RPM)
B	Feed rate/teeth, *f* (mm/z)	0.1	0.2	0.3
C	Depth of cut, *a* (mm)	0.5	1.0	1.5

time in terms of reduction in the number of experiments to be performed. After each machining pass, the surface roughness is measured using Taly Surf 50 (Taylor Hobson make). Similarly, after each machining pass, the microhardness is measured using Micro Vickers Hardness device HM – 200 (Mitutoyo make). The load used was 50 gf for the duration of 10 s. No tool wear of any form was observed during the experiments conducted and also there was no built-up edge (BUE) or built-up layer (BUL) formed. Videm[20], *et al.* have stated that carbide inserts' life when machining Mg is five to ten times higher than that of machining Al. This is due to the fact that the insert material (carbide) is very hard and will not be harmed from machining a softer material such as magnesium alloys even at the high speed (v=900 m/min) condition. The carbide cutting inserts' superior hardness makes it very resistant to wear against abrasion by hard β-phases of the workpiece material. These facts make carbide inserts a good choice for cutting magnesium alloys such as AZ91 even at high speed conditions.

3. RESULTS AND DISCUSSION

3.1 Experimental Results

Table 2 shows the mean results of roughness and microhardness mean values measured from the experiments.

3.2 Grey Relational Analysis

In this study, GRA is the technique used to optimise the roughness and microhardness. Combining the design of experiment with GRA is a useful tool for problems having more than a single objective. From GRA, the multiple objectives are transformed to a single one, so that higher level of surface characteristics can be obtained. GRA involves the following steps:

3.2.1 Normalizing the Measured Values

The normalisation techniques adopted based on lower the better and higher the better for roughness and hardness respectively. 'Lower the better' & 'Higher the better' equations are as follows:

$$y_i^*(k) = \left(\frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \right) \tag{1}$$

Table 2. Results of roughness and hardness

Experiment No.	**Speed *v***	**Feed *f***	**Depth *a***	**Roughness Ra (µm)**	**Microhardness HV**
RAW (As received)				0.438	-
RAW (Fine Polished)				0.160	69.4
L9 Taguchi Design					
1	500	0.1	0.5	0.094	86.2
2	500	0.2	1.0	0.096	91.8
3	500	0.3	1.5	0.154	91.2
4	700	0.1	1.0	0.070	84.0
5	700	0.2	1.5	0.124	88.4
6	700	0.3	0.5	0.208	86.8
7	900	0.1	1.5	0.067	87.1
8	900	0.2	0.5	0.087	89.7
9	900	0.3	1.0	0.148	74.4
Additional experiments (for validation purpose)					
10	700	0.2	1.0	0.118	89.1
11	700	0.3	1.0	0.128	90.4
12	900	0.2	1.0	0.078	86.4

and

$$y_i^*(k)=\left(\frac{x_i^0(k)-\min x_i^0(k)}{\max x_i^0(k)-\min x_i^0(k)}\right) \tag{2}$$

here, $x_i^0(k)$ = measured values, $\max x_i^0(k)$ = maximum value of $x_i^0(k)$ values, $\min x_i^0(k)$ = minimum of $x_i^0(k)$ values, i = number of tests, k = quality characteristic.

3.2.2 *Grey Relational Coefficient (GRC)*

GRC is calculated using the formula:

$$\in_i(k)=\left(\frac{\Delta_{\min}-\zeta\Delta_{\max}}{\Delta_{0i}(k)-\zeta\Delta_{\max}}\right) \tag{3}$$

here, $\Delta_{0i}(k)$ = offset in the absolute values between the reference $y_0^*(k)$ and comparability $y_i^*(k)$ sequence, ζ = 0.5 = distinguishing coefficient, $\Delta_{\min}$ and $\Delta_{\max}$ = least and highest of $\Delta_{0i}(k)$.

3.2.3 *Grey relational grade (GRG):*

GRG is evaluated by averaging the GRC's:

$$\gamma_i=\frac{1}{n}\sum_{k=1}^{n}\in_i(k) \tag{4}$$

here, γ_i varies between 0 to 1, & n = number of tests. Normalised values and deviation sequence values for roughness and hardness, using Eqn (1) & Eqn (2), are listed in Table 3. The GRC's are evaluated using Eqn (3). Table 3 also shows the GRG's using Eqn (4) and the corresponding ranks based on these. From Table 3, it is clear that the highest GRG value represents the best condition of parameter for improved surface characteristics. Therefore, the most optimum parameters combination is chosen as A1B2C2(Rank 1): *V*=500 m/min, *f*=0.2 mm/teeth, & *a*=1 mm. All calculations and analysis of GRA is performed using MS Excel 2016 software.

3.3 Signal to Noise Ratio

S/N ratios are evaluated for surface roughness, microhardness and GRG's using MINITAB 17 statistical software[9-11,19]. Normally, the higher Signal to Noise ratio value indicates the most optimal choice of parameters. Under usual circumstances, without using GRA, the optimum condition can be obtained from S/N graphs.

From Table 4, the roughness is observed to have been greatly influenced by feed rate, which is identified by researchers[5-16,18-19] in their study on AZ series alloys. For microhardness, the most significant parameter is observed to be the cutting speed. There is not much evidence for this finding, as there is very limited research on the microhardness of machined AZ alloys. However, among the findings from previous researchers, there has been evidence of speed and feed rate having significant influence on microhardness. Shi[13], *et al.* revealed the feed rate as more impactful on microhardness whereas, Uddin[23], *et al.* have found the speed as the dominant factor. Further, from Fig. 2 (a) & (b) the optimum conditions for lowest surface roughness is A3B1C2: *V*=900 m/min, *f*=0.1 mm/teeth, & *a*=1.0 mm, and for highest microhardness is A1B2C3: *V*=500 m/min, *f*=0.2 mm/teeth, & *a*=1.5 mm.

Overall, Table 4 and Fig. 3 shows the influence of each machining parameter on GRGs. A higher GRG value represents the best condition. So, the predicted optimum combination of factors for better surface roughness & microhardness are selected as A1B2C3: *V*=500 m/min, *f*=0.2 mm/teeth, & *a*=1.5 mm. And, it can also be concluded that feed rate is the most influential factor affecting the AZ91 alloy in terms of roughness & hardness.

3.4 Analysis of Variance

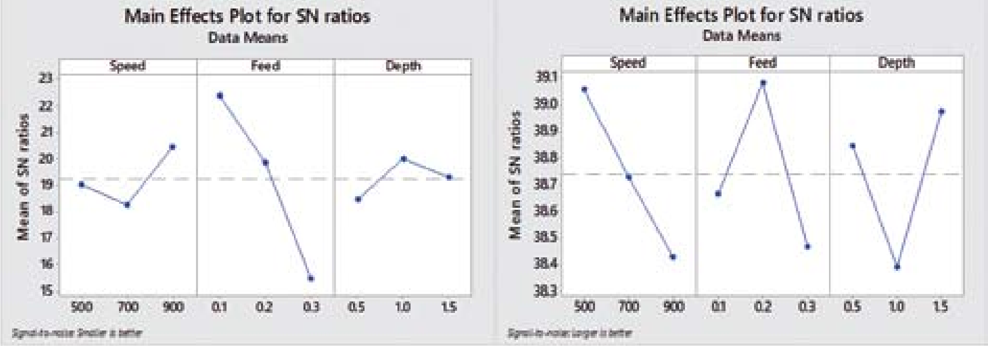
ANOVA is a collection of statistical techniques and their related estimation procedures are utilised to evaluate the differences among means. Many researchers[7-11,18-19] in their work on surface integrity studies, have utilised ANOVA to

Table 3. Grey relational analysis

Exp. No.	Ra	HV	Ra	HV	Ra	HV	GRG	RANK
	Normalised		*DEV. SEQ.*		*GRC*			
1	0.806	0.678	0.194	0.322	0.721	0.608	0.665	6
2	0.790	1.000	0.210	0.000	0.704	1.000	0.852	1
3	0.381	0.966	0.619	0.034	0.447	0.935	0.691	5
4	0.974	0.552	0.026	0.448	0.950	0.527	0.739	4
5	0.592	0.805	0.408	0.195	0.551	0.719	0.635	7
6	0.000	0.713	1.000	0.287	0.333	0.635	0.484	8
7	1.000	0.730	0.000	0.270	1.000	0.649	0.825	2
8	0.855	0.879	0.145	0.121	0.776	0.806	0.791	3
9	0.423	0.000	0.577	1.000	0.464	0.333	0.399	9

Table 4. Response Table

Surface Roughness - Ra (Smaller is better)				**Microhardness - HV (Larger is better)**				**GRG (Larger is better)**			
Level	*V*	*f*	*a*	Level	*V*	*f*	*a*	Level	*V*	*f*	*a*
1	19.04	22.39	18.46	1	39.06	38.67	38.85	1	-2.716	-2.618	-3.964
2	18.27	19.88	20.00	2	38.73	39.08	38.39	2	-4.292	-2.460	-4.001
3	20.45	15.49	19.30	3	38.43	38.47	38.98	3	-3.900	-5.830	-2.943
Delta	2.17	6.90	1.53	Delta	0.63	0.61	0.59	Delta	1.576	3.371	1.058
Rank	2	1	3	Rank	1	2	3	Rank	2	1	3



(a) (b)

Figure 2. Effect of machining conditions on (a) Ra and (b) HV.

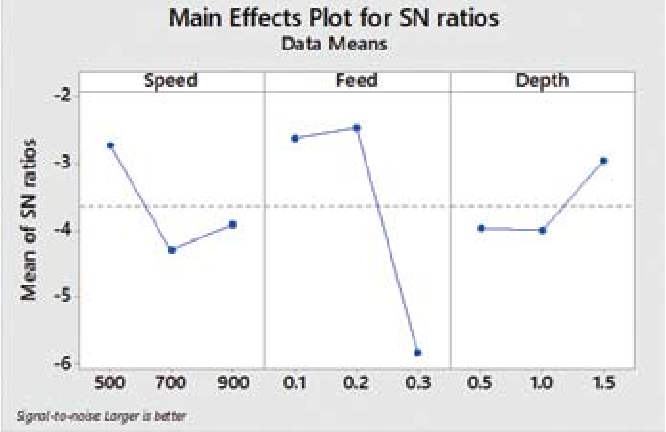


Figure 3. Effect of machining conditions on GRG.

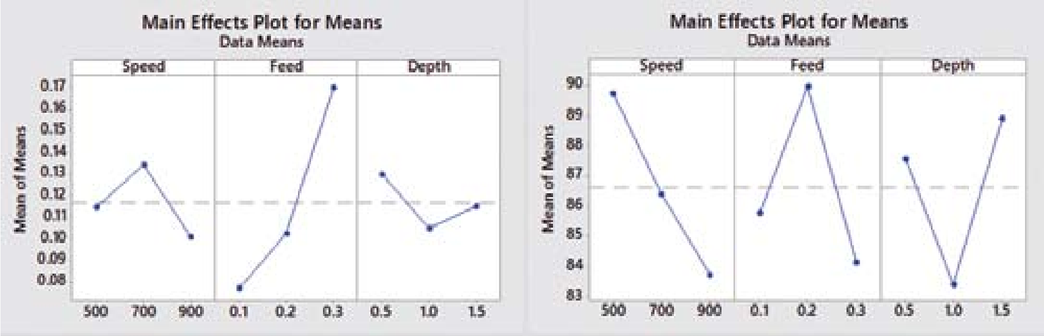
identify the most influential parameters affecting the output. The ANOVA results of the present study on surface roughness, microhardness and GRG's are presented in Table 5. For surface roughness, the feed rate is the most dominant factor followed by cutting speed and cutting depth. The contribution of feed, speed & depth of cut on roughness is 82.51 %, 8.22 % and 3.98 % respectively as shown in Table 5. For microhardness, cutting speed is most dominant followed by feed and depth of cut respectively. The contribution of speed, feed & depth of cut on microhardness is found to be 24.57 %, 24.52 % and 23.60 % respectively (Table 5), with marginal differences. Finally, the ANOVA for GRGs is performed and the results are shown in Table 5. The feed rate was observed to have more contribution (56.06 %) with lesser contributions from cutting speed (10.42 %) & depth of cut (5.58 %).

Table 5. ANOVA Results

Factors	DOF	SS	MS	Contribution (%)
Surface Roughness - Ra				
Cutting speed	2	7.287	3.644	8.22
Feed rate	2	73.149	36.574	82.51
Depth of cut	2	3.537	1.768	3.98
Error	2	4.674	2.337	
Microhardness - HV				
Cutting speed	2	.5890	.2945	24.57
Feed Rate	2	.5878	.2939	24.52
Depth of cut	2	.5658	.2629	23.60
Error	2	.6539	.3270	
GRG				
Cutting speed	2	4.038	2.019	10.42
Feed Rate	2	21.707	10.853	56.06
Depth of cut	2	2.163	1.081	5.58
Error	2	10.813	5.407	

3.5 Experimental Validation

The ANOVA and S/N Plots identified the most influential parameters affecting the surface characteristics of the selected material. Further, Taguchi mean plots for surface roughness and microhardness are shown in Fig. 4 (a) and (b) respectively. The most influential factor (feed rate) on surface roughness



(a) (b)

Figure 4. Trend for (a) Ra and (b) HV.

showed an incremental trend, which means the roughness increased with increasing feed rate[5-9,13-16,19]. As feed increase, the material removal rate increases, which leads to an increase in friction at the tool–workpiece contact area resulting in high surface roughness[21-22]. Similarly, the most influential factor (cutting speed) on microhardness showed a decremental trend, which means the microhardness decreased with increasing cutting speed[21-22,24]. This phenomenon is due to the increase in temperature in dry machining with increased cutting speed, leading to thermal softening[22,25-26].

These conclusions are further validated using additional machining experiments listed in Table 2. Validation experiments in the present study are actually the additional experimental data generated that provide more support to the results observed from the use of statistical tools such as ANOVA & S/N (Fig. 4 (a) & (b)).These additional experiments are designed to show more proof for the trend of feed rate on roughness (By keeping constant speed & constant depth of cut) and trend of cutting speed on hardness (By keeping constant feed & constant depth of cut). Here, the depth of cut is kept constant due to its negligible influence (5% overall) on the surface characteristics of the alloy. Experiment no. 4, 10, 11 have varying feed rates f=0.1, 0.2, 0.3 mm/teeth with constant speed V=700 m/min & constant depth of cut a=1 mm. Further, the Ra variation with respect to varying feed rates is plotted using results from these experiments (Fig. 5). The trend clearly showed the surface roughness value increasing with increased feed rate. Similarly, experiment no. 2, 10, 12 have varying speeds V=500, 700, 900 m/min with constant feed rate f=0.2 mm/teeth & constant depth of cut a=1 mm. The microhardness variation with respect to varying cutting speeds is plotted (Fig. 6). Here, the trend clearly showed a decrease in microhardness with increased cutting speed. This validated the effect of the most influential factors on individual surface quality characteristics namely surface roughness & microhardness.

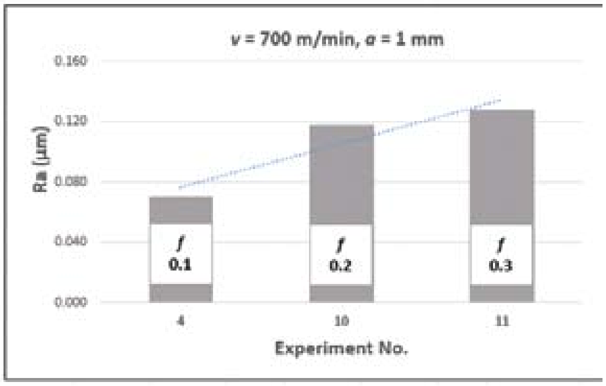


Figure 5. Surface roughness vs feed rate.

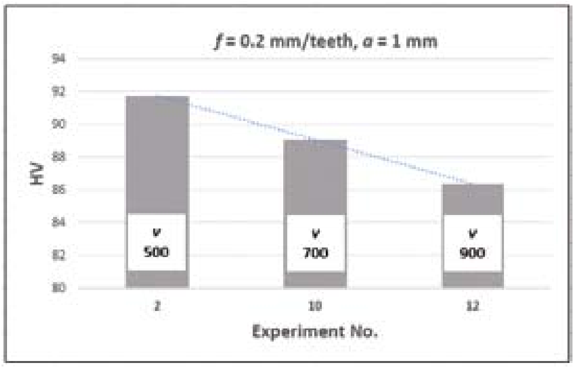


Figure 6. Microhardness vs cutting speed.

3.6 Discussion

Surface roughness is a major factor in the study of material surface integrity due to its relation to corrosion resistance. Samaneigo[27], *et al.* and Reddy[28], *et al.* in their work on AZ series alloys have discussed the impact of surface roughness on material corrosion properties, which is smoother the surface better is the corrosion resistance. In the studies using turning operation[5,19,22,29-32], the lowest roughness value reported is 0.21 µm at condition (v=40 m/min, f=0.1 mm/rev, a=0.5 mm) and in the studies using milling operation[9,13-16,18,23,33-37], the lowest roughness value reported is 0.061 µm at condition (v = 900 m/min, f = 0.03 mm/z, a = 0.2 mm). In the present study, the lowest Ra value (0.067 µm) is observed at the combination of the highest speed and lowest feed condition (Exp. No. 7), which is similar to the observations reported elsewhere[28,38]. The hardness of the machined surface is another aspect that plays a key role in deciding the surface integrity of the material in terms of improving wear and corrosion resistance[13,29]. The resultant hardness values obtained in the present study are in agreement with the findings reported elsewhere[18,33]. The highest surface hardness value observed in the present study is for the combination of lowest speed and intermediate feed condition (Exp. No. 2), which is similar to the observation made elsewhere[18].

To summarise, for the selected range of testing parameters (speed=500-900 m/min, feed=0.1-0.3 mm/teeth, depth of cut=0.5-1.5 mm) in the present study, surface roughness is most dominated by feed rate and can be reduced by machining at low feed rate. Whereas, microhardness is most dominated by cutting speed and can be increased by machining at low cutting speed. Therefore, lower feed is preferred if the objective is only to reduce the surface roughness and both experimental results (Optimal: A3B1C2= V=900 m/min, f=0.1 mm/teeth, & a=1.0 mm) and ANOVA results (Optimal: A3B1C3= V=900 m/min, f=0.1 mm/teeth, & a=1.0 mm have confirmed the condition with lowest feed as the most optimal condition for the objective of lower surface roughness. Whereas, lower speed is preferred if the objective is only to increase microhardness and both experimental results (Optimal: A1B2C2 = V=500 m/min, f=0.2 mm/teeth, & a=1 mm) and ANOVA results (Optimal: A1B2C3: V=500 m/min, f=0.2 mm/teeth, & a=1.5 mm) have confirmed the conditions with lowest speed as the most optimal condition for the objective of higher hardness.

4. CONCLUSIONS

In this paper, high speed dry milling on AZ91 magnesium alloy is performed to improve its surface characteristics - surface roughness & microhardness. For all the obtained results from the Taguchi design of experiments, a multiple objective optimisation is performed using GRA to find the most optimal machining conditions. Further, S/N & ANOVA are used to find the most influential factor affecting each surface characteristic as well as GRGs. The current study is more inclined towards applying optimisation techniques for identifying conditions for obtaining good surface characteristics as there is less focus on the physics behind the process involved, which will be covered in future publication. The conclusions can be summarised as follows–

(i) High speed milling greatly improved the surface roughness and microhardness. The lowest roughness (0.067µm) is an 85% improvement and highest microhardness (91.8 HV) is a 33% improvement from the raw material.

(ii) GRA successfully identified the optimal machining conditions for a combined criteria – lower the better roughness & higher the better hardness. As per GRA, the optimum condition was A1B2C2: V= 500 m/min, f= 0.2 mm/teeth, & a=1 mm.

(iii) S/N ratio plots predicted the optimal condition for the best surface roughness as - A3B1C2. This prediction is very close to the best condition from the experimental results – A3B1C3 (Ra = 0.067 µm). Similarly, the predicted optimal condition for the best microhardness is A1B2C3. This prediction is also very close to the best condition from the experimental results – A1B2C2 (HV = 91.8). S/N ratio plot for the GRG showed the predicted optimal condition as - A1B2C3. This prediction comes near to the GRA's top ranked condition A1B2C2.

(iv) The ANOVA and response table revealed that the feed rate is most dominant for roughness and cutting speed is dominant for hardness. Overall, feed rate is the most dominant on GRGs.

(v) Further, Taguchi mean plots revealed the most influential factor (feed rate) on surface roughness showing an increasing trend and the most influential factor (cutting speed) on microhardness decreased with cutting speed. Additional validation experiments established these trends.

REFERENCES

1. Zhu, L.; Li, N. & Childs, P. Light-weighting in aerospace component and system design. *Prop. Power Res.,* 2018, **7**(2), 103-119.
   doi: 10.1016/j.jppr.2018.04.001.
2. Marino, M. & Sabatini, R. Advanced lightweight aircraft design configurations for green operations. *In* Practical Responses to Climate Change, Engineers Australia, 2014.
   doi: 10.13140/2.1.4231.8405.
3. Ostrovsky, I. & Henn, Y. Present state and future of magnesium application in Aerospace industry. *In 'ASTEC'07 International Conference-New Challenges in Aeronautics*, Moscow, Russia, 2007, 1-5.
4. Jayaraja, J.; Prasanth, M.; Srinivasan, A.; Pillai, U. & Pai, B. Magnesium – in Indian Context. *Indian Foundry J.*, 2015, **61**(2), 49-55.
5. Zeyveli, M. The effect of aging and cutting parameters on surface roughness of az91 magnesium alloys. *In* 53th International Foundry Conference: Portorož *2015*, Portoroz, Slovenia, 2015.
6. Rubio, E.M.; Valencia, J.L.; Saa, A.J. & Carou, D. Experimental study of the dry facing of magnesium pieces based on the surface roughness. *Int. J. Precision Eng. Manufacturing,* 2013, **14**(6), 995-1001.
   doi:10.1007/s12541-013-0132-9.
7. Carou, D.; Rubio, E.M.; Lauro, C.H. & Davim, J.P. Experimental investigation on finish intermittent turning of UNS M11917 magnesium alloy under dry machining. *Int. J. Adv. Manufacturing Technol.*, 2014, **75**(9–12), 1417–1429.
   doi: 10.1016/j.measurement.2014.06.020.
8. Carou, D., Rubio, E., Lauro, C., & Davim, J. Experimental investigation on surface finish during intermittent turning of UNS M11917 magnesium alloy under dry and near dry machining conditions. *Measurement,* 2014, **56***,* 136-154.
   doi: 10.1016/j.measurement.2014.06.020.
9. Ruslan, M.S.; Othman, K.; A. Ghani, J.; Kassim, M.S. & CheHaron, C.H. Surface roughness of magnesium alloy az91d in high speed milling. *Journal Technology,* 2016, **78**(6-9).
10. Viswanathan, R.; Ramesh, S. Optimization of machining parameters for Magnesium alloy using Taguchi approach and RSM. *In* International Conference on Advances in Design and Manufacturing (ICAD&M'14), 2014, 337-340.
    doi: 10.13140/2.1.1515.6801.
11. Eker, B.; Ekici, B.; Kurt, M. & Bakir, B. Sustainable machining of the magnesium alloy materials in the CNC lathe machine and optimization of the cutting conditions. *Mechanics,* 2014, **20**(3).
    doi: 10.5755/j01.mech.20.3.4702.
12. Gziut, O.; Kuczmaszewski, J. & Zagórski, I. Surface Quality Assessment Following High Performance Cutting of AZ91HP Magnesium Alloy. *Management Production Eng. Rev.*, 2015, **6**(1), 4–9.
    doi: 10.1515/mper-2015-0001.
13. Shi, K.; Zhang, D.; Ren, J.; Yao, C. & Huang, X. Effect of cutting parameters on machinability characteristics in milling of magnesium alloy with carbide tool. *Adv. in Mech. Eng.,* 2016, **8**(1).
    doi: 10.1177/1687814016628392.
14. Klonica, M.; Matuszak, J. & Zagorski, I. Effect of milling technology on selected surface Layer Properties. *In* 2019 IEEE 5th International Workshop on Metrology for AeroSpace (MetroAeroSpace), Turin, Italy, 2019.
    doi: 10.1109/metroaerospace.2019.8869621.
15. Zagorski, I. & Korpysa, J. Surface Quality in Milling of AZ91D Magnesium Alloy. *Adv. Sci. Technol. Res. J.,* 2019, **13**(2), 119-129.
    doi: 10.12913/22998624/108547.
16. Zagorski, I. & Korpysa, J. Surface Quality Assessment after Milling AZ91D Magnesium Alloy Using PCD Tool. *Materials,* 2020, **13**(3), 617.
    doi: 10.3390/ma13030617.
17. Sunil, B. R.; Ganesh, K.; Pavan, P.; Vadapalli, G.; Swarnalatha, C.; Swapna, P.; Bindukumar, P. & Pradeep Kumar Reddy, G. Effect of aluminium content on machining characteristics of AZ31 and AZ91 magnesium alloys during drilling. *J. Magnesium Alloys,* 2016, **4**(1),

15-21.
doi: 10.1016/j.jma.2015.10.003.

18. Shi, K.; Zhang, D. & Ren, J. Optimization of process parameters for surface roughness and microhardness in dry milling of magnesium alloy using Taguchi with grey relational analysis. *Int. J. Adv. Manufacturing Technol.*, 2015, **81**, (1–4), 645–651.
doi: 10.1007/s00170-015-7218-8.
19. Ramesh, S.; Vishwanathan, R. & Ambika, S. Measurement and optimization of surface roughness and tool wear via grey relational analysis, TOPSIS and RSA techniques. *Measurement,* 2016, **78**, 63-72.
doi: 10.1016/j.measurement.2015.09.036.
20. Videm, M.; Hanse, R.; Tomac, N. & Tonnesen, K. Metallurgical Considerations for Machining Magnesium Alloys. *SAE Technical Paper No. 940409, SAE, Detroit, USA,* 1994.
doi: 10.4271/940409.
21. Dinesh. S.; Senthilkumar, V.; Asokan, P. & Arulkirubakaran, D. Effect of cryogenic cooling on machinability and surface quality of bio-degradable ZK60 Mg alloy. *Mater. Design,* 2015, **87***,* 1030-1036.
doi: 10.1016/j.matdes.2015.08.099.
22. Danish, M.; Ginta, T.L.; Abdul Rani, A.M.; Carou, D.; Davim, J.; Rubaiee, S. & Ghazali, S. Investigation of surface integrity induced on AZ31C magnesium alloy turned under cryogenic and dry conditions. *Procedia Manufacturing,* 2019, **41***,* 476-483.
doi: 10.1016/j.promfg.2019.09.035.
23. Uddin, M.S.; Rosman, H.; Hall, C. & Murphy, P. Enhancing the corrosion resistance of biodegradable Mg-based alloy by machining-induced surface integrity: influence of machining parameters on surface roughness and hardness. *Int. J. Adv. Manufacturing Technol.,* 2016, **90**(5-8), 2095-2108.
doi: 10.1007/s00170-016-9536-x.
24. Kaynak, Y.; Tobe, H.; Noebe, R.; Karaca, H. & Jawahir, I. The effects of machining on the microstructure and transformation behaviour of NiTi Alloy. *Scripta Materialia,* 2014, **74***,* 60-63.
doi: 10.1016/j.scriptamat.2013.10.023.
25. Danish, M.; Ginta, T. L.; Habib, K.; Carou, D.; Rani, A.M.A. & Saha, B.B. Thermal analysis during turning of AZ31 magnesium alloy under dry and cryogenic conditions. *Int. J. Advanced Manufacturing Technol.,* 2017, **91**(5-8), 2855-2868.
doi: 10.1007/s00170-016-9893-5.
26. Danish, M.; Ginta, T.L.; Habib, K.; Abdul Rani, A. M. & Saha, B.B. Effect of Cryogenic Cooling on the Heat Transfer during Turning of AZ31C Magnesium Alloy. *Heat Transfer Eng.,* 2018, **40**(12), 1023-1032.
doi: 10.1080/01457632.2018.1450345.
27. Samaniegro, A.; Llorente, I. & Feliu, S. Combined effect of composition and surface condition on corrosion behaviour of magnesium alloys AZ31 and AZ61. *Corrosion Science,* 2013, **68**, 66-71.
doi: 10.1016/j.corsci.2012.10.034.
28. Reddy, U.; Dubey, D.; Panda, S.S.; Ireddy, N.; Jain, J.; Mondal, K. & Singh, S.S. Effect of Surface Roughness Induced by Milling Operation on the Corrosion Behavior of Magnesium Alloys. *J. Mater. Eng. Performance,* 2021, **30**(10), 7354-7364. doe: 10.1007/s11665-021-05933-8.
29. Danish, M.; Raubaiee, S. & Ijaz, H. Predictive Modelling and Multi-Objective Optimization of Surface Integrity Parameters in Sustainable Machining Processes of Magnesium Alloy. *Materials*, 2021, **14**(13), 3547.
doi: 10.3390/ma14133547.
30. Viswanathan, R.; Ramesh, S.; Maniraj, S. & Subburam. V. Measurement and multi-response optimization of turning parameters for magnesium alloy using hybrid combination of Taguchi-GRA-PCA technique. *Measurement*, 2020, **159**, 107800.
doi: 10.1016/j.measurement.2020.107800.
31. Lu, L.; Hu, S.; Liu, L. & Yin, Z. High speed cutting of AZ31 magnesium alloy. *J. Magnesium Alloys*, 2016, **4**(2), 128-134.
doi: 10.1016/j.jma.2016.04.004.
32. Bekir, Y. & Eylul, O. Experimental Investigation on Turning of Casted Magnesium Alloy Used in Manufacturing Automotive Parts. *In* Advances in Materials & Processing Technologies Conference, Madrid, Spain, 2015.
33. Mostafapour, A.; Mohammadi, M. & Ebrahimpour, A. The Influence of Milling Parameters on the Surface Properties in Milled AZ91C Magnesium Alloy. *Iranian J. Mater. Sci. Eng.*, 2021, **18**(2).
doi: 10.22068/ijmse.1971.
34. Anandan, N. & Ramulu, M. Study of machining induced surface defects and its effect on fatigue performance of AZ91/15%SiCp metal matrix composite. *J. Magnesium Alloys*, 2020, **8**(2), 387-395.
doi: 10.1016/j.jma.2020.01.001.
35. Basmaci, G.; Taskin, A. & Koklu, U. Effect of tool path strategies and cooling conditions in pocket machining of AZ91 magnesium alloy. *Indian J. Chem. Technol. (IJCT)*, 2019, **26**(2), 139-145.
36. Sivam, S.; Bhat, M.; Natarajan, S. & Chauhan, N. Analysis of residual stresses, thermal stresses, cutting forces and other output responses of face milling operation on ZE41 magnesium alloy. *Int. J. Modern Manufacturing Technol.*, 2018, **10**(1), 92-100.
37. Pradeepkumar, M.; Venkatesan, R. & Kaviarasan, V. Evaluation of the surface integrity in the milling of a magnesium alloy using an artificial neural network and a genetic algorithm. *Mater. Technol.*, 2018, **52**(3), 367-373.
doi: 10.17222/mit.2017.198.
38. Guo, Y.B. & Liu, Z.Q. Sustainable high speed dry cutting of magnesium alloys. *Mater. Sci. Forum*, 2012, **723**, 3-3.
doi: 10.4028/www.scientific.net/msf.723.3.

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