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Machining parameter optimization and study the turning operation behaviour of hybrid Al/Mg composites

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Abstract

The exposures of Al/Mg alloy hybrid nanocomposite found in automotive applications have specific behaviours such as low specific weight, good hardness, superior tensile strength, better thermal stability, economic, and excellent corrosion resistance. Besides, non-homogenous particle dispersion could damage the tool surface, resulting in low surface roughness. This investigation synthesizes and studies the machinability behaviour of Al/Mg alloy hybrid nanocomposite embedded with 5wt% of Al_2O_3 and 15wt% of SiC nanoparticles via vacuum stir cast route. Synthesized composite is subjected to a CNC turning process with varied input process parameters of 1000-1600 rpm speed (N), 0.2-0.8 mm depth of cut (DOC), and 0.1-0.4mm/rev^{-1}feed rate (f). The impact of machining parameters on tool wear (TW), surface roughness (Ra), and composite temperature is experimentally measured. Its process parameters are optimized through ANOVA Taguchi L16 design with a 99.5% confidence level. With the excellence of ANOVA, the 1000-1200 rpm (N), 0.1 mm/rev^{-1} (f) and 0.2-0.4mm (DOC) performed good machinability behaviour, including low tool wear (0.03-0.033µm), surface roughness (0.58-0.59µm), and temperature (84.5-88.4ºC) respectively.

Keywords: Al/Mg alloy nanocomposite; ANOVA; Turning behaviour.

1. Introduction

With unique properties like better tensile strength, good ductility, high corrosion resistance, improved stability and good machinability reasons, the aluminium alloy is referred to due to its importance in automotive weight management applications [1]. However, specific properties of aluminium alloy are attained by the additions of hard phase ceramic particles [2], which are processed via liquid state stir process [3-4] because of economic, produce any complex shapes, and quality composite with enhanced properties [5-6]. However, composite material machining resulted in poor surface roughness and reduced tool life due to high frictional force [7]. The presence of hard ceramic particles in the aluminium alloy was the reason for poor machining performance [8]. The advanced machining process recently found good characteristics and operated under a coolant nature [9]. Recently, the composite materials were machined by CNC machines adopted with coated tool material, which was found to have good machinability behaviour compared to traditional machining processes [10-11]. The turning operation was the most common secondary operation, which was used for different engineering applications [12]. Besides, the composites have better specific properties [13] and are utilized for automotive and aerospace utilization [14].

The aluminium alloy (Al6061) hybrid composites are synthesized with 10 wt% Al_2O_3 and 5 wt% SiC via stir casting process and evaluated its machining behaviour on surface roughness, material removal rate, minimizing the over cut. For finding the optimum machining process inputs, a fuzzy artificial bee colony algorithm is used [15]. With the adaptations of computer numerical control (CNC) machines, the machining quality of composite is increased as well as productivity. This model is analyzed via a finite element analysis (FEA) platform to fill the gap in real machining work [16]. Similarly, the mathematical modelling was executed for finding the correlation between the actual machining to model analysis, which helps to minimize the gap between the real time machining operation and enhancing the machining quality [17].

Moreover, the analysis of variance (ANOVA) Taguchi technique with the general linear model (GLM) technique found better optimization results for composite machining with a set of various input parameters like speed, feed, depth of cut, etc. [18]. Based on the references, the composites are produced by an advanced fabrication process to enhance and attain the specific properties and are involved in machining studies for automotive industry applications [19] and also their processing parameters were optimized via the ANOVA route [20]. This is suitable for industrial mass production with the optimized machining process parameter influences as to get better quality, improved material

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removal rate, and reduced surface roughness, [21]. The literature related to aluminium alloy composite machining by CNC machine with various coated inserts under varied input parameters related to output like machining time, surface, and MRR was discussed above, in that TiCN coated insert found good machinability behaviour [22] and ANOVA technique exposed better optimization results [23].

The aluminium composite machining-related past literature is discussed with technical details for machining aluminium alloy composite through a computer numerical control machine adopted with a Fanuc controller. Non-homogenous particles spread over the Al/Mg alloy matrix during machining limited the tool wear and machining surface quality. It may lead to time delay, which affects productivity. With this concern, the study's main objective is synthesizing and studying the turning behaviour of Al/Mg alloy composite embedded with 15wt% silicon carbide (SiC) and 5wt% alumina (Al_2O_3) nanoparticles via vacuum stir casting. Concerning past literature, the present study focuses on turning the Al/Mg alloy hybrid nanocomposite with Titanium Carbo-nitride (TiCN) insert,and their process parameters are 1000-1600rpm speed (N), 0.2-0.8mm (DOC), & 0.1-0.4 mm/rev^{-1}(f). The output TW, Ra, and T were measured and optimized via ANOVA L16 analysis. The optimized input machining parameter is suggested for automotive industrial workshops for machining the shaft at a higher production rate. It is used for automotive shaft applications.

2. Materials and methods

2.1. Materials

This combination of Al/Mg exposed better specific strength, lightweight, improved mechanical and better machinability behaviour [3]. For this reason, the Al/Mg alloy with the ratios of 75:25 is chosen as a matrix material for making the hybrid nanocomposite fabrication. Likewise, the silicon carbide (SiC) and alumina (Al_2O_3) nanoparticles (50nm) are selected as reinforcement for the preparation of the composite. The SiC nanoparticles have better thermal stability, improved melting point, and high hardness value [15]. Similarly, the Al_2O_3 nanoparticle is exposed to better hardness, increased thermal stability, and leads to a better strength effect [4]. Based on the previous literature reported by Sekaran et al. [3], the SiC and $Al_2O_3$are selected as 15 weight percentages (wt%) and 5 wt%, respectively. It exposed better tensile, hardness, and impact strength values.

2.2. Composite fabrication details

The pure aluminium (Al) and magnesium (Mg) ingot of 75:25 ratios is kept in an electrical furnace and heated by 500ºC to remove the moisture. Likewise, the SiC and Al_2O_3 nanoparticles were externally preheated at 300ºC for a duration of 30min helps to limit the moisture content [3 and 5]. The heated Al/Mg alloy is melted at 700 degrees Celsius with an argon nature, which provides the inert atmosphere effect and limiting oxidation during the Mg melting [4]. The preheated SiC and Al_2O_3 nanoparticles were embedded with a molten matrix and blended with a mechanical stir at 700rpm for 10 min. The blended molten metal and reinforcement slurry were transferred into a preheated (300ºC) tool steel mould with an applied vacuum pressure of $2x10^5$ MPa. The synthesized composite is involved in machinability studies.

2.3. Machining operation details

The present turning operation was executed with computer numerical control (CNC) Fanuc configured Super Jobber, which makes a computer numerical controller turner machine, illustrated in Fig. 1. With significant behaviour like good thermal stability, high resistance against wear, maximum hardness (1580Hv) and excellent toughness [22], the titanium carbo nitrides (TiCN) is selected as an insert tool for present turning operations.

Before the turning operation, the composite circularity was checked using the diametral route and weight as W_b, and then it was holed by an electro-mechanical chuck. The experiment is made by following of Table 2 design approach. During the turning operation, the temperature was taken at three different places via a HTC-made MTX-1 model pistol thermometer (range from -50 to 550ºC), and its average value was fixed as a mean value. Similarly, the machining time was measured by using a Racer made AVI4984165 model stopwatch (Digital). After the machining process, the sample was weighted as W_a. Finally, Mitutoyo made an SJ-210 model surface roughness tester with the ASTM D7127 standard to measure the turned surface quality. According to equation 1, the turning cutting speed was measured.

$$Cutting\ speed\ (v) = \frac{\pi * D * N}{1000} \quad (1)$$

Where D – Shaft diameter (mm) and N – Shaft rotating speed (rpm)

Figure 1. CNC Fanuc configured Super Jobber makes computer numerical controller turner machine.

2.4. Design Approach

Table 1 presents the ANOVA design approach for the machining process parameters along with levels and factors. During the design setup, the number of process parameters is three, namely speed (N in rpm), feed rate (f in mmrev^{-1}), and depth of cut (DOC in mm), respectively. Because of this, three parameters are important for machining the composite material [10]. Specifically, the 1300-1500 rpm with 0.2-0.25 mmrev^{-1} and 0.1-0.2 mm executed turning operation offered better machining quality reasons; the present study of turning operation executed with 1000-1600rpm, 0.1-0.4 mmrev-1, and 0.2 to 0.6 mm of speed, feed, and DOC.

Table 1. Process parameters level and factor design

Levels	Factors (Turning operation)		
	Speed	Feed rate	Depth of cut
	N in rpm	f in mmrev^{-1}	DOC in mm
1	1000	0.1	0.2
2	1200	0.2	0.4
3	1400	0.3	0.6
4	1600	0.4	0.8

Based on the input factors and their levels, the L16 Taguchi design (orthogonal array) is available and found suitable for optimizing the 4 levels and 3 factors easily. As mentioned earlier, Faisal et al. [10] and Kesarwani et al. [11] executed their research with the L16 Taguchi design approach, which is suitable for finding the most optimum input factor and its level for best machining. For this reason, the present study has chosen as L16 Taguchi design, and its design details are presented in Table 2. During the analysis, the 99 % confidence level is chosen to find the best interactions for attaining the least tool wear, reduced surface roughness and minimum machining temperature. This output response parameter is related to increasing productivity with economic operation. As earlier, Faisal et al. [10] reported that a higher confidence level of 99.5% found better optimization results.

3. Results and discussions

As earlier, the Al/Mg alloy hybrid nanocomposite synthesized with 15wt% silicon carbide (SiC) and 5wt% alumina (Al_2O_3) nanoparticle via vacuum stir casting offered a maximum tensile strength of 259.73 MPa and microhardness of 65.43 HV [3].

3.1. Optimize the tool wear toa minimum.

Fig. 2 indicates the main effect plot (Tool wear) along with different input machining factors and their levels. During the Taguchi design analysis, the smaller is best option as it selected and executed their mean effect with the design dominate factors like DOC, N, and f identified as 1, 2, and 3. With reference to Fig. 2, the mean tool wear is 0.0364µm. The 0.2-0.4 mm DOC executed with 1000-1400rpm at 0.1-0.2 mmrev^{-1} meets their conditions of smaller is best. Moreover, the tool wear influences the machining surface quality [7 and 10].

With the technique of GLM executed with a 99 % confidence level it is found that the significant factors for fixing the minimum tool wear and its SS test details are detailed in Table 3 with excellence of 86.58% R-Sq.

Table 2. L16 Taguchi design and its output response

Array No.	Speed	Feed rate	Depth of cut	Temperature	Surface roughness	Tool wear
	N in rpm	f in mmrev^{-1}	DOC in mm	T_{avg}	Ra	TW
	Levels			°C	µm	µm
L1	1000	0.1	0.2	84.5	0.58	0.03
L2	1000	0.2	0.4	87.2	0.69	0.032
L3	1000	0.3	0.6	90.1	0.67	0.041
L4	1000	0.4	0.8	99.5	0.63	0.044
L5	1200	0.1	0.4	88.4	0.62	0.033
L6	1200	0.2	0.2	87.5	0.59	0.031
L7	1200	0.3	0.8	97.3	0.7	0.043
L8	1200	0.4	0.6	91.5	0.69	0.045
L9	1400	0.1	0.6	77.4	0.73	0.029
L10	1400	0.2	0.8	100.7	0.78	0.04
L11	1400	0.3	0.2	78.1	0.68	0.032
L12	1400	0.4	0.4	87.8	0.6	0.033
L13	1600	0.1	0.8	101.1	0.66	0.045
L14	1600	0.2	0.6	85.8	0.68	0.04
L15	1600	0.3	0.4	92.8	0.63	0.035
L16	1600	0.4	0.2	89.4	0.73	0.031

Table 3. Analysis of Variance for Tool wear in µm, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Test excellence in %	Position
Depth of cut in mm	3	0.0003525	0.0003525	0.0001175	10.2	0.009	68.58	1
Speed in rpm	3	0.0000515	0.0000515	0.0000172	1.49	0.309	10.02	2
Feed rate in mm/rev	3	0.000041	0.000041	0.0000137	1.19	0.39	7.98	3
Error	6	0.000069	0.000069	0.0000115			13.42	-
Total	15	0.000514					100.00	-

S = 0.00339116 R-Sq = 86.58% R-Sq(adj) = 66.44%

Fig. 3 presents the residual plots for tool wear along with their normal probability, residual with fitted values, and histogram. With the references of normal probability plots for residuals, more than 0.0025 residual reached more than 90 % excellence. The major deviation is noted by L8, L9, L11,and L14 sequences. However, 0.03 to 0.0364 µm tool wear meets best fit with the residual plot. It is the optimum value during the turning operation to get the least tool wear [17 and 24].

Based on the main effect plot and residual plot, Table 4 shows the possible factors for getting smaller wear.

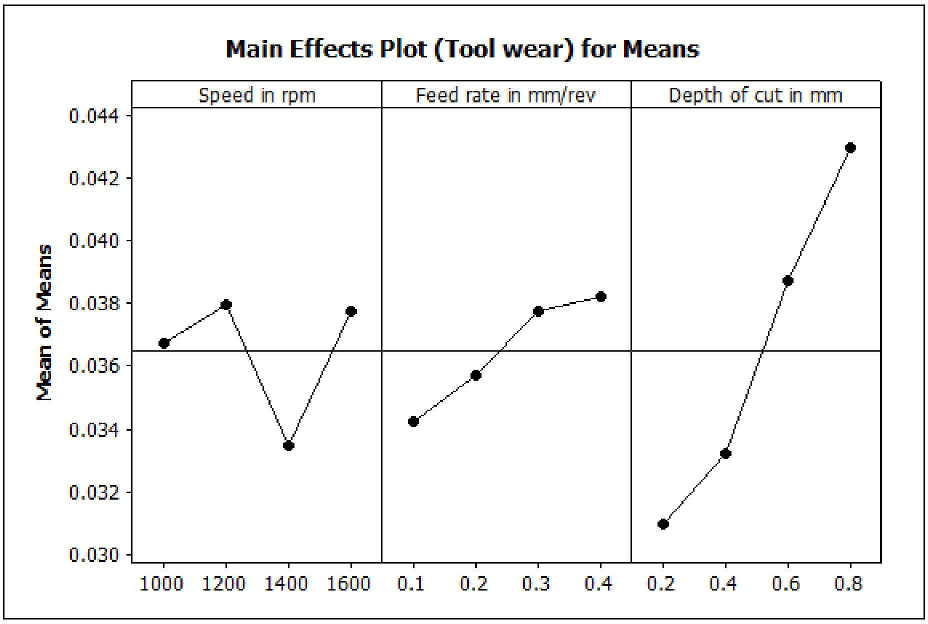

Figure 2. Main effect plot (Tool wear) for Means

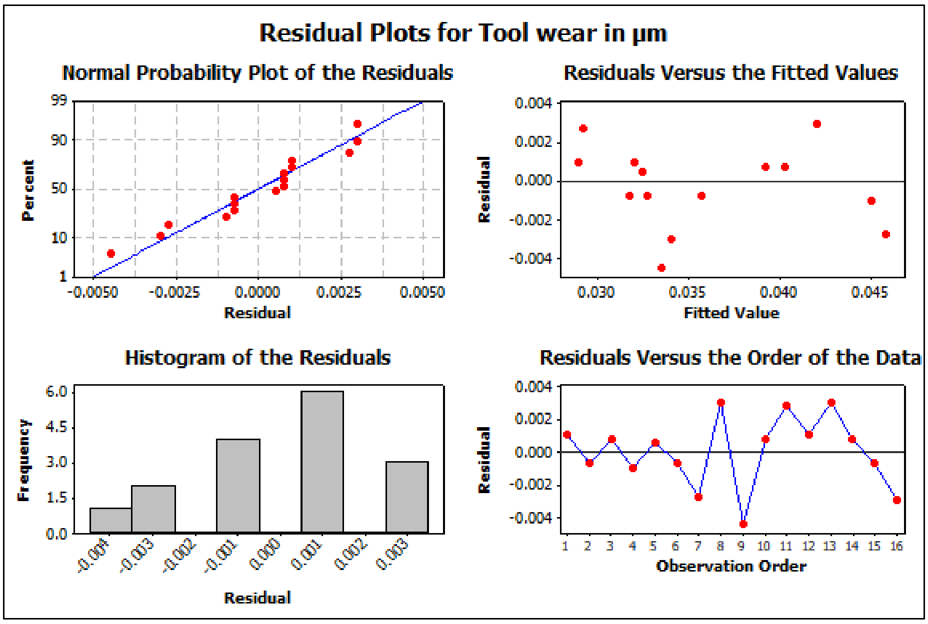

Figure 3. Residual plots for tool wear

Table 4. Possible factors and their levels for smaller tool wear

Array No.	Speed	Feed rate	Depth of cut	Temperature	Surface roughness	Tool wear
	N in rpm	f in mmrev^{-1}	DOC in mm	T_{avg}	Ra	TW
		Levels		°C	µm	µm
L1	1000	0.1	0.2	84.5	0.58	0.03
L2	1000	0.2	0.4	87.2	0.69	0.032
L5	1200	0.1	0.4	88.4	0.62	0.033
L6	1200	0.2	0.2	87.5	0.59	0.031

3.2. Optimize the surface roughness to a minimum.

The main effect plot (surface roughness) means varied factors, and their levels are highlighted in Fig. 4. Based on the tool insert and material compositions, the surface quality of the machined surface is decided [16 and 25]. The executed design analysis shows the minimum and maximum surface roughness is 0.63 and 0.70 µm, with its mean lyingat 0.665µm. According to this, the DOC is 0.2-0.4mm operated with 1000-1200rpm at 0.1 and 0.4mmrev^{-1} is spotted as minimum surface roughness.These parameters influence the surface roughness of machined composites.

ANOVA GLM route analyzed SS test results are highlighted in Table 5 with an accuracy level of 46.94 % R.Sq, the DOC, N, and f are spotted as 1, 2, and 3 levels of factors for fixing the surface roughness.

Fig. 5 indicates the residual plots for the surface roughness of the machined composite sample. It is revealed from Fig. 5 that the normal probability plot for the residual meets their actual value, and more than 0.05 residuals have reached more than 90 %.

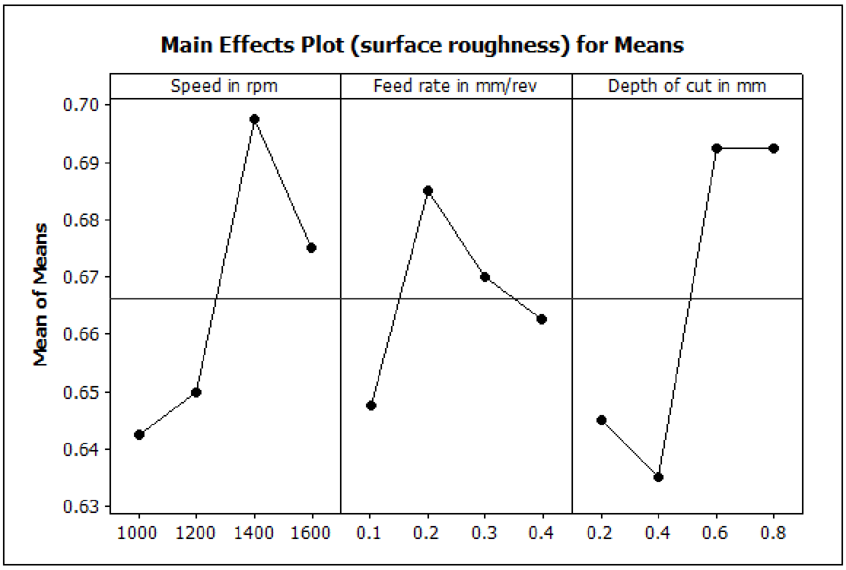

Figure 4. Main effect plot (Surface roughness) for Means

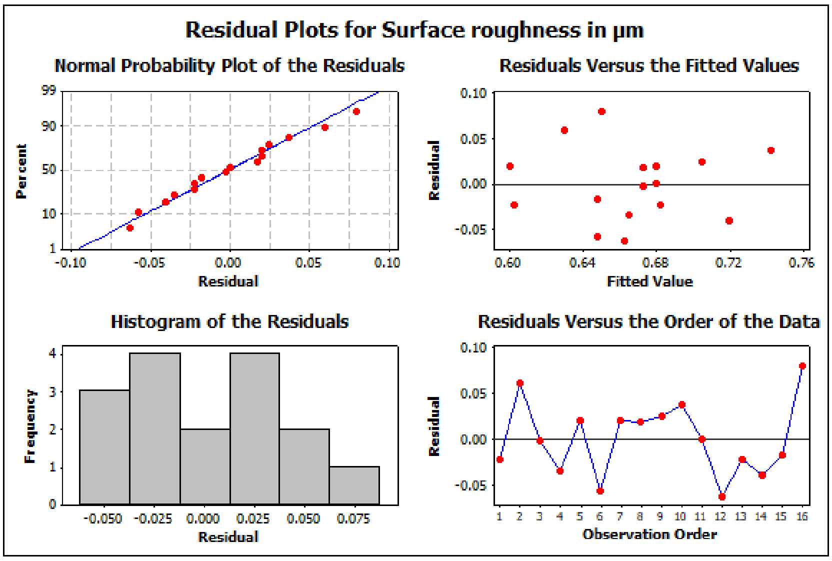

Figure 5. Residual plots for surface roughness

Table 5. Analysis of Variance for Surface Roughness in µm, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Test excellence in %	Position
Depth of cut in mm	3	0.011225	0.011225	0.003742	0.92	0.487	24.31	1
Speed in rpm	3	0.007525	0.007525	0.002508	0.61	0.63	16.30	2
Feed rate in mm/rev	3	0.002925	0.002925	0.000975	0.24	0.866	6.33	3
Error	6	0.0245	0.0245	0.004083			53.06	-
Total	15	0.046175					100	-

S = 0.0639010 R-Sq = 46.94% R-Sq(adj) = 0.00%

Optimum fitted values are located between 0.6 -0.69, which is the minimum surface roughness value [11]. Moreover, L2, L6, L12, and L16 are deviated from the level of 0.68 µm and ordered by the optimum sequence lies between the -0.05 to 0.05 residual, which is evidenced in Fig. 5. Compared to 0.5mm performed Al/6wt% eggshell/6wt% boron carbide composite, but the surface quality is enhanced by 258 % [11].According to the main effect and residual plot, the optimum factors and their levels are summarized in Table 6.

3.3. Optimize the temperature as optimum.

Fig. 6 illustrates the main effect plot (Temperature) means with its input factors and levels. During the turning machining operation, the higher temperature was generated by high frictional force [11]. It influences the limits of the surface quality as well as it changes their metallurgical phases [17]. Taguchi design analysis shows the DOC and speed are the most dominating factors for deciding the temperature of turning operation. The main effect plot indicates that the DOC, N, and f area sequence of fixing the temperature of the turning operation. Based on this, the mean temperature is spotted as 90ºC, and related input factors with their levels are 0.2-0.6 mm DOC, 1000 - 1400rpm N and 0.1-0.3 mmrev$^{-1,}$ respectively.

Moreover, the GLM is executed with a 99% confidence level to find the contribution of the input factor for fixing the turning operation temperature. With this, Table 7 indicates the SS tests for the analysis of variance for temperature, and the DOC contributed 70.77 %, which contributes more than other factors like speed and feed rate. The output of GLM is recorded with 87.44 % accuracy of its R-Sq, and the speed & feed rate were the next level dominating factors for deciding the temperature of the machining operation. The applied high f results improved temperature of 84.6 ºC, greater than the reported value of 500rpm speed, 0.1 mm/rev^{-1}f, & 0.5mm performed Al/6wt% eggshell/6wt% boron carbide composite [11 and 26].

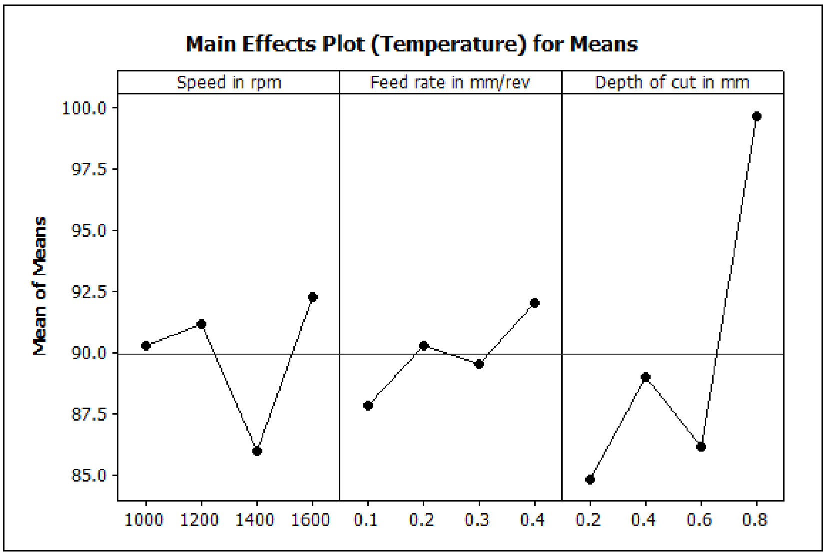

Figure 6. Main effect plot (Temperature) for Means

Table 6. Possible factors and their levels for smaller surface roughness

Array No.	Speed	Feed rate	Depth of cut	Temperature	Surface roughness	Tool wear
	N in rpm	f in mm/rev^{-1}	DOC in mm	T_{avg}	Ra	TW
	Levels			ºC	µm	µm
L1	1000	0.1	0.2	84.5	0.58	0.03
L5	1200	0.1	0.4	88.4	0.62	0.033

Table 7. Analysis of Variance for Temperature in ºC, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P	**Test excellence in %**	Position
Depth of cut in mm	3	538.87	538.87	179.62	11.3	0.007	70.77	1
Speed in rpm	3	90.6	90.6	30.2	1.9	0.231	11.90	2
Feed rate in mm/rev	3	36.33	36.33	12.11	0.76	0.556	4.77	3
Error	6	95.6	95.6	15.93			12.56	-
Total	15	761.4					100.00	-

S = 3.99163 R-Sq = 87.44% R-Sq(adj) = 68.61%

Residual plots for temperature with normal probability, fitted value, histogram, and observation order are shown in Fig. 7. With the support of Fig. 7, and the 81-91°C fitted values meetthe optimum temperature value. The normal probability image indicates the 0.0 to 5.0 residual is matched with the actual line and attained the chances of minimum failure with an improved percentage of more than 50 %. From the observation order, the L3 and L10 are deviated and cross the residual limits of -2 to 2. Besides the results from the main effect and residual plots, the possible input factors and their levels are summarized in Table 8.

According to Tables 4, 6, and 8, the intersecting array is noted for the best turning output response like reduced tool wear, surface roughness, and minimized machining temperature and highlighted in Table 9.

The current optimized results of Al/Mg alloy hybrid nanocomposite machinability studies are compared with previous results, and the details are mentioned in Table 10. The 1000-1200rpm operated with 0.1 mm/rev^{-1}f under 0.2-0.4mm DOC parameter is found to have low tool wear and improved surface quality (0.58-0.62µm).The applied high f results improved temperature of 84.6 °C, greater than the reported value of 500rpm speed, 0.1 mm/rev^{-1}f, & 0.5mm performed Al/6wt% eggshell/6wt% boron carbide composite. Still, the surface quality is enhanced by 258 % and minimized tool wear of 0.033µm [11].

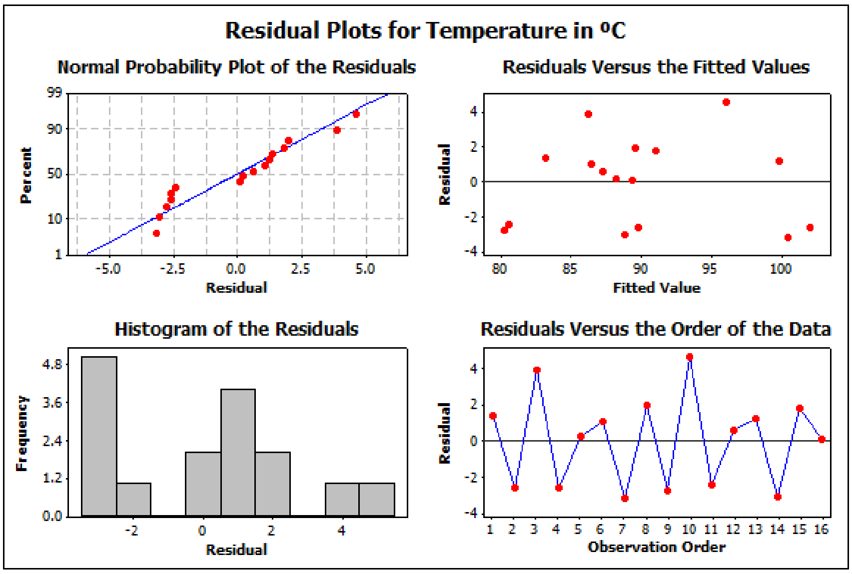

Figure 7. Residual plots for temperature

Table 8. Possible factors and their levels for optimum temperature

Array No.	Speed	Feed rate	Depth of cut	Temperature	Surface roughness	Tool wear
	N in rpm	f in mm/rev^{-1}	DOC in mm	T_{avg}	Ra	TW
		Levels		°C	µm	µm
L1	1000	0.1	0.2	84.5	0.58	0.03
L2	1000	0.2	0.4	87.2	0.69	0.032
L3	1000	0.3	0.6	90.1	0.67	0.041
L5	1200	0.1	0.4	88.4	0.62	0.033
L6	1200	0.2	0.2	87.5	0.59	0.031
L9	1400	0.1	0.6	77.4	0.73	0.029
L11	1400	0.3	0.2	78.1	0.68	0.032

Table 9. Best input factors and levels for better turning operation of Al/Mg alloy hybrid composites

Array No.	Speed	Feed rate	Depth of cut	Temperature	Surface roughness	Tool wear
	N in rpm	f in mm/rev^{-1}	DOC in mm	T_{avg}	Ra	TW
		Levels		°C	µm	µm
L1	1000	0.1	0.2	84.5	0.58	0.03
L5	1200	0.1	0.4	88.4	0.62	0.033

Table 10. Comparison of current investigations related to previous literature

S.No	Descriptions	Machining conditions	Tool wear	Surface roughness	Temperature	Ref
			µm	µm	°C	
1	AA6061 alloy	1300-1500rpm N, 0.2-0.25 mm/rev^{-1}f, and 0.1mm DOC	20.56min (tool life)	-	-	10
2	Stir cast made Al/6wt% eggshell/6wt% boron carbide	500rpm N, 0.1 mm/rev^{-1}f, and 0.5mm DOC	-	2.2252	51.1	11
4	Al/Mg/5wt% of Al_2O_3 and 15wt% of SiC	1200rpm N, 0.1 mm/rev^{-1}f, and 0.4mm DOC	0.033	0.62	88.4	Present work

4. CONCLUSION

TiCN coated insert used CNC operation of Al/Mg alloy hybrid nanocomposite was successfully machined with different sources of 1000-1600rpm (N), 0.2-0.6mm (DOC), and 0.1-0.4 mm/rev^{-1}(f).The effect of input turning parameters on tool wear, surface roughness, and temperature was optimized through the ANOVA L16 design approach.The F-test found the contribution level of each parameter subjected to output response (99.5% confidence level). With the significance, the ANOVA exposed that the L1 and L5 arrays found the best interaction for obtaining low tool wear, surface roughness and temperature. With this concern, the hybrid nanocomposite sample was spotted by a 1000-1200rpm operated sample machined with 0.2to 0.4mm depth of cut under 0.1 mm/rev^{-1}showed the 0.03-0.033µm tool wear, 0.58-0.62µm surface roughness, and the temperature lies between 84.5-88.4ºC. It was suitable for mass production during the Al/Mg alloy hybrid nanocomposite machining. The micro-drilling machining studies with more number of levels are extending for studying their performance will be planned for future studies.

DECLARATIONS

Data Availability

All the data required are available within the manuscript

Funding

No funding was used for this study.

Competing & financial interests

Authors declare no conflicts of interest

Ethics approval

This is an observational study of Machining parameter optimization and study of the turning operation behaviour of hybrid Al/Mg composites. The Research Ethics Committee has confirmed that no ethical approval is required.

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