Pertanika J. Sci. & Technol. 25 (1): 255 - 262 (2017)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Temperature Measurement and Optimisation in Machining Magnesium Alloy Using RSM and ANOVA

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ABSTRACT

This paper focuses on examining the ‘cutting zone temperature’ while performing turning operation on AZ91Mg alloy using cemented carbide tools. The regression model is developed by using the RSM techniques based on experimental results. It is revealed that the cutting speed (v) is the most dominant factor affecting cutting zone temperature. The developed models of cutting zone temperature sufficiently map within the range of the turning conditions considered. The adequacy and accuracy of the regression equation is justified through ANOVA. It is found that the optimal combinations of machining parameters minimize the cutting temperature.

Keywords: ANOVA, Cutting temperature, Magnesium, Optimization, Turning and Response surface methodology

INTRODUCTION

Several studies (Kleiner et al., 2003; Thein at al., 2009; Hirsch & Al-Samman, 2013) proposed that the main advantage of magnesium alloy is its low density of 1.8 g/$cm^{3.}$ Since it possesses a high stiffness- to-weight ratio and a high strength-to-weight, it has been considered the best choice for utilisation automobile and aerospace industry.

The main problem in the machining of magnesium alloy is auto ignition risk and the particles size generated in the machining process. In the event of a fire accident it is important that a water based coolant is not

Article history:
Received: 08 January 2016
Accepted: 11 November 2016

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ISSN: 0128-7680

used to extinguish a magnesium fire due to the formation of highly explosive hydrogen when water reacts with magnesium (Tomac & Tonnessen, 1991; Weinert et al., 2004; Kulekci, 2008).

In the machining process, majority of the energy is transformed into heat (Peloubet, 1965; Diniz & José de Oliveira, 2004; Park et al., 2009). The heat generation during machining process increases the cutting zone temperature. An Investigation was carried out on the AISI 52100 alloy steel with multilayer coated carbide insert. The effect of cutting parameters were determined using ANOVA. The quadratic model equation was used to predict the output response. Response surface methodology (RSM) was utilized to find out the optimal machining parameters. It is concluded the cutting temperature is highly influenced by cutting speed and feed rate (Shihab et al., 2014).

In machining operations, cutting forces, tool life and workpiece surface integrity, are strongly affected by cutting temperature. The yield strength of the workpiece material was decreased at higher cutting temperatures. Tool life was reduced due increased workpiece surface temperatures (Ghani et al., 2008).

Montgomery (1997) exposed that, Design of experiments (DoE) is widely used in machining investigations because it refers to the process of planning the experiments. Design methods such as taguchi methods, response surface methodology and factorial designs are now widely used in the experimental approach (Chomsamutr & Jongprasithporn, 2012).

The objective of this study is to select the most influential factors and to consequently select the optimal turning conditions that generate minimum cutting zone temperature.

EXPERIMENTAL PROCEDURE

In this experiment, magnesium alloy (AZ91D) is employed as workpiece in the form of a cylinder. The experiments were conducted based on 3 levels i.e. 3 factor designs of experiment. In turning of AZ91D magnesium alloy, the three main influential process parameters - Cutting speed (V), Feed rate (f) and Depth of cut(d) at three different levels are considered. The input parameters and their levels are designated as shown in table 1. In this work, experiments were conducted based on Taguchi's L9 orthogonal array measured output response are shown in table 2. The turning operations were conducted in a Kirloskar Turn master 35 lathe in dry environment using cemented carbide tools. Cutting zone temperature is measured using METRAVI MT-9 made compact IR thermometer with dual laser targeting with specification of IR range of -50°C to 1000°C.

Table 1

Turning parameters with machining conditions

Control parameters	**Levels**		
	1	**2**	**3**
Cutting Speed (V), m/min	40	80	120
Feed (f), mm/rev	0.10	0.15	0.20
Depth of cut (d), mm	0.50	0.75	1.00

Table 2
Experimental result based on L9 orthogonal array

Trial	Designation	Actual factor			Cutting Zone Temperature T (°C)	S/N ratio
		V (m/min)	f (mm/rev)	d (mm)		
1	$A_1B_1C_1$	40	0.10	0.5	62	-35.85
2	$A_1B_2C_2$	40	0.15	0.75	65	-36.26
3	$A_1B_3C_3$	40	0.20	1	68	-36.65
4	$A_2B_1C_2$	80	0.10	0.75	79	-37.95
5	$A_2B_2C_3$	80	0.15	1	82	-38.28
6	$A_2B_3C_1$	80	0.20	0.5	75	-37.50
7	$A_3B_1C_3$	120	0.10	1	98	-39.82
8	$A_3B_2C_1$	120	0.15	0.5	92	-39.28
9	$A_3B_3C_2$	120	0.20	0.75	90	-39.08

OPTIMIZATION OF PROCESS PARAMETERS

The tools used in this study are Taguchi method of optimization, Response surface methodology and Regression analysis for developing the empirical model.

Taguchi method

Ramesh et al. (2012) state that, taguchi method of robust design has been extensively used in the manufacturing processes for single performance/quality characteristics. The aim may be to minimize surface roughness of the machined parts, maximize metal removal rate, minimize cutting force, and minimize tool wear rate. Taguchi algorithm aids in converting the quantitative evaluation of particular objective as signal to noise (S/N) ratio. The target value of the objective is achieved by minimizing the variation with ability of S/N ratio.

In present work, smaller the better type S/N quality was utilized to obtain optimal parameter for cutting zone temperature. Hence smaller the better type S/N ratio is expressed in eqn (1).

$$S/N = -10\log\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

Where *S/N* is the signal-to-noise ratio, *n* is the no. of measured observations, and *y* is the experimentally measured data.

Regression analysis

Regression analysis is mainly used to determine the relationship between input factors and experimental results. Almost all engineering fields and technologies are utilizing this statistical tool for developing a model for output response (Ashvin & Nanavati, 2013). The estimated regression coefficient of cutting zone temperature is shown in table 3. The p value for the output response model is obtained as less than 0.05 which indicates that the model terms are significant. In addition, the R^2 value is 0.9909 and the Adj. R^2 is 0.9854. The predicted R^2 value 0.9666 is very close to Adj. R^2 value. The obtained R^2 value is close to the desired 1.

Table 3

Estimated regression coefficient for cutting zone temperature (T)

Predictor	Coef	SE Coef	T	P
Constant	44.167	2.969	14.88	0.000
Cutting Speed (v)	0.35417	0.01559	22.72	0.000
Feed (f)	-20.00	12.47	-1.60	0.170
Depth of cut (d)	12.667	2.494	5.08	0.004

Response surface methodology was utilized to develop model from the experimental observation with the view of understanding the turning process. In this study, MINITAB 16 software package was used for the optimization work. The following regression equation was developed using RSM method. The cutting zone temperature is predicted using the Eq. (2).

The regression equation is

$$\text{Cutting Zone Temperature (T)} = 44.2 + 0.354\ \text{Cutting Speed (V)} - 20.0\ \text{Feed (f)} + 12.7\ \text{Depth of cut (d)} \quad (2)$$

From table 4 on the cutting zone temperature, the optimal parameter is identified as cutting speed - 40m/min, feed rate - 0.2mm/rev and depth of cut - 0.5mm. Hence the optimum condition is represented as $A_1B_3C_1$. Figure 1 shows the main effect plot for cutting zone temperature. It reveals that cutting temperature increases as cutting speed increases and feed rate does not impact on the cutting temperature.

Table 4

Response table for cutting zone temperature

Level	Cutting Speed (v)	Feed (f)	Depth of cut (d)
1	-36.25	-37.87	-37.54
2	-37.91	-37.94	-37.77
3	-39.40	-37.75	-38.25
Delta	3.14	0.19	0.71
Rank	1	3	2

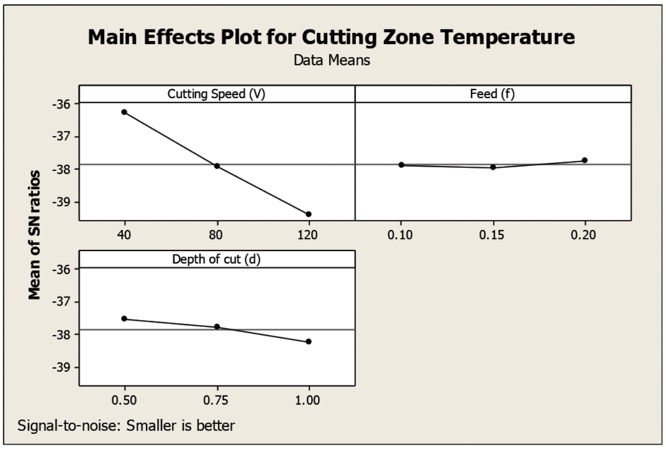

Figure 1. Main effect plot for Cutting Zone Temperature

To determine the control parameter that has a major effect on cutting zone temperature, ANOVA is performed and the results are given in the table 5. From the ANOVA table it is seen that cutting speed (v) is the most critical control factor significantly contributing 94.61% followed by depth of cut by 4.72% whereas the contribution of feed rate is negligible.

Table 5
ANOVA for cutting zone temperature (T)

Source	DF	Seq SS	Adj MS	F	P	% Contribution
Cutting Speed (V)	2	1204.17	1204.17	516.07	0.000	94.61
Feed (f)	2	6.00	6.00	2.57	0.170	0.47
Depth of Cut (d)	2	60.17	60.17	25.79	0.004	4.72
Residual Error	2	11.67	2.33			0.18
Total	8	1282.00				

The model's adequacy has been investigated by the assessment of residuals. In Figure 2 the normal probability plot of the residuals follows a straight line in which all the points are very nearer to the straight line and distributed evenly on both sides of the straight line. In residual versus fit plot, the residual appears to be randomly scattered around zero. The histogram of residual shows the distribution of residual for cutting zone temperature, distributed evenly on both sides zero residual. Residual versus order graph shows that the residual is higher for the observation order 8 and for majority of the observation, the residual values are situated zero line. The Figure 3 represents the similarity of experimental and predicted values of cutting zone temperature. It is revealed that the predicted values are agreed with the measured values.

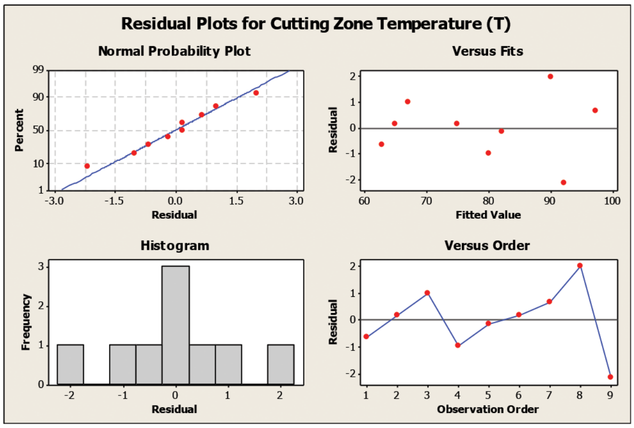

Figure 2. Residual plot of cutting zone temperature during regression analysis

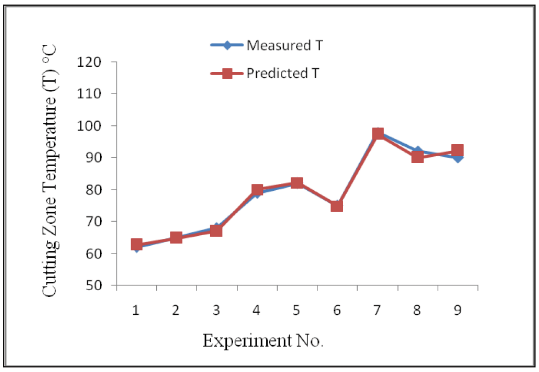

Figure 3. Comparison of experimental and predicted responses

Response Surface Methodology

The main aim of the work associated with machining magnesium alloy is to attain the minimum cutting temperature of the optimal control factors. The response surface optimization technique is used to find out optimal cutting parameters. Here, the objective is to minimize cutting temperature (T). RSM optimization results for cutting zone temperature are shown in Figure 4 and Table 6. From Figure 4, it can be seen that the cutting speed is the main impact factor on the cutting zone temperature. Feed have no significant effect on the output response. Optimal machining parameters are found to be cutting speed (V) at 40 m/min, feed (f) at 0.2 mm/rev and depth of cut (d) at 0.5 mm. The optimized cutting zone temperature parameter is T = 60.667°C.

Table 6

Response optimization for cutting zone temperature

Parameters	Goal	Optimum condition			Lower	Target	Upper	Pre.res	Desirability
		v (m/min)	F (mm/rev)	d (mm)					
T (°C)	Minimum	40	0.20	0.5	62	62	98	60.667	1

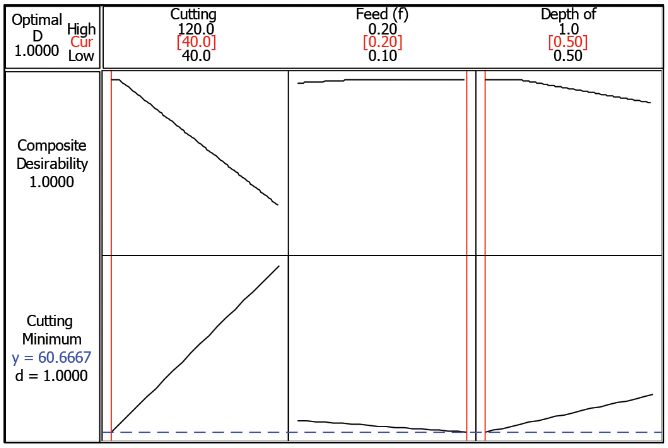

Figure 4. Response optimization for cutting zone temperature parameters

Confirmation test

With the identified optimal process parameter, the confirmation test is conducted to validate the analysis. In the confirmation test, an experiment has been conducted with optimal process parameter settings. Table 7 shows the comparison of experimentally obtained temperature value with RSM predicted value. Hence the model equation for the cutting zone temperature developed using RSM can be used to effectively predict the cutting zone temperature.

Table 7

Conformation test values

optimal process parameters			Experimental	Predicted	Error
v (m/min)	f (mm/rev)	d (mm)	T (°C)	T (°C)	%
40	0.20	0.50	63	60.667	3.70

CONCLUSION

The following conclusions have been derived on turning of AZ91D Magnesium alloy. The results are as follows:

(a) The cutting speed (V) is the main dominant factor on the cutting zone temperature (T). Increasing the cutting speed increases cutting zone temperature.

(b) From regression analysis, a prediction model has been developed for the cutting zone temperature in conditions of control factors. Predicted values are in good agreement with measured output responses.

(c) From RSM optimization, the minimum cutting zone temperature is found to be turning cutting speed at 40m/min, feed at 0.2mm/rev and depth of cut at 0.50mm.

(d) A conformation test result proves that the developed regression model can be used for turning of Mg alloy less than 4% error.

ACKNOWLEDGEMENTS

The authors would like to convey their gratefulness to the KCG College of Technology, Chennai, India for having given its fullest assistance for carrying out this work.

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