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Predictive modeling of surface roughness in end milling of Al/SiCp metal matrix composite

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ABSTRACT

In the present work, an attempt has been made to model the machinability evaluation through the response surface methodology in machining LM25 Al/SiC$_p$ MMC manufactured through stir cast route. The influence of four machining parameters including spindle speed (N), feed rate (f), depth of cut (d), and various percentage weight of silicon carbide (S) on surface roughness (R_a) was studied. The concept of Design of Experiments (DOE) was used for necessary experimentation. The experimental results were analyzed statistically to study the influence of process parameters on surface roughness.

Keywords: Metal matrix composites (MMC), Response surface methodology (RSM), Mathematical modeling, Surface roughness (R_a), Residual Plots and Surface plots.

INTRODUCTION

Metal-matrix composites (MMC$_s$) have been increasingly used in industries because of their improved properties over those of non-reinforced alloys. Among the various types of MMC$_s$, aluminum-based composites have been found in various engineering applications such as the aerospace and automobile industries. The most popular reinforcements are silicon carbide (SiC) and alumina (Al2O3). Aluminum, titanium, and magnesium alloys are commonly used as the matrix phase. The density of most of the MMCs is approximately one third that of steel, resulting in high-specific strength and stiffness [1]. It is possible to produce high-quality MMC components to near-net shape through various manufacturing techniques, but additional machining is unavoidable to achieve the desired surface quality and dimensional tolerance for efficient assembly [2]. Several studies have been done in order to examine the efficiency of different cutting tool materials, such as carbide, coated carbide, and diamond in turning, milling, drilling, reaming, and threading of MMC materials. The main problem while machining MMC is the extensive tool wear caused by the very hard and abrasive reinforcements. Manna et al.

investigated the machinability of Al/SiC MMC and found that no built-up edge (BUE) is formed during machining of Al/SiC MMC at high speed and low depth of cut and also observed a better surface finish at high speed with low feed rate and low depth of cut[3]. Kumar Reddy et al. studied quality of components produced during end milling of Al/SiC particulate metal matrix composites (PMMCs). The results showed that the presence of the reinforcement enhances the machinability in terms of both surface roughness and lower tendency to clog the cutting tool, when compared to a non-reinforced Al alloy[4]. Palanikumar developed a model for surface roughness through response surface method (RSM) while machining GFRP composites. Four factors five level central composite rotatable design matrix was employed to carry out the experimental investigation. Analysis of variance (ANOVA) was used to check the validity of the model[5]. Muthukrishnan et al. developed two modeling techniques used to predict the surface roughness namely ANOVA and ANN [6]. Oktem et al. developed an effective methodology to determine the optimum cutting conditions leading to minimum surface roughness while milling of mold surfaces by coupling RSM with a developed genetic algorithm (GA) [7]. Alauddin et al. predicted the surface roughness of 190 BHN steel after end milling using a mathematical model depending on cutting speed, feed rate and depth of cut. They used the response surface methodology (RSM) to explore the effect of these parameters on surface roughness [8]. Liu and Cheng presented a practical method for modelling and predicting the machining dynamics and surface roughness/waviness in peripheral milling [9]. C-olak et al. predicted surface roughness of milling surface related to cutting parameters by using the genetic expression programming method. They considered cutting speed, feed rate and depth of cut of end milling operations for predicting surface roughness and predicted a linear equation for surface roughness related to experimental study [10]. The researchers also used response surface methodology (RSM) to explore the effect of such cutting parameters as cutting speed, feed rate and depth of cut on surface roughness. Alauddin et al. also established a mathematical model for predicting the tool in the end milling process of 190 BHN steel under dry cutting conditions. The model included the following variables: cutting speed, feed rate and axial depth of cut. It also verified the suitability of the prediction model via ANOVA [11]. This paper focuses on machining of Al/SiC_p metal matrix composites which is widely used in engineering applications. The chemical composition of the LM25 aluminum alloy is shown in Table-1.

Table 1. Chemical composition of LM25 aluminum alloy

Material	Si	Mg	Mn	Fe	Cu	Ni	Ti
LM25 Al alloy	7	0.33	0.3	0.5	0.1	0.1	0.2

RESPONSE SURFACE METHOD

Response surface modeling was used to establish the mathematical relationship between the response (Y_u) and the various process parameters [12, 13]. The general second order polynomial response surface mathematical model, which analyses the parametric influences on the various response criteria, can be described as follows:

$$Y_u = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{j>1}^{k} b_{ij} x_i x_j \quad \text{--------------------------- (1)}$$

Where Y_u is response and $x_{i\ (1,2,\ \ldots\ ,k)}$ are coded levels of k quantitative variables. The coefficient b_0 is the constant term; the coefficients b_i, b_{ii}, and b_{ij} are the linear, quadratic, and interaction terms. After logarithmic transformation the nonlinear form of Equation 1 was converted into a linear form, which then was used to develop response surface regression model. To establish the prediction model, a software package MiniTab was used to determine the coefficients of mathematical modeling based on the response surface regression model.

Table 2. Levels of parameters.

Factors / Coding of levels	-2	-1	0	+1	+2
Spindle speed, *N* (RPM)	2000	2500	3000	3500	4000
Feed rate, f (mm/rev)	0.02	0.03	0.04	0.05	0.06
Depth of cut, d (mm)	0.5	1	1.5	2	2.5
Silicon Carbide, S (%wt.)	5	10	15	20	25

Table 3. Experimental design matrix and results

Ex. No.	Coded values				Surface roughness (R_a) (μm)		% Error
	X_1	X_2	X_3	X_4	Experimental	Predicted	
1.	-1	-1	-1	-1	4.406	4.418	-0.27
2.	1	-1	-1	-1	3.812	3.768	1.17
3.	-1	1	-1	-1	6.034	6.035	-0.02
4.	1	1	-1	-1	5.229	5.234	-0.10
5.	-1	-1	1	-1	4.472	4.468	0.09
6.	1	-1	1	-1	3.802	3.823	-0.55
7.	-1	1	1	-1	6.032	6.098	-1.08
8.	1	1	1	-1	5.312	5.301	0.21
9.	-1	-1	-1	1	4.978	4.998	-0.40
10.	1	-1	-1	1	4.395	4.334	1.41
11.	-1	1	-1	1	6.789	6.773	0.24
12.	1	1	-1	1	5.945	5.958	-0.22
13.	-1	-1	1	1	5.071	5.070	0.02
14.	1	-1	1	1	4.402	4.410	-0.18
15.	-1	1	1	1	6.804	6.857	-0.77
16.	1	1	1	1	6.054	6.046	0.13
17.	-2	0	0	0	6.202	6.143	0.96
18.	2	0	0	0	4.638	4.682	-0.94
19.	0	-2	0	0	3.679	3.709	-0.81
20.	0	2	0	0	7.008	6.962	0.66
21.	0	0	-2	0	5.062	5.103	-0.80
22.	0	0	2	0	5.299	5.242	1.09
23.	0	0	0	-2	4.334	4.316	0.42
24.	0	0	0	2	5.639	5.641	-0.04
25.	0	0	0	0	5.183	5.189	-0.12
26.	0	0	0	0	5.177	5.189	-0.23
27.	0	0	0	0	5.221	5.189	0.62
28.	0	0	0	0	5.163	5.189	-0.50
29.	0	0	0	0	5.155	5.189	-0.66
30.	0	0	0	0	5.199	5.189	0.19
31.	0	0	0	0	5.229	5.189	0.77

MATERIALS AND METHODS

Experimental Details

LM25 Aluminum alloy reinforced with silicon carbide particles of size 25 μm with 5%, 10%, 15%, 20% and 25% weight manufactured through stir casting route is used for experimentation. The dimensions of the specimens were 100mm × 60mm × 40mm. The experiments were conducted on HASS vertical machining center with 12mm diameter, 4 flute carbide end mill cutter under dry condition. The level of parameters selected for the experiments were given in the Table-2. Thirty one experiments are carried out according to the central composite design (CCD). The surface roughness (Ra) of the machined test specimens was measured using a Talysurf tester with a sampling length of 10mm. The Experimental design matrix and results were given in Table-3.

RESULTS AND DISCUSSION

Experiments have been carried out using the vertical machining centre on LM25Al-SiC_p to study the influence of some of the predominant process parameters such as spindle speed, feed rate, depth of cut, and %wt. of silicon carbide (S) on surface roughness. The mathematical relationship for correlating the surface roughness and the considered process variables has been obtained as follows:

$$R_a = 4.716 - (0.002\, X_1) + (61.948\, X_2) + (0.050\, X_3) + (0.099\, X_4) + (365.551\, X_2^2) - (0.017\, X_3^2) - (0.002\, X_4^2) - (0.008\, X_1 X_2) + (0.612\, X_2 X_3) + (0.789\, X_2 X_4) + (0.002\, X_3 X_4) \quad \text{------------------(2)}$$

The second-order polynomial models were developed for surface roughness. The fit summary indicates that the quadratic model is statistically significant for analysis of surface roughness. The value of R is 99.85 %, which indicates that the developed regression model is adequately significant at a 95 % confidence level. It provides an excellent relationship between the process parameters and the response surface roughness.

Table 4. Analysis of variance for surface roughness (R_a)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	22.0127	22.013718	1.572334	763.09	0.000
Linear	4	21.7361	0.313339	0.078294	38.00	0.000
Square	4	0.2282	0.228666	0.057041	27.68	0.000
Interaction	6	0.0485	0.048455	0.008076	3.92	0.013
Residual Error	16	0.0330	0.032508	0.002060		
Total	30	22.0456				

An analysis of variance (ANOVA) was performed for surface roughness is presented in Table 4. The associated p-value for the model is lower than 0.05 (i.e. level of significance α=0.05, or 95 % confidence), which indicates that the model can be considered statistically significant. It is evident from the table 3 that the error between the experimental value and predicted value is less than 5%.The result proves that the feed rate, spindle speed and %wt. SiC_p enhance the surface finish. The normal probability plot is presented in Fig.1. It can be noticed that the residuals fall on a straight line, which means that the errors are normally distributed and the regression model is well fitted with the observed values. Figure 2 shows the residual values with fitted values for surface roughness. Figure 2 indicates that the maximum variation of -0.075 to 0.050, which shows the high correlation that exists between fitted values and observed values.

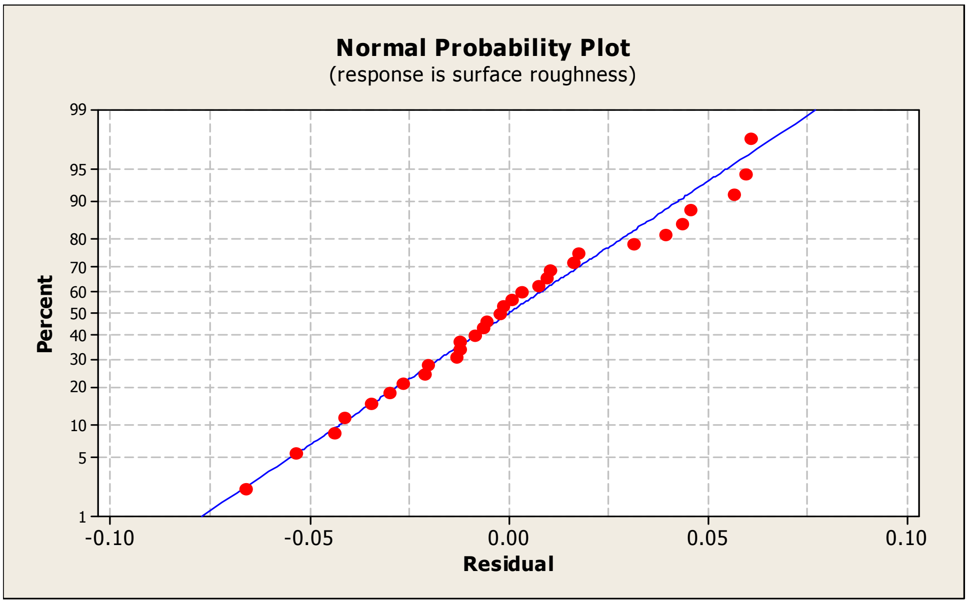

Fig. 1: Normal probability plot for surface roughness

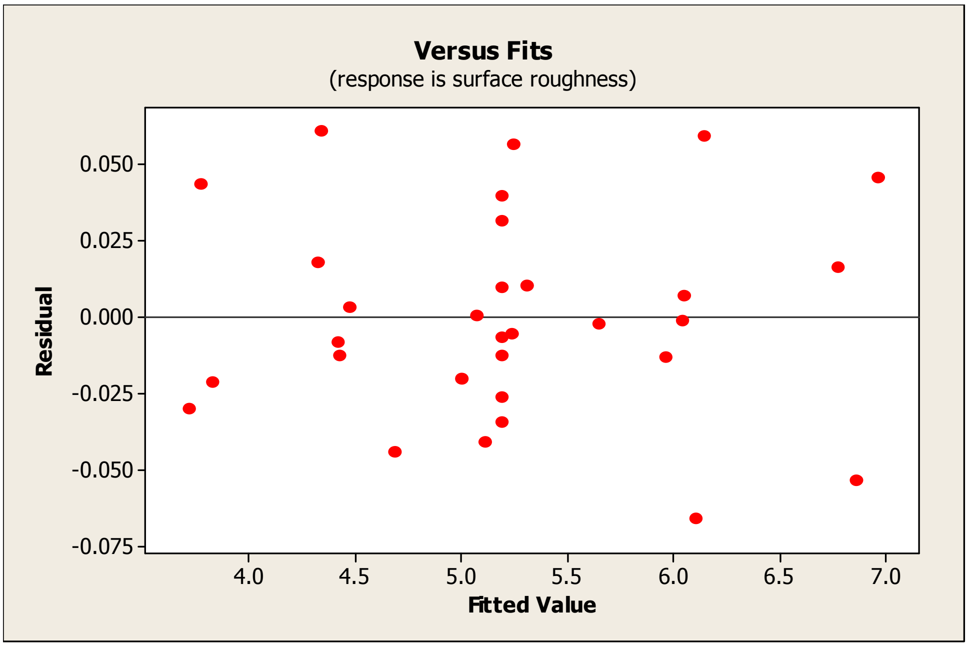

Fig. 2: Residual Vs fitted values for surface roughness

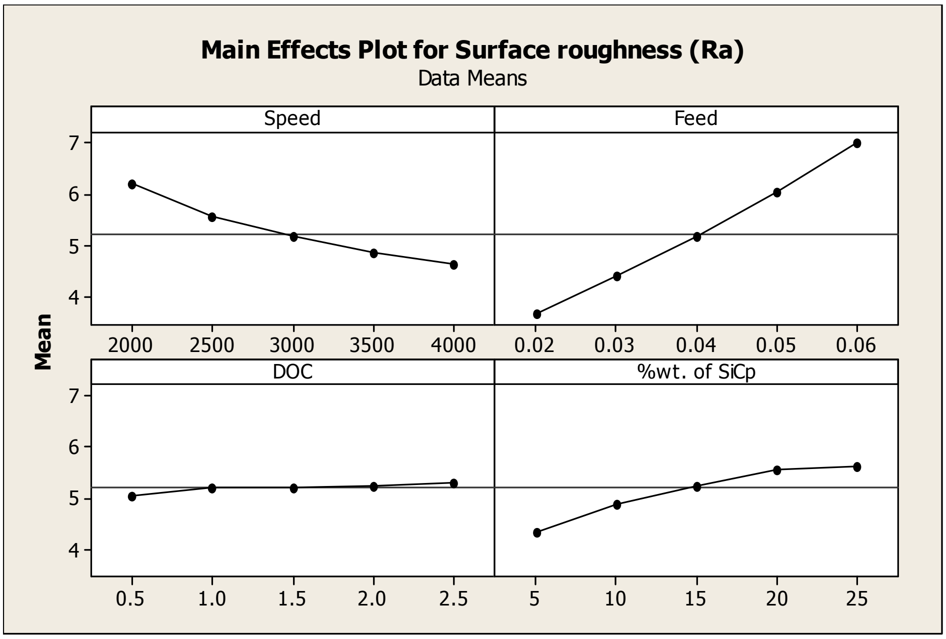

Fig. 3: Main effects plot for surface roughness

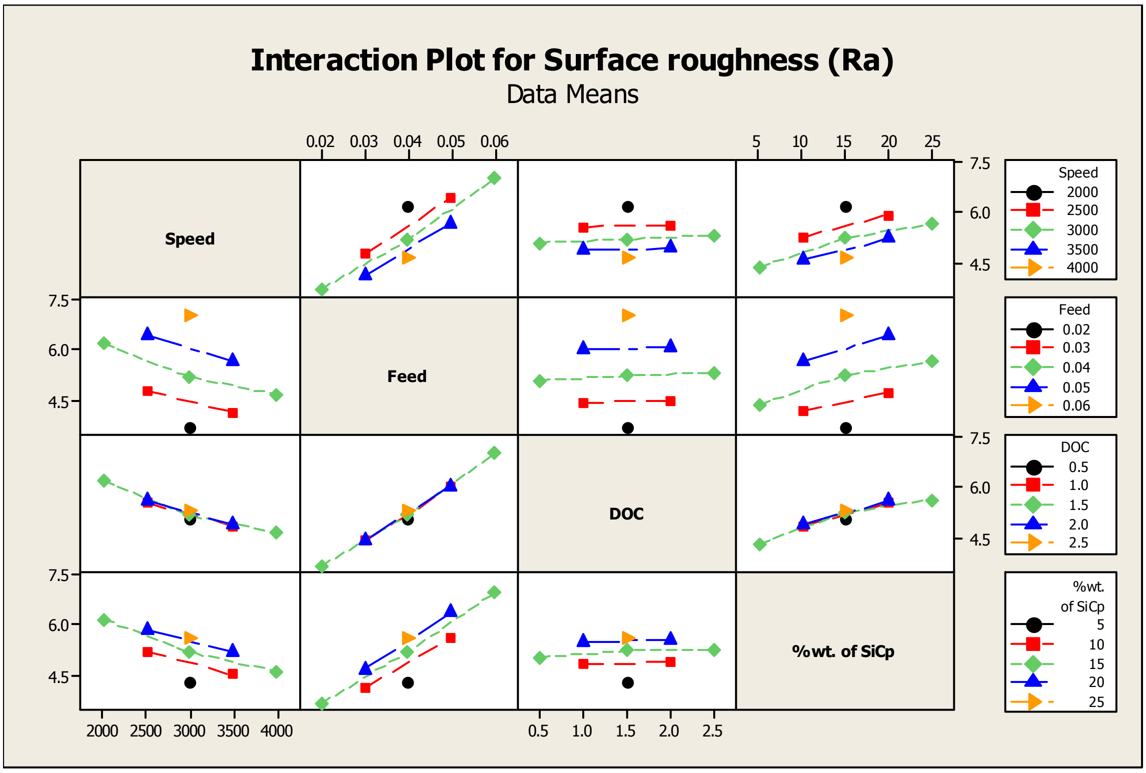

Fig. 4: Interaction plot for surface roughness

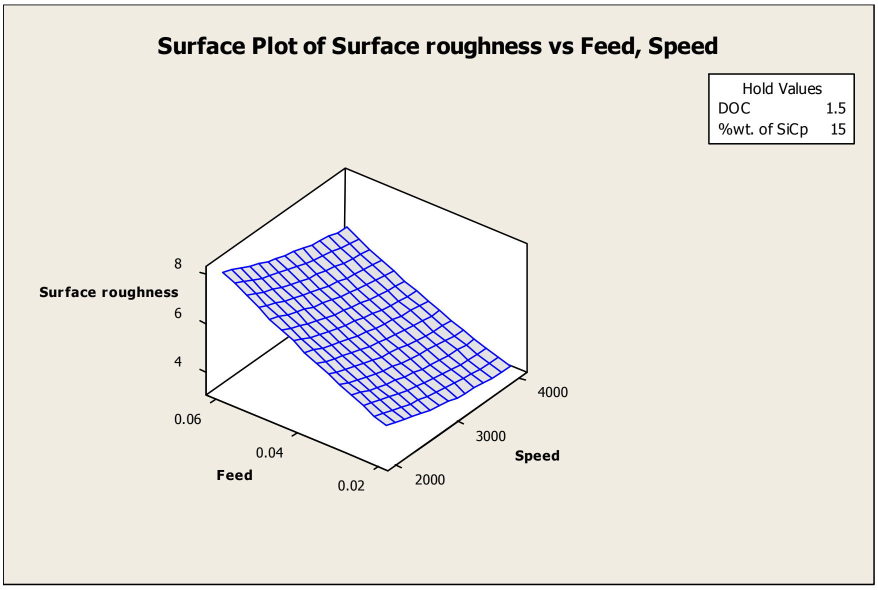

Fig. 5: **Surface Plot of Surface roughness vs. Speed, Feed**

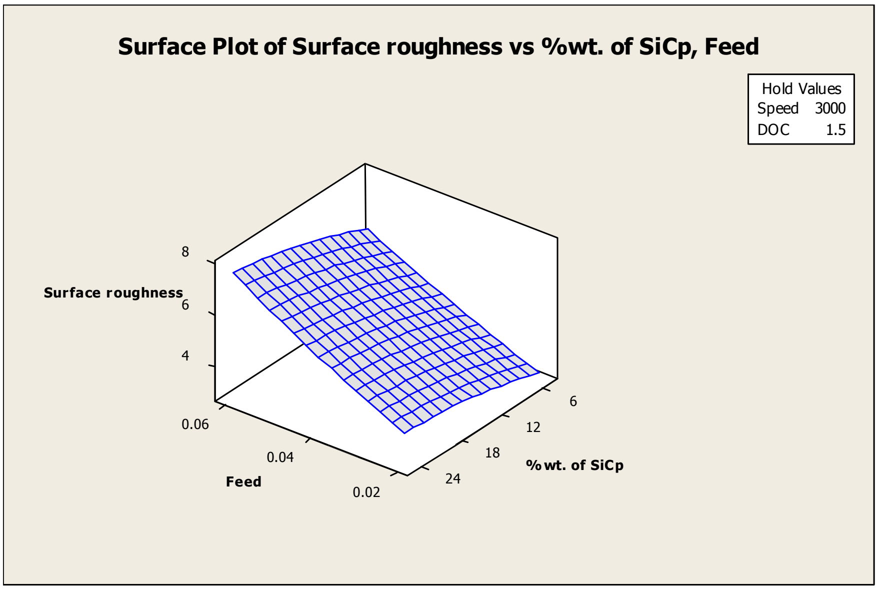

Fig. 6: **Surface Plot of Surface roughness vs. Feed, %wt. of SiCp**

The data was further analyzed to study the interaction among process parameters and the main effects plot and interaction plots were generated and shown in Figures 3 and 4, respectively. It indicates that feed rate, spindle speed and %wt. SiC_p enhance the surface finish. Depth of cut has less influence on surface roughness while end milling of LM25 Al/SiC_p MMC.

Figure 5 shows that functional dependence of Ra on the spindle speed and feed rate for the invariable depth of cut value of 1.5 mm and SiC_p value of 15%wt. It can be seen that the surface roughness decreases when feed rate decreases, but surface roughness increases when spindle speed decreases. Figure 6 shows that functional dependence of Ra on the feed rate and %wt. of SiC_p for the invariable spindle speed value of 3000 RPM and SiC_p value of 15%wt. It can be seen that the surface roughness decreases when feed rate decreases, but surface roughness increases when %wt. of SiC_p increases.

CONCLUSION

The experiments were conducted on a vertical milling machine for the machining of LM25 Al/SiC_p. The tool used for the machining operation is a carbide tool. The response surface roughness was studied.

1. The second-order polynomial models were developed to predict the surface roughness using response surface methodology.
2. The model indicates that the feed rate was the most dominant parameter on surface roughness followed by spindle speed and %wt. of SiC_p. Depth of cut has less influence on surface roughness.
3. The residual plots for surface roughness are generated. From the plots it is observed that regression model is well fitted with the observed values and high correlation that exists between fitted values and observed values.
4. The main effect plot for surface roughness indicates that the feed rate was the most dominant parameter on surface roughness followed by spindle speed and %wt. of SiC_p. Depth of cut has less influence on surface roughness.
5. The interactions plots for surface roughness was analyzed and strong interactions were observed between Feed rate-Spindle speed and Feed rate-% wt. of SiC_p on surface roughness.
6. The surface roughness model produced during this research work may be used in enhancing the surface quality of a product as process parameters are optimized and can give better surface finish.

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