Research Article

# Tool wear optimization in CNC milling operation of Al–$Mg_2Si$ alloys by Taguchi method

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**Abstract**
In this research, Taguchi technique was applied to find out the optimum tool wear in CNC milling operation of magnesium silicide alloys with aluminum. A L9 orthogonal array, S/N ratios and ANOVA techniques are used to analyze the performance characteristics of spindle speed; feed rate and depth of cut as machining parameters with tool wear as responded variable. The result of the analysis reveals that the chosen machining parameters are affecting the tool wears drastically, while machining magnesium silicide alloys with aluminum and also point out the spindle speed is the most influencing parameter of compare to feed rate and depth of cut. At last, the results are confirmed by validation experiments.

**Keywords** Al–$Mg_2Si$ alloys · CNC milling · Machining parameters · Tool wear · Taguchi

## 1 Introduction

In order to compete effectively on the global marketplace, organizations need to be able to create a range of high-quality, low-cost goods that completely fulfill the requirements of clients. Those companies that make fundamental changes in the way they develop technologies and design and produce products will be the industry leaders of tomorrow [1].

Dr. Genichi Taguchi's strategy to quality improvement is presently the most commonly used engineering method in the globe, acknowledged by nearly any engineer, although other quality attempts have gained popularity in company media and have lost popularity [2]. For example, the catch phrase "total quality management" (TQM) in the last part of the twentieth century placed Japan on the global map along with the revolution in automotive quality.

Taguchi utilizes standard statistical instruments in essence, but he simplifies them by defining a set of stringent rules with a power conversion model—a centered engineering scheme for experimental design and outcomes assessment. Taguchi used and supported quality statistical techniques from the view of an engineer rather than a statistician [3].

As Taguchi's concepts have become more prevalent, more and more design engineers in their everyday life are using Taguchi's methodology. As robust design methods become increasingly popular, more and more quality and engineering experts have changed their quality paradigm from checking defects and solving problems to developing quality and reliability into products or procedures [4].

Taguchi's design strategy emphasizes continuous improvement and covers various elements of the design process divided into three primary phases [5]:

1. Design of the system. This is generally consistent with conceptual design in the design process's generalized model. System design is the conceptual design phase where knowledge in science and engineering is applied to the development of fresh and original tech-

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niques. Robust development does not concentrate on the system design phase using the Taguchi technique.

2. Design of parameters. Parameter design is the phase of optimization of a chosen idea. Many factors may influence the function of a system. From an engineering point of view, the variables must be defined. The parameter design goals are to (a) find a combination of settings of control factors that allow the system to achieve its ideal function, and (b) remain insensitive to variables that cannot be monitored. The design of parameters offers possibilities to decrease the cost of product and production.
3. Design for tolerance. While usually regarded part of the comprehensive design phase, Taguchi views this as a separate phase to be used when it is not possible to achieve adequately tiny variability within a parameter design. Tolerances are generally taken to be relatively broad initially because narrow tolerances often incur elevated expenses of supply or manufacture. Tolerance design can be used to define those tolerances that generate the most significant efficiency improvements when tightened.

## 2 Literature

In a manufacturing sector, product and process designs have a significant impact on the future of a company, but in a service industry such as telecommunications, traffic, or finance, designing production systems to generate services is an important role [6]. There are two phases in the design phase: (a) synthesis and (b) evaluation. Quality engineering classifies the synthesis phase into two further stages: (a) system selection (concept) and (b) nominal system parameter selection (design constants). Designer creativity is appropriate for the former, and a patent can be protected if a designer invents a fresh technique [7].

The latter has to do with the development cycle time and the engineering of quality. How a designer determines concentrations of constants in design (nominal system parameters), which can be chosen at the discretion of a designer, changes a product's functional stability under different circumstances of use [8]. Parameter design is called a method to minimize deviation of a product function from an optimal function under different circumstances by changing nominal design constants. It is also a problem in quality engineering to balance functional robustness and cost and improve efficiency (minimize quality and cost) by taking advantage of the loss function after improving robustness [9].

Only the parameter design approach is demonstrated here. Research and design mainly consists of selecting system and designing parameters. While creating fresh technologies and ideas is very crucial, it is uncertain whether a chosen system can become competitive enough in the marketplace until parameter design is complete [10]. It is therefore crucial to efficiently design parameters for the chosen scheme in the brief term. In the case of a large-scale or feedback control system, we should divide and simultaneously develop a total system into subsystems to streamline the design of the entire system. Proper system division is the duty of the design leader. The foundation of product design is to enhance functional robustness (reliability) so that a product can work well on the market [11].

This implies that the parameters of studies and design should be drawn up so that a product can operate over the product life span under different circumstances on the marketplace. The current design of simulation approaches an objective function [12]. We should approach the objective function using only normal circumstances after enhancing robustness (the normal SN ratio).

It is essential to reduce variability. Parameters should be distributed in simulations around normal values. Control and noise variables are all parameters in a scheme. If calculation of simulation takes a long time, it is possible to compound all noise variables into two levels. In this situation, we need to verify the initial qualitative inclination of compound noises [13]. To do this, we explore compounded noise impacts in an orthogonal array to which, under original design circumstances, only noise is allocated, mostly the second level of control variables.

Orthogonal means "balanced," "separable" or "not blended" in the design of experiments. A significant feature of Dr. Taguchi's use of orthogonal arrays is the flexibility and ability to assign an amount of factors. However, an even more significant characteristic is the "reproducibility" or "repeatability" of the findings drawn from small-scale studies, in product/process design research and development job, as well as in real manufacturing and field. For many years, orthogonal arrays have been in use, but Dr. Taguchi's implementation has some unique features. At first glance, the techniques of Dr. Taguchi appear to be nothing more than a fractional factorials implementation [14].

However, in his strategy to quality engineering, the primary objective is to optimize product/process design for minimal sensitivity to "noise." The main role of an orthogonal array in Dr. Taguchi's methodology is to allow technicians to assess a product design with regard to "robustness" against "noise" and the costs involved. It is, in fact, an inspection tool to stop a "bad design" from going "downstream." According to Dr. Taguchi, quality engineering focuses on factor levels' contribution to robustness [15].

Unlike pure research, industry quality engineering apps do not look for interactions of cause and effect.

Usually such a comprehensive strategy is not cost-effective. Instead, excellent technicians should be able to involve their expertise and experience in the design of experiments by choosing features with minimal interactions to concentrate on sheer major impacts. Dr. Taguchi emphasizes the need for an experiment with confirmation. If strong interactions exist, they will be shown by a confirmatory experiment. The experiment must be re-developed if expected outcomes are not confirmed. The convention for naming arrays is La ($b^c$) where a is the number of experimental runs, b is each factor's number of levels, and c is the number of columns in the array [16].

Arrays can have factors with many concentrations, although the most frequently found are two and three level factors. For instance, an L8 array can manage seven variables under eight experimental circumstances at two stages each. L12, L18, L36, and L54 arrays are among a group of arrays specially intended to allow the physician to concentrate on the primary impacts. Such a strategy helps to make small-scale experimentation more efficient and reproducible as established by Dr. Taguchi [17].

Robust design using the Taguchi technique is an effective and systematic method—Taguchi methodology which uses statistical experimental design to improve the design of the item and the production process. The development of solid structure by Genichi Taguchi is a wonderful accomplishment in engineering. concurrent engineering in the U.S. sector became common by 1990. It brought a lot of improvements. Pioneers like Ford and Xerox, however, realized that they required more. In particular, robust design had to be commonly practiced during the creation of fresh products and procedures [18].

## 3 Experimental

With all the viewing platform above, the aim of the research is to optimize the tool wear in CNC milling operation of Al–$Mg_2Si$ alloys by using end mill cutter with the assistance of Taguchi's L9 orthogonal array, signal to noise ratio, ANOVA in addition to carried out the optimal levels of each cutting parameters such as spindle speed, feed rate and depth of cut with their percentage charities. At last, the results are secondary confirmed by validation experiments before confirmation run. The experimental set up is shown in Fig. 1. The mechanical properties of Al–$Mg_2Si$ alloys represented in Table 1 and machining parameters and their levels noted in Table 2 for experimental work.

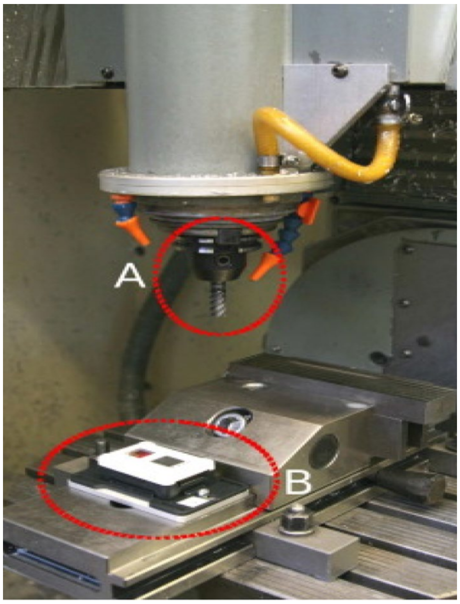


**Fig. 1** Experimental set-up **A** Tool **B** Wear monitoring

### 3.1 Grouping of appropriate orthogonal array and signal to noise (S/N) ratio

Taguchi technique has been used to study on the influence of three machining parameters such as spindle speed; feed rate and depth of cut on tool wear. For appropriate choosing of orthogonal array, degree of freedom (DOF) is calculated. The total degree of freedom intended for three machining parameter at three levels is known by,

Degree of Freedom = 3*(3 − 1) = 6

So, a three level orthogonal array using at least six degree of freedom was to be carefully chosen. Therefore, L9 orthogonal array was carefully selected for this study. In this research it was presumed that no interaction occurs between the machining parameters. The investigational plan using L9 orthogonal array with responses, mean value of responses and their corresponding signal to noise (S/N) ratio is specified in Table 3.

Since, tool wear is a 'smallest is the better' type of quality distinctive, for the reason that objective is to minimize the tool wear, thus, the S/N ratio for 'smaller is the better' type of response was used which is known by the succeeding equation:

$$S/N = -10\log\sum_{i=0}^{n}\left(\frac{Y_i^2}{n}\right) \quad (1)$$

Now, n signifies the experimental trial conditions and $Y_1$, $Y_2$, $Y_3$…Yn signifies the values of responses designed for quality characteristics. The S/N ratios were considered

**Table 1** Mechanical properties

| Grade | Al-4% $Mg_2Si$ | Al-8% $Mg_2Si$ | Al-12% $Mg_2Si$ |
|---|---|---|---|
| Ultimate tensile strength (Mpa) | 149.34 | 164.21 | 185.22 |
| Yield strength (Mpa) | 24.8 | 34.8 | 54.6 |
| Elongation (%) | 12.8 | 10.3 | 8.1 |
| Hardness rockwell (B) | 51.92 | 58.08 | 66.97 |

**Table 2** Machining parameters and their levels

| Factors | Factors code | Levels | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Spindle speed (rpm) | A | 750 | 1000 | 1250 |
| Feed rate (mm/min) | B | 100 | 200 | 300 |
| Depth of cut (mm) | C | 0.5 | 0.75 | 1 |

**Table 3** L9 orthogonal array for three factors at three levels

| Run | Spindle speed (rpm) | Feed (mm/min) | Depth of cut (mm) | Tool flank wear (µm) (Mean value) | S/N ratio |
|---|---|---|---|---|---|
| 1 | 750 | 100 | 0.5 | 106.87 | 58.91 |
| 2 | 750 | 200 | 0.75 | 125.2 | 60.53 |
| 3 | 750 | 300 | 1 | 131.87 | 60.88 |
| 4 | 1000 | 100 | 0.75 | 128.53 | 60.81 |
| 5 | 1000 | 200 | 1 | 148.53 | 62.28 |
| 6 | 1000 | 300 | 0.5 | 150.2 | 62.38 |
| 7 | 1250 | 100 | 1 | 143.53 | 61.93 |
| 8 | 1250 | 200 | 0.5 | 126.87 | 60.72 |
| 9 | 1250 | 300 | 0.75 | 146.87 | 62.16 |

**Table 4** Response table for mean estimation

| Level | Spindle speed (rpm) (A) | Feed (mm/min) (B) | Depth of cut (mm) (C) |
|---|---|---|---|
| 1 | 121.3 | 126.3 | 128 |
| 2 | 142.4 | 133.5 | 133.5 |
| 3 | 139.1 | 143 | 141.3 |
| Delta | 21.1 | 16.7 | 13.3 |
| Rank | 1 | 2 | 3 |

using Eq. (1) for all of the nine trails and their corresponding values are noted in Table 3.

The mean response, it means, the average value of the presentation characteristics for all the machining parameters at various levels were calculated. These average values of tool wear for all the machining parameters at levels 1, 2, 3 are specified in Table 4 and shown in Fig. 2.

In the same way, the average values of S/N ratios of the each three parameters at dissimilar levels are evaluated and are shown in Table 5 and Fig. 3.

It is clear that from the above Table 4 and Fig. 2 that tool wear is lowest at first level of parameter A (spindle speed), first level of parameter B (feed rate) along with first level of parameter C (depth of cut). The S/N ratio study from the above Table 5 and Fig. 3 similarly shows that the identical results that tool wear of end mill cutter inserts in CNC milling Al–$Mg_2Si$ alloys is lowest at $A_1$, $B_1$ and $C_1$. These outcomes are also confirmed in Fig. 4 of surface plot of spindle speed, feed rate and depth of cut.

At present, to study the proportion contribution of all the machining parameters ANOVA was executed. The outcome of ANOVA of the fresh data or mean of reaction of tool wear is specified in Table 6 and also the outcomes of ANOVA of S/N ratios are specified Table 7. It is clear, as of these tables that the spindle speed, feed rate and depth of cut knowingly affect the significance of tool wear. The percentage influences all the machining parameters are enumerated in the final column of both the tabular. Both the tabular column proposes that the effect of spindle speed (A) and feed rate (B) on tool wear is considerably greater than the effect of depth of cut (C). These influences of machining parameters are correspondingly inferred from Figs. 5, 6 and 7.

The analytic proving has been completed through normal probability plot used for the current study which is exposed in Fig. 8. The residuals are usually plotting on straight line suggestions that errors are distributed generally. From the Fig. 8 it can be decided that all the plotted values are within the range of confidence level of interval like 95%, so these plotted values are provides greater results in upcoming prediction within the parameters.

### 3.2 Prediction of mean tool wears at the nominal condition

The optimum values of tool wear is forecast at the designated levels of machining parameters which are $A_1$, $B_1$ and $C_1$.The calculated mean of tool wear at optimum condition have to be evaluated as:

$$U_{FWW} = A_1 + B_1 + C_1 - 2T_{FWW}$$

**Fig. 2** Main effects plot for means of tool wear

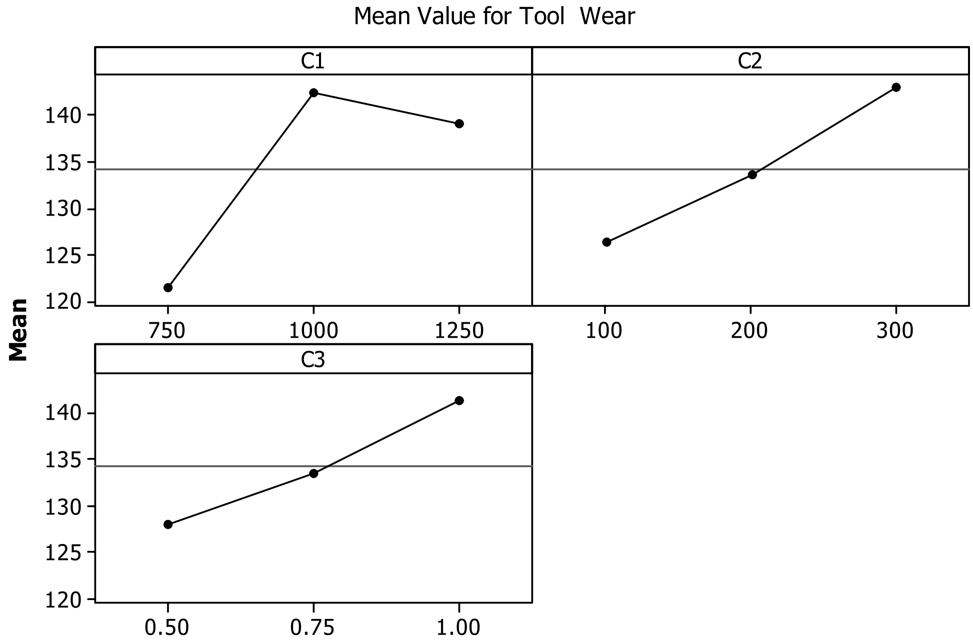


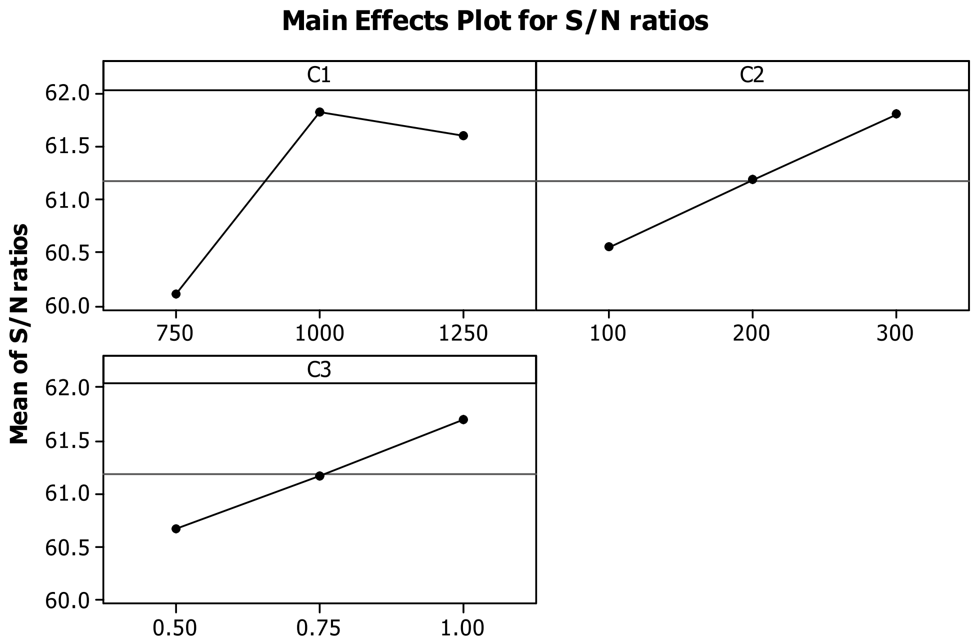
**Table 5** Response table for mean estimation of S/N ratios

| Level | Spindle speed (rpm) (A) | Feed (mm/min) (B) | Depth of cut (mm) (C) |
|---|---|---|---|
| 1 | 60.11 | 60.55 | 60.67 |
| 2 | 61.82 | 61.18 | 61.17 |
| 3 | 61.6 | 61.81 | 61.7 |
| Delta | 1.72 | 1.26 | 1.03 |
| Rank | 1 | 2 | 3 |

where $U_{FWW}$ = Predicted mean response of tool wear, $A_1 = 121.3$ μm, $B_1 = 126.3$ μm, $C_1 = 128.0$ μm, $T_{FWW}$ = Overall mean of tool wear = 134.27 μm

Thusly, $U_{FWW} = 121.3 + 126.3 + 128.0 - 2 \times 134.27 = 07.06$ μm. So, the expected mean response confirmation that there is 20.26% reduces in mean tool wear when functioning at optimum condition.

**Fig. 3** Main effects plot for means of S/N ratios



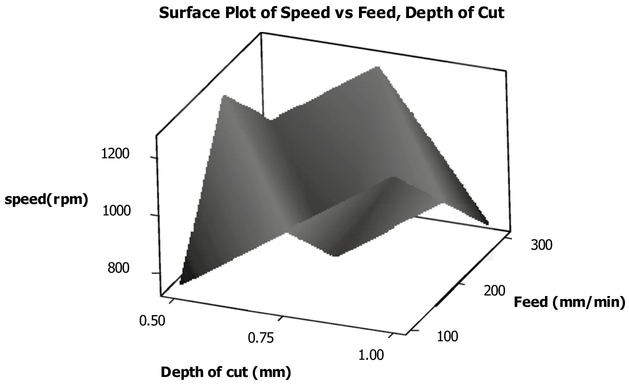


**Fig. 4** Surface plot of spindle speed, feed rate and depth of cut

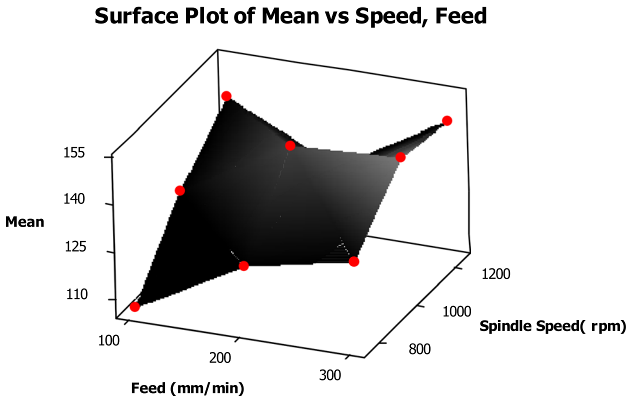


**Fig. 5** Surface plot of mean tool wear versus speed, feed rate

**Table 6** Analyses of variance for mean tool wear

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| *Analysis of variance* | | | | | |
| Regression | 3 | 1157.38 | 385.79 | 4.10 | 0.082 |
| Residual error | 5 | 470.73 | 94.15 | | |
| Total | 8 | 1628.11 | | | |

| Source | DF | Seq SS |
|---|---|---|
| C1 | 1 | 474.01 |
| C2 | 1 | 416.83 |
| C3 | 1 | 266.53 |

**Table 7** Analyses of variance for S/N ratios of tool wear

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| *Analysis of variance* | | | | | |
| Regression | 3 | 7.3099 | 2.4366 | 4.23 | 0.077 |
| Residual error | 5 | 2.8769 | 0.5754 | | |
| Total | 8 | 10.1868 | | | |

| Source | DF | Seq SS |
|---|---|---|
| C1 | 1 | 3.3600 |
| C2 | 1 | 2.3688 |
| C3 | 1 | 1.5811 |

## 3.3 Confirmation run

Three verification runs were carried out at the chosen optimal settings of CNC milling process parameters elected. In this validation trials the average tool wear of end mill cutter while machining Al–$Mg_2Si$ alloys was found to be 110.21 µm. These outcomes are very much closer to the forecasted value and this validation run outcomes confirmed the success of the study.

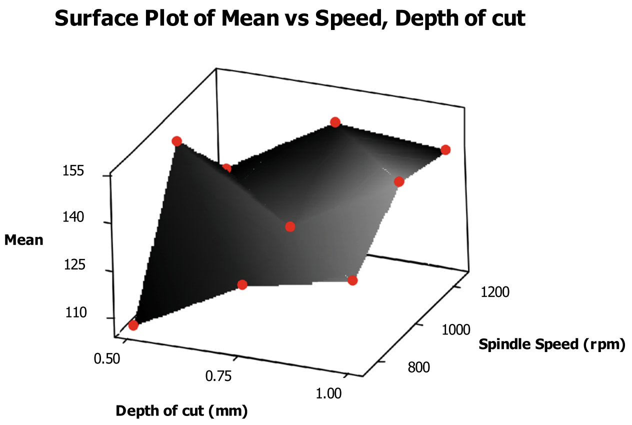


**Fig. 6** Surface plot of mean tool wear versus speed and depth of cut

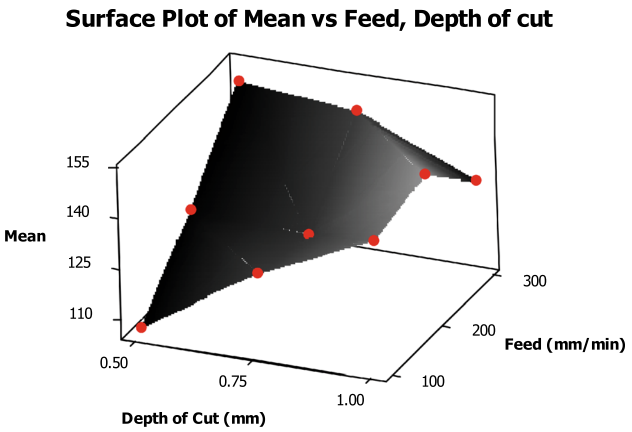


**Fig. 7** Surface plot of mean tool wear versus feed rate, depth of cut

# 4 Conclusion

## 4.1 Summary of results

- Taguchi technique is apt to optimize the tool wear of end mill cutter while machining Al–$Mg_2Si$ alloys.
- The levels of machining parameters for minimum tool wear of end mill cutter while machining Al–$Mg_2Si$ alloys are spindle speed at level one-750 rpm, feed rate at level one- 100 mm/min and depth of cut also at level one- 0.5 mm.
- From the investigational outcomes it is identify that tool wear is decreased by 20.26% when working at nominated levels of machining parameters.

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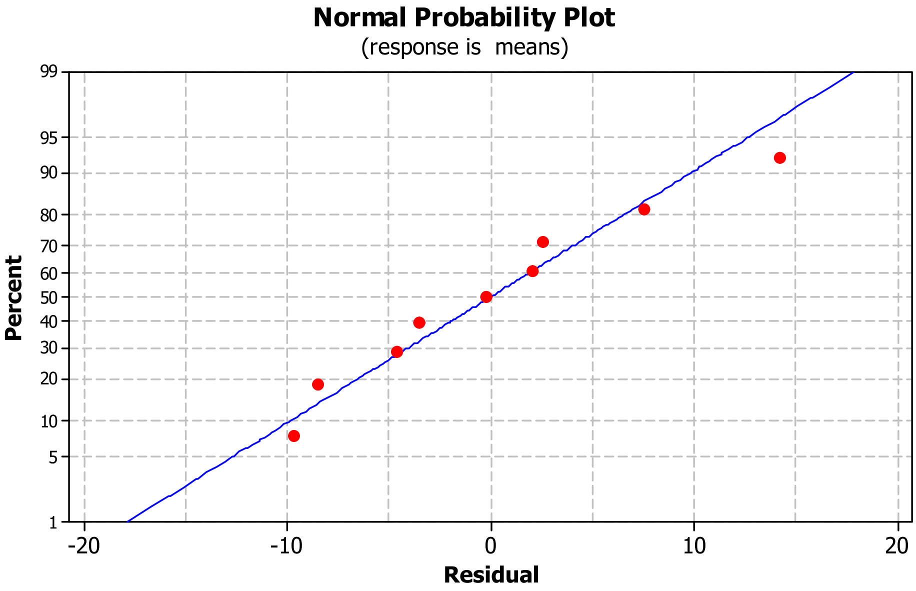
## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Fig. 8** Normal probability plot for tool wear



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