Multi-objective optimization using TOPSIS in turning of Al 6351 alloy

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Abstract. Surface finish and machining rate are the important machining criteria in turning process and plays a vital role in manufacturing environment. This work focused on the parametric optimization of cutting velocity, feed and depth of cut in turning of AA 6351 alloy with carbide tool for maximization of machining rate and minimization of surface roughness simultaneously using technique for order Preference by similarity to ideal solution (TOPSIS) method. Contribution of every machining parameter on multi objectives is spotted by employing analysis of variance (ANOVA). Finally results are validated with a confirmation experiment. Significant improvement within the responses is observed using the TOPSIS method.

1. Introduction

The quality of surface and material removal rate are the predominant parameters in any manufacturing industry to assess the production rate of machine tools and the quality of the machined components. Hence, obtaining the required surface finish is essential for the functional requirement of designed parts. Surface quality affects on the several properties like fatigue strength, wear rate, friction coefficient, lubrication and corrosion resistance of the machined parts [1]. But the machining rate (MR) and surface roughness (SR) are the two conflicting machining criteria. When we try two increase the one the other affected worse. So, products must be produced with the required surface quality with optimum cost. This can be achievable when simultaneously maximize the MR and minimize the SR.

The influence of speed and feed on SR and MR were observed by Ranganath et al.[2] using Taguchi experimental design in turning of A 6061 alloy and observed that good surface finish at high cutting speed. MR and time of machining (TM) were optimized in machining (turning) of Al 7075 aluminium alloy with carbide tool by taking depth of cut, speed and feed as process parameters and observed that speed is the most important parameter that effects on MR and TM [3]. In [4] Al6061 alloy, silicon carbide (10%wt) and graphite (3%wt) hybrid metal matrix composites were turned on a CNC lathe and MRR and SR were optimized by using response surface methodology (RSM) with depth of cut, speed, feed and tool material as input parameters. Surya et al.[5] did the multi response (MRR, SR and tool wear rate) optimization using grey relational analysis (GRA) and ANOVA in machining of Al 7075 aluminium alloy with speed, depth of cut and feed as process parameters.

The affect of depth of cut, speed and feed on MR and SR were investigated by Goyal et al. [6] in machining of AISI 1020 low-carbon steel using WNMG332RP carbide insert tip and observed that signal to noise (S/N) ratio decreases on increasing cutting speed, while S/N ratio increases with an increase in depth of cut and feed. Parametric optimization was carried out in CNC
turning process [7] using Taguchi method with grey analysis for optimizing the different performance measures such as MR, total machining cost and SR in turning of LM 25 Al alloy with speed, feed, depth of cut and flow rate of cutting fluid as input parameters. Rahul and Vijaykumar [8] obtained the empirical model to predict MR in terms of cutting velocity, feed and depth of cut using regression models and also used genetic algorithms for optimal combination of machining parameters to optimize MR in turning of aluminium alloy. Affect of depth of cut, nose radius, feed and cutting speed on MR and surface finish was investigated by Ahmeda and Rajesh [9] in machining of Al 6351 T6 and the influence of the input parameters were analyzed using ANOVA. ANOVA results showed that feed the most influencing machining parameter on SR followed by speed and for MR the significant parameters are speed and the feed followed by the wt% of reinforced particles in turning of TiB₂ particles reinforced Al 6063 metal matrix composites using K20 carbide insert [10].

TOPSIS method was used in [11] for the simultaneous optimization of SR and MRR in abrasive water jet machining of Inconel 625 alloy. Balasubramaniyan and Selvaraj [12] did the multi objective optimization in turning of EN25 steel with carbide tools using combined Analytic Hierarchy Process (AHP) and TOPSIS methods and obtained the optimal input parameters. TOPSIS analysis was used for optimization of SR and MR simultaneously in turning of GFRP composites with speed, feed, and depth of cut as machining parameters [13].

TOPSIS method was used in various multiresponse optimization problems like optimal selection of stir casting parameters to obtain maximum tensile strength of Al–15%Mg2Si composite [14], multiobjective optimization of mechanical properties of aluminum composites with different reinforcing particles [15], to select optimal machining parameters in turning of Titanium [16], optimization of the machining parameters in EDM of Al–24%SiC metal matrix composite[17], etc.

From the above literature it is notified that less work was done on multiresponse optimization in turning using TOPSIS method. In this work MRR and SR are simultaneously optimized by using TOPSIS method in turning of Al 6351 alloy.

2. Experimentation

In the present work Al alloy 6351 was machined on CNC lathe with a carbide tool. Experiments were designed based on Taguchi’s L27 orthogonal array. Experiments were conducted by varying the machining parameters. Machining rate is measured using Eq. (1) and the surface roughness values were measured by using Talysurf tester (Mituto211). The considered input parameters with their levels are shown in Table 1.

\[
\text{MR} = \text{V} \times \text{f} \times \text{d} \text{ mm}^3/\text{min} \quad (1)
\]

| Input parameters | Cutting velocity (V) | Feed (f) | Depth of cut (d) |
|------------------|----------------------|----------|-----------------|
| Level 1          | 15                   | 0.06     | 0.45            |
| Level 2          | 20                   | 0.09     | 0.60            |
| Level 3          | 25                   | 0.12     | 0.75            |
3. Methodology

Experiments are designed using Taguchi L27 full factorial orthogonal array. TOPSIS is one of the multiple attribute decision-making (MADM) methods used for solving many-objective problems. In this method feasible solutions are obtained by constructing the ideal solutions and negative ideal solutions to the multi-objective problems and then finding the closeness to the ideal solutions and being far away from the negative ideal solutions [18]. The steps in the TOPSIS are:

Step 1: Formulate the experimental decision matrix (M) using multiple objectives.

\[ M_{ij} = \begin{bmatrix} R_{11} & R_{1j} & R_{1m} \\ R_{11} & R_{ij} & R_{1m} \\ R_{n1} & R_{nj} & R_{nm} \end{bmatrix} \]  

(2)

Where i is the number of experimental trails (= 1, 2, 3, 4, …, n) and in this case, it is 27. j represent the number of responses (j = 1, 2, …, m) and in this study, it is equal to two (MRR & SR).

Step 2: Normalize the responses to eliminate the difference in measuring units and bring them on a same scale in the range of 0 and 1 using Eq. (3)

\[ N_{ij} = \frac{r_{ij}}{\sqrt{\sum_{j=1}^{m} r_{ij}^2}} \]  

(3)

Step 3: Find the weighted normalized matrix by multiplying the weight of each response (w_j) as given in Eq. (4).

\[ W_{ij} = w_j \times N_{ij} \]  

(4)

Step 4: Then, calculate the ideal positive (P⁺) and ideal negative (P⁻) alternative of the response using the Eqs. (5) & (6).

\[ P^+ = \text{Max}(W_{ij}) \text{ for larger the better response or Min}(W_{ij}) \text{ for smaller the better} \]  

(5)

\[ P^- = \text{Max}(W_{ij}) \text{ for smaller the better response or Min}(W_{ij}) \text{ for larger the better} \]  

(6)

Step 5: Now determine the separation measures (S⁺ and S⁻) from positive ideal (P⁺) and negative ideal (P⁻) to obtain the separation of every substitute to the ideal substitute and evaluated with Euclidean distance by using the Eqs. (7) and (8).

\[ S^+ = \sqrt{\sum_{i=1}^{n} (W_{ij} - P^+)^2} \]  

(7)

\[ S^- = \sqrt{\sum_{i=1}^{n} (W_{ij} - P^-)^2} \]  

(8)

Step 6: The multi response index (MRI) or closeness coefficients of each substitute to the ideal solution are determined using the Eq. (9). This MRI is used as a single objective function in the Taguchi method.

\[ \text{MRI} = \frac{S^-}{S^+ + S^-} \]  

(9)
4. Results and discussions

Experiments were carried out by changing the depth of cut, cutting speed and feed as per the Taguchi design and the responses MR and SR were measured for each experiment. The experimental matrix and the measured responses are shown in Table 2.

| Exp. No. | V  | f   | d (mm) | MR(mm³/s) | SR(µm) |
|----------|----|-----|--------|-----------|--------|
| 1        | 15 | 0.06| 0.45   | 6.750     | 0.402  |
| 2        | 15 | 0.06| 0.60   | 9.000     | 0.430  |
| 3        | 15 | 0.06| 0.75   | 11.250    | 0.455  |
| 4        | 15 | 0.09| 0.45   | 10.125    | 0.471  |
| 5        | 15 | 0.09| 0.60   | 13.500    | 0.485  |
| 6        | 15 | 0.09| 0.75   | 16.875    | 0.509  |
| 7        | 15 | 0.12| 0.45   | 13.500    | 0.532  |
| 8        | 15 | 0.12| 0.60   | 18.000    | 0.550  |
| 9        | 15 | 0.12| 0.75   | 22.500    | 0.577  |
| 10       | 20 | 0.06| 0.45   | 9.000     | 0.374  |
| 11       | 20 | 0.06| 0.60   | 12.000    | 0.397  |
| 12       | 20 | 0.06| 0.75   | 15.000    | 0.425  |
| 13       | 20 | 0.09| 0.45   | 13.500    | 0.430  |
| 14       | 20 | 0.09| 0.60   | 18.000    | 0.441  |
| 15       | 20 | 0.09| 0.75   | 22.500    | 0.454  |
| 16       | 20 | 0.12| 0.45   | 18.000    | 0.485  |
| 17       | 20 | 0.12| 0.60   | 24.000    | 0.500  |
| 18       | 20 | 0.12| 0.75   | 30.000    | 0.521  |
| 19       | 25 | 0.06| 0.45   | 11.250    | 0.386  |
| 20       | 25 | 0.06| 0.60   | 15.000    | 0.401  |
| 21       | 25 | 0.06| 0.75   | 18.75     | 0.435  |
| 22       | 25 | 0.09| 0.45   | 16.875    | 0.405  |
| 23       | 25 | 0.09| 0.60   | 22.500    | 0.432  |
| 24       | 25 | 0.09| 0.75   | 28.125    | 0.461  |
| 25       | 25 | 0.12| 0.45   | 22.500    | 0.433  |
| 26       | 25 | 0.12| 0.60   | 30.000    | 0.440  |
| 27       | 25 | 0.12| 0.75   | 37.500    | 0.465  |
### 4.1 TOPSIS results

The normalized and weighted normalized values are determined using Eqs. (3) and (4) respectively and are given in Table 3. In this work equal importance is given for MR and SR. Therefore the weight of each response is taken as 0.5.

After that the ideal and negative-ideal solutions of each response was computed using Eqs. (5) and (6) and presented in Table 4. In the present work MRR is treated as the “higher the better” quality characteristic and SR is considered as the “lower the better” one.

| Exp. No. | Normalized values | Weighted Normalized |  |
|----------|------------------|---------------------|---|
|          | MR               | SR                  | MR | SR   |
| 1        | 0.066852         | 0.168908            | 0.033426 | 0.084454 |
| 2        | 0.089135         | 0.180672            | 0.044568 | 0.090336 |
| 3        | 0.111419         | 0.191176            | 0.05571  | 0.095588 |
| 4        | 0.100277         | 0.197899            | 0.050139 | 0.09895  |
| 5        | 0.133703         | 0.203782            | 0.066852 | 0.101891 |
| 6        | 0.167129         | 0.213866            | 0.083564 | 0.106933 |
| 7        | 0.133703         | 0.223529            | 0.06852  | 0.111765 |
| 8        | 0.178271         | 0.231092            | 0.089135 | 0.115546 |
| 9        | 0.222838         | 0.242437            | 0.111419 | 0.121218 |
| 10       | 0.089135         | 0.157143            | 0.044568 | 0.078571 |
| 11       | 0.118847         | 0.166807            | 0.059424 | 0.083403 |
| 12       | 0.148559         | 0.178571            | 0.074279 | 0.089286 |
| 13       | 0.133703         | 0.180672            | 0.06852  | 0.090336 |
| 14       | 0.178271         | 0.185294            | 0.089135 | 0.092647 |
| 15       | 0.222838         | 0.190756            | 0.111419 | 0.095378 |
| 16       | 0.178271         | 0.203782            | 0.089135 | 0.101891 |
| 17       | 0.237694         | 0.210084            | 0.118847 | 0.105042 |
| 18       | 0.297118         | 0.218908            | 0.148559 | 0.109454 |
| 19       | 0.111419         | 0.162185            | 0.05571  | 0.081092 |
| 20       | 0.148559         | 0.168487            | 0.074279 | 0.084244 |
| 21       | 0.185699         | 0.182773            | 0.092849 | 0.091387 |
| 22       | 0.167129         | 0.170168            | 0.083564 | 0.085084 |
| 23       | 0.222838         | 0.181513            | 0.111419 | 0.090756 |
| 24       | 0.278548         | 0.193697            | 0.139274 | 0.096849 |
| 25       | 0.222838         | 0.181933            | 0.111419 | 0.090966 |
| 26       | 0.297118         | 0.184874            | 0.148559 | 0.092437 |
| 27       | 0.371397         | 0.195378            | 0.185699 | 0.097689 |

Table 3 Normalized and weighted normalized responses
Now separation measures are obtained using the Eqs. (7) and (8). Then closeness coefficient or multi response index is obtained using Eq. (9). Finally S/N ratios of MPI are calculated using Eq. (10). These values are shown in Table 5.

Table 5. Separation measures, MPI and S/N ratio of each experiment

| Exp. No. | Separation measures | MPI  | S/N ratio |
|----------|---------------------|------|-----------|
|          | $S^+$   | $S^-$ |       |
| 1        | 0.152387 | 0.036764 | 0.194364 | -14.2277 |
| 2        | 0.141621 | 0.03283  | 0.188192 | -14.508  |
| 3        | 0.131099 | 0.033962 | 0.205757 | -13.7329 |
| 4        | 0.137084 | 0.027842 | 0.168817 | -15.4517 |
| 5        | 0.121114 | 0.038611 | 0.241735 | -12.3332 |
| 6        | 0.105999 | 0.052134 | 0.329683 |  -9.6381 |
| 7        | 0.123396 | 0.034737 | 0.219668 | -13.1647 |
| 8        | 0.103401 | 0.055997 | 0.351305 |  -9.0863 |
| 9        | 0.085652 | 0.077993 | 0.476599 |  -6.4369 |
| 10       | 0.141131 | 0.044078 | 0.23799  | -12.4688 |
| 11       | 0.126368 | 0.045889 | 0.2664   | -11.4893 |
| 12       | 0.111934 | 0.051852 | 0.316587 |  -9.9901 |
| 13       | 0.119428 | 0.045508 | 0.275911 | -11.1846 |
| 14       | 0.097584 | 0.062609 | 0.390833 |  -8.1602 |
| 15       | 0.076157 | 0.082162 | 0.51864  | -5.6973  |
| 16       | 0.09934  | 0.058967 | 0.372485 | -8.5778  |
| 17       | 0.071902 | 0.086939 | 0.547335 | -5.2349  |
| 18       | 0.048302 | 0.115732 | 0.705535 | -3.0296  |
| 19       | 0.130014 | 0.045898 | 0.260915 |  -11.67  |
| 20       | 0.111564 | 0.055101 | 0.330609 |  -9.6137 |
| 21       | 0.09373  | 0.066491 | 0.414996 | -7.6391  |
| 22       | 0.102342 | 0.061802 | 0.376512 | -8.4844  |
| 23       | 0.075273 | 0.083731 | 0.526598 | -5.5704  |
| 24       | 0.049893 | 0.108617 | 0.685236 | -3.2832  |
| 25       | 0.075307 | 0.083655 | 0.526257 | -5.576   |
| 26       | 0.039644 | 0.118676 | 0.749595 | -2.5035  |
| 27       | 0.019118 | 0.15408  | 0.889617 | -1.0159  |
The main effect graph for S/N ratio is shown in Fig. 1. From the Fig. 1 it is observed that third level of cutting speed, feed and depth of cut gives the maximum S/N ratio, i.e. V3, f3 and d3 gives the optimum multi machining criteria. From the delta values it is observed that cutting speed is the main parameters that affects on multi-objective optimization followed by feed and depth of cut.

![Main effect graph for S/N ratios](image)

**Figure 1.** Main effect graph for S/N ratios

### 4.2 Results of ANOVA

ANOVA results for S/N ratios are given in Table 6. From this it is observed that all the three process parameters have the significant influence on the multiple machining criteria since their P values are less than 0.05. From the ANOVA results it is confirmed that cutting velocity is the most important parameter followed by feed and depth of cut.

| Source | DF | SS     | MS  | F      | P value | Contribution (%) |
|--------|----|--------|-----|--------|---------|------------------|
| V      | 2  | 160.160| 80.080 | 78.99  | 0.000   | 38.68            |
| f      | 2  | 142.886| 71.443 | 70.47  | 0.000  | 34.51            |
| d      | 2  | 90.756 | 45.378 | 44.76  | 0.000  | 21.91            |
| Error  | 20 | 20.277 | 1.014 |        |         | 4.9              |
| Total  | 26 | 414.079|      |        |         |                  |
4.3 Confirmation experiment

A confirmation test was conducted to confirm the optimal input parameter setting expected by the TOPSIS method. The machining criteria measured from confirmation test conducted at the optimal parametric combination i.e., cutting velocity=25 m/min, depth of cut=0.75 mm and feed=0.12 mm/rev are compared with the responses measured at the initial parameter setting (cutting speed=15 m/min, feed=0.06 mm/rev and depth of cut=0.45 mm). The results of confirmatory test are given in Table 7. From this test it is noticed that a satisfactory results within the improvement of responses.

| Responses | Initial parameter setting | TOPSIS parameter setting | Improvement |
|-----------|---------------------------|--------------------------|-------------|
|           | Response value | S/N ratio | Response value | S/N ratio | Response value | %     |
| MRR       | 6.750          | 16.5861   | 37.5          | 27.0437 | 30.75          | 82.00 |
| SR        | 0.402          | -7.91548  | 0.465         | -4.77648| 0.063          | 13.55 |

Parameter setting: $V_1 f_1 d_1$, $V_3 f_3 d_3$, $V_3 f_3 d_3$

5. Conclusions

In this work Al 6315 alloy was turned on CNC machine by varying the cutting velocity, feed and depth of cut and the responses machining rate and surface roughness are measured and multi-objective optimization was done using TOPSIS. The conclusions of this work are as follows.

- From the results of ANOVA, it is noticed that the major process parameter affecting on the multi responses is cutting velocity with a contribution of 38.68% followed by 34.51% contribution of feed and the contribution of depth of cut is 21.91%.
- Predicted optimal combination by the TOPSIS method for maximization of MR and minimization SR is cutting velocity=25 m/min, feed=0.12 mm/rev and depth of cut=0.75 mm.
- The responses are improved significantly with the help of TOPSIS method.

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