Selection of optimum Cutting Parameters for Minimization of Specific Energy Consumption during Machining of Al 6061

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Abstract. Manufacturing sector consumes a significant amount of energy globally. Machine tools are one of the major equipments in manufacturing sector and hence major consumer of energy. The electrical energy consumed by the machine tools results in emission of harmful gases and substantial stress on environmental. This work focuses on selection of optimum cutting parameters to minimize specific energy consumption (SEC) during turning of Al 6061 with tungsten carbide inserts in dry condition. Experiment are planned using L27 orthogonal array and Taguchi method is applied to determine optimum and most influencing cutting parameters for minimizing SEC. Results shows that feed is the dominating factor followed by cutting speed and depth of cut. The optimum value of feed (mm/rev), cutting speed (m/min) and depth of cut (mm) are found 0.12, 46.2 and 1.0 respectively. Further the energy consumption maps are developed to analyse the influence of cutting parameters on specific energy consumption. The developed energy consumption maps can be used for correllating the region of minimum SEC with selected cutting parameters.

Keywords: Energy consumption; Turning; Taguchi; cutting speed; feed; depth of cut

1. Introduction

Global warming and the exploitation of natural resources is a prime concern for sustainable development of the world [1]. The U.S. Energy Information Administration (EIA) report revealed that the global energy consumption has increased to 28% in between 2015 to 2040 [2]. The industrial sector is the major stakeholder with almost more than 50% of global energy consumption and plays crucial role in the global economic growth [3]. International directives [4], economic, political and social issues are continuously building pressure to perk up the overall energy competence of the industrial sector [5]. Machine tools consumes a significant amount of total energy demand of the manufacturing sector. Energy efficiency of the machine tools are less than the 30%, and even few researchers reported 15% [6]. Also 99% ecological influences are owing to the electrical energy feeding of machine tools during their use phase [3]. The energy consumption of machine tools can be minimized by scrutinising the influence of cutting parameter on energy consumption. The workpiece material, tool material, tool geometry, cutting parameters significantly affect the energy demand of a machine tool [7-8]. Selection of optimum cutting parameters, tool material, and tool path design can lead to minimization of energy consumption up to 6-40% [9]. The researchers have utilized different optimization approaches (e.g. Taguchi method and soft computing methods) to achieve the finest cutting conditions to minimize cutting forces, power consumption and improve surface quality etc. in machining process [10–15]. Mia M and Dhar NR [16] optimized cutting parameters (cutting speed, feed and work material hardness) in
varying cutting environment (dry and high pressurized coolant jet) for improving surface quality and reducing heat generation during hard machining of AISI 1060 using Taguchi method and concluded that the material hardness is the dominating element for both surface quality and heat generation. Mia M [17] used RSM and Taguchi to determine optimum cutting parameters (cutting speed and feed) in minimum quantity lubrication environment for hard milling of AISI 4140 to minimize SCE and surface roughness. Asilturk and Neşeli [18] presented multi-objective optimization model for surface roughness \((R_{a} \text{ and } R_{z})\) to determine optimum cutting variables (i.e. feed \((f)\), cutting speed \((v)\) and depth of cut \((d)\)) during machining of AISI 304 stainless steel by means of Taguchi method, and revealed that \(R_{a}\) and \(R_{z}\) dominantly govern by feed. Aggarwal et al. [19] analysed the influence of process parameters (i.e. \(v, f, d\) and nose radius) on power demand during machining of steel (grade P-20) using RSM and Taguchi and revealed that both techniques showed similar results. Li et al. [20] studied and optimize cutting parameters for minimizing SEC by means of integrating Taguchi and different soft computing methods.

The present study focuses on determining optimum cutting parameters to minimize SEC during turning of Al 6061 by means of tungsten carbide inserts. Experiments are planned by using \(L_{27}\) orthogonal array and Taguchi method is applied to determine optimum and most influencing cutting parameters for minimizing SEC. The outline of the paper is organized as follows; Section 2 discussed experimental planning and Taguchi methodology, Section 3 presented the results trailed by the Section 4 that is conclusion.

2. Experimental Planning and Taguchi methodology

2.1. Experiment planning

In this study three cutting parameters cutting speed \((v \text{ in m/min})\), feed rate \((f \text{ in mm/rev})\) and depth of cut \((d \text{ in mm})\) are consider as input variables to investigate their influence on SEC. The selection of cutting variables comprises the limiting cutting conditions available on machine tool and manufacturer’s recommendations. Experiments were planned by using \(L_{27}\) orthogonal array and Taguchi method is applied to determine optimum and most influencing cutting parameters for minimizing SEC. The outline of the paper is organized as follows; Section 2 discussed experimental planning and Taguchi methodology, Section 3 presented the results trailed by the Section 4 that is conclusion.

| Levels | 1     | 2     | 3     |
|--------|-------|-------|-------|
| \(v\)  | 46.2  | 60    | 78    |
| \(f\)  | 0.06  | 0.12  | 0.18  |
| \(d\)  | 0.50  | 0.75  | 1.00  |

Experiments are conducted on a heavy-duty HMT Centre lathe machine tool having maximum 2300 rpm and 5.5 kW motor rating. Work piece material Aluminium (Grade: Al 6061) is selected for the turning because it has wide range of industrial and commercial applications. The cutting environment is kept dry. The carbide cutting inserts of grade TNMG 16 04 04 is used for cutting along with tool holder PTGNR 2020K16. The details of experimental setup are shown in Kant and Sangwan [21]. The experimental data of power consumption was normalized by MRR to get the unit power that is the SEC. SEC is the power consumed to take away unit volume of material from the workpiece that is a ratio of power consumption to corresponding material removal volume. SCE comprises material removal volume and thus it is more suitable parameters as compared to cutting power [8].

2.2. Taguchi methodology

Taguchi robust design is intendent to improve the product performance during their useful life span irrespective to its working environment. These working environments that are not in the control of designer are known as noises. The performance of product will enhance by minimizing these noises by improving product quality. Taguchi design robustness bank on its two controlling tools: orthogonal arrays to conduct the experiments and \(s/n\) ratio to evaluate quality [22]. Conventional experiment design methods are very tedious and difficult to practice since increasing experiments directly associated
to the additional experimental overheads and time. Taguchi technique is a robust investigational design process to reduce the experiments by applying orthogonal arrays and subsequently diminish the effects of the uncontrolled variable [18]. Additionally, it determines optimum values of independent variable with reference to dependent output variable. Taguchi uses signal to noise ratio \( s/n \) to estimate and evaluate process performance characteristics and give clear illustration of the influencing parameters arranged in their ranking. The available optimization values are as follows [17]:

Nominal is the best principle:
\[
\frac{s}{n} = 10 \log \left( \frac{\bar{X}}{s_X} \right),
\]

(1)

Smaller is the better principle:
\[
\frac{s}{n} = -10 \log \left( \frac{1}{n} \left( \sum X^2 \right) \right),
\]

(2)

Larger is the better principle:
\[
\frac{s}{n} = -\log \left( \frac{1}{n} \left( \sum \frac{1}{X^2} \right) \right),
\]

(3)

Here: \( X \), the investigational values of dependent variable (SEC), \( \bar{X} \) is the average of \( X \), \( s_X \) is the deviation of \( X \) and \( n \) is the total experiments conducted.

3. Results and Analysis

Taguchi technique is used to determine the most influencing parameter for SEC by analysing \( s/n \) ratio of the all three independent factors that is cutting parameters in our case. Design of the experiments and analysis of experimental results has been done using Taguchi method in Minitab 2018 software. In our study the objective is to minimize the SEC and thus equation (2), ‘smaller is the better’ is used. The number of experiments runs designed by consider \( L_27 \) orthogonal arrays along with the corresponding SEC are tabulated in Table 2. The responses \( s/n \) are tabulated in Table 3, corresponding to Taguchi principle ‘smaller is better’ criterion discovered that “feed” is the dominating variable for the SEC trailed by “cutting speed” and “depth of cut”. The ranked are grounded on the Delta values which quantify the scale of the effect by considering change between maximum and minimum characteristics average for the input variable (i.e. \( v, f \) and \( d \)).

The main effect plots for \( s/n \) for data means are displayed in Fig 1. The figure displays the deviation of SEC corresponding to \( v, f \) and \( d \). In the figure, axis X, reveals the value of each cutting parameter at their different levels and axis Y shows corresponding SEC. The mean value of the SEC is shown by the horizontal line. The figure clearly shows that the feed is the dominating variable among the three factors (i.e. \( v, f \) and \( d \)). Camposeco-negrete C [22] also reported that total energy demand mainly governed by the feed. Warsi et al. [8] investigation also stated that feed is dominating factor among the considered variables to reduce SEC. The \( s/n \) ratio increases with increase in feed up to 0.12 mm/rev and after that it started declining. In actual, the \( s/n \) ratio should increase beyond the feed value of 0.12 mm/rev. As the experiments are carried out on the conventional lathe machine, the noise parameters cannot be ruled out due to which the \( s/n \) ratio shown the reversal trend. The \( s/n \) ratio shows inversely proportional relationship with cutting speed while depth of cut has not shown any significant contribution. The optimum cutting parameters levels as shown in figure 1 which have highest \( s/n \) ratios are I level of cutting speed (46.2 m/min), II level of feed (0.12 mm/rev) and III level of depth of cut (1.00 mm).

The specific energy consumption maps for the SEC are shown in Figure 2. Figure 2 (a) shows the SEC variation with \( f \) and \( d \) at \( v = 60 \) m/min. It reveals SEC increases at low values of feed rate with increase in depth of cut and reduced with increase in \( f \).
### Table 2. Experimental outcomes for SEC

| Experiment | Cutting speed levels | Feed rate levels | Depth of cut levels | Specific energy consumption SEC \( (\text{j/mm}^3) \) | \( S/N \) ratio |
|------------|----------------------|-----------------|---------------------|-------------------------------|----------------|
| 1          | 1                    | 1               | 1                   | 1.99                          | -5.98          |
| 2          | 1                    | 1               | 2                   | 2.74                          | -8.76          |
| 3          | 1                    | 1               | 3                   | 2.12                          | -6.53          |
| 4          | 1                    | 2               | 1                   | 0.84                          | 1.47           |
| 5          | 1                    | 2               | 2                   | 1.43                          | -3.10          |
| 6          | 1                    | 2               | 3                   | 0.64                          | 3.90           |
| 7          | 1                    | 3               | 1                   | 1.50                          | -3.53          |
| 8          | 1                    | 3               | 2                   | 1.35                          | -2.59          |
| 9          | 1                    | 3               | 3                   | 1.35                          | -2.60          |
| 10         | 2                    | 1               | 1                   | 1.23                          | -1.82          |
| 11         | 2                    | 1               | 2                   | 1.80                          | -5.11          |
| 12         | 2                    | 1               | 3                   | 1.93                          | -5.73          |
| 13         | 2                    | 2               | 1                   | 1.52                          | -3.62          |
| 14         | 2                    | 2               | 2                   | 1.36                          | -2.64          |
| 15         | 2                    | 2               | 3                   | 1.37                          | -2.71          |
| 16         | 2                    | 3               | 1                   | 1.19                          | -1.50          |
| 17         | 2                    | 3               | 2                   | 1.34                          | -2.55          |
| 18         | 2                    | 3               | 3                   | 1.31                          | -2.32          |
| 19         | 3                    | 1               | 1                   | 2.13                          | -6.56          |
| 20         | 3                    | 1               | 2                   | 1.81                          | -5.16          |
| 21         | 3                    | 1               | 3                   | 1.92                          | -5.68          |
| 22         | 3                    | 2               | 1                   | 1.42                          | -3.06          |
| 23         | 3                    | 2               | 2                   | 1.89                          | -5.52          |
| 24         | 3                    | 2               | 3                   | 1.68                          | -4.50          |
| 25         | 3                    | 3               | 1                   | 1.74                          | -4.79          |
| 26         | 3                    | 3               | 2                   | 1.05                          | -0.41          |
| 27         | 3                    | 3               | 3                   | 1.23                          | -1.80          |

### Table 3. Responses for \( S/N \) (‘Smaller is better’)

| Levels | \( v \) | \( f \) | \( d \) |
|--------|--------|--------|--------|
| I      | -3.08  | -5.703 | -3.266 |
| II     | -3.11  | -2.2   | -3.982 |
| III    | -4.166 | -2.453 | -3.109 |
| Delta  | 1.086  | 3.504  | 0.873  |
| Rank   | 2      | 1      | 3      |
Figure 1: Main Effects Plot for S/N ratio

Figure 2a. Specific Energy Consumption map for varying $f$ and $d$ at $v = 60$ m/min
Figure 2 (b) shows the SEC variation with \( v \) and \( f \) at \( d = 0.75 \) mm. It shows that at low rate of \( f \), SEC is high and reduced significantly by increase in \( f \). The \( v \) has not shown significant influence on SEC.

**Figure 2b.** Specific Energy Consumption map for varying \( v \) and \( f \) at \( d = 0.75 \) mm

Figure 2 (c) shows SEC variation with \( v \) and \( d \) at \( f = 0.12 \) mm/rev. It shows that at high values of \( d \) and \( v \) the SEC is high and at even low values of \( v \) with increase in \( d \), SEC increases.

**Figure 2c.** Specific Energy Consumption map for varying \( v \) and \( d \) at \( f = 0.12 \) mm/rev.
3.1. Discussion

Undeform chip thickness increases with increase in feed and depth of cut, therefore more cutting force is required to remove the material from the work piece for this corresponding increase in cutting area which demands the machine tool to consume more SEC as depicted in Figure 2 (a) and Figure 2 (c). Shear angle increases with further increase in $f$ and $v$ which leads to smoother cutting and reduces cutting forces (i.e. cutting power) [8].

4. Conclusion

In the presented work, experiments are carried out using $L_{27}$ orthogonal array for turning of Al 6061 using tungsten carbide inserts. Taguchi method is applied to determine optimum cutting parameters leading to minimum specific energy consumption along with most influencing cutting parameter factor. The following conclusions are drawn:

- Feed rate is the dominating factor followed by cutting speed and depth of cut to minimize specific energy consumption.
- Minimum SEC is found corresponding to optimal values of $v = 46.2$ m/min, $f = 0.12$ mm/rev and $d = 1.0$ mm.
- The developed energy consumption maps can be used for correlating the region of minimum SEC with selected machining parameters.

The methodology shown experimentally and statistically in this work can be used as an approach for determining the optimum parameters for machining process.

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