Experimental Investigation and Theoretical Modelling of P20 Steel by using CNC End Milling Machining Process

Vishal Yashwant Bhise¹ and Bhagwan F Jogi²

¹Ph.D Research Scholar and ²Associate Professor
Department of Mechanical Engineering, Dr. Babasaheb Ambedkar Technological University, Lonere - 402103, Maharashtra, India.
vishalbhise79@gmail.com, bfjogi@dbatu.ac.in
Mobile: +91 8898554582, +91 9421166370

Abstract. In current scenario the sustainability principles has to be adopted to tackle the challenges facing in the various industrial sectors. As the machining processes consumes natural resources to a great extent, it has become mandatory for manufacturers to go for sustainable management practices. The sustainability in manufacturing processes can be achieved by integrating all small factors and thus achieving sustainable machining conditions. Machining plays a vital role in the industrial economy and it contributes more than 5% to the country’s economy. The machining processes have gone through significant changes in the last decades. Competition has increased drastically to gain more profit. Machining processes are been widely used and attempts have been made to minimize the machining cost and the energy consumption. The machining parameters like speed, feed, depth of cut and the coolants used play an important role in machining economy. Main focus in this work is to enhance the surface integrity and the tool life by utilizing least resources and to reduce the energy consumption. The P20 steel have wide application in the moulds for plastic injection cavities and tooling. Also, it is used in the die casting of dies for zinc. Thus, the surface roughness plays an important role in the machining of the P20 steel. In this paper, the experiments have carried out on P20 steel on CNC milling process by adopting Taguchi Analysis to optimize surface roughness and tool life. Besides, analysis of cutting forces by using fuzzy logic is studied to evaluate the energy consumption.

Key words: End milling machining, P20 steel, Taguchi Analysis, Energy consumption, surface roughness, tool life.

1. Introduction
The real market demand has to be considered in dependence to cost, quality that has to consider while the delivery of the final product (short to avoid storage capacities and financial investment). Another important stage of manufacturing/machining is associated with economical resource utilization [1]. The machining using CNC machines are increasing rapidly due to its reliability and higher productivity. Thus the face milling by using the CNC machine enhances machining performance as compared to conventional milling machines and provides flexibility in selecting the variety of ranges of cutting parameters. Various milling processes which can be used for machining are plain, side, face, end and gang milling etc. End milling is the most popular machining process widely used in aerospace industry.
and metal based manufacturing firms. In end milling machining, unlike the other milling processes, the cutter has teeth on sides and end of the mill. Grguraš et al [1] studied high speed milling machining process to analyze full body ceramic end milling tools along with carbide tools. They found that the ceramic milling tools enhanced the productivity of difficult-to-cut nickel based superalloy Inconel 718 but overall efficiency is low compared to carbide tools. It is [2–4] found that the performance of ceramic cutting tools reinforced with SiC for milling superalloy Inconel 718. The tool failures while milling at full depth with cutting speeds of 200 to 400 m/min was found as notch wear. The round inserts possesses the stronger cutting edge and have better resistance to notch wear.

Teja et al [5] investigated the effects of process parameters on the hardened EN24 steel using hot machining process as material removal rate and surface finish were considered as responses. By Taguchi’s orthogonal arrays. They observed that due to hot end milling process machinability improved with better surface finish and material removal rate (MRR) got doubled. The energy consumption allowance (ECA) applied to establish a discrete manufacturing system [6]. It helped to solve the complex energy consumption problems in machining which include the refinement of energy management and thus improving the energy efficiency of the machining operation.

The study on effects of different process parameters like speed, feed, depth of cut, dry, wet, MQL and the type of cutting tools on power consumption [7] was carried out along with analysis of variance (ANOVA) and Response Surface Methodology (RSM) to design the experiments. It was observed that surface roughness is highly influenced by cutting environment and the type of tool. Further, it was found that material removal rate (MRR) and power required is influenced by type of tool, feed, depth of cut and cutting velocity. The performance of multilayer hard coatings (TiC/TiCN/Al2O3) on cemented carbide substrate was carried out by using chemical vapor deposition (CVD) for machining of hardened AISI 4340 steel by using Taguchi method [8]. It was found that, the optimal combination of low feed rate and low depth of cut with high cutting speed is helpful for minimizing cutting force. Higher values of feed rates are required to reduce the specific cutting force. The [9] investigation on the effects of machining parameters on machining of 7075 Al alloy 15 wt% SiC with Response surface methodology (RSM) has been carried out and found that values of machining parameters obtained by multi response optimization through desirability analysis route helped to reduce power consumption by 13.55% and also increases tool life by 22.12%.

In this study, the P20 steel has been adopted for investigation of the milling process by adopting methodology given in Fig. 1. The optimization of the process parameters, the tool life and power consumption based on the maximization of surface roughness study was carried out.

![Figure 1](image)

**Figure 1.** Methodology used for the work
2. Selection of Material and Tools

P20 is pre-hardened steel with hardness range from 29 to 39 HRC, having good polishability and less texture making properties. The sample of the work-material has been taken in the form of a rectangular plate of dimensions 150 x 300 x 16mm. Table 1 represents the chemical composition of P20 steel which was mostly used in the plastic injection moulds and in the die casting dies of zinc. Also, this steel is used in car accessories, electronic equipment plastic moulds and home appliances. Hence, P20 steel is selected as testing material which is hard due to high content of Manganese, Nickel, Carbon, etc. The cutting tool material selected as TiCN for the machining having the hardness 87 RC as per the past experiences.

| Table 1. Chemical composition of P20 steel |
|-------------------------------------------|
| C  | Si  | Mn  | S  | Cr  | Mo  | Ni |
| 0.35 | 0.45 | 0.85 | 0.35 | 0.035 | 1  | 0.8 |

3. Machining, Characterization Methods and Pilot Experiments

The machining experiments were conducted on a BFW Agni BMV45 CNC Milling machine having table size of 500mm x 200mm and positional accuracy is 0.020mm. As P20 steel is very hard to machine material and limited work was found on end milling operations. The samples were prepared as shown in fig.2. The surface roughness was measured by Mitutoyo surface tester SJ-210. The surface tester is a shop–floor type surface-roughness measuring instrument, which traces the surface of various machine parts and calculates the surface roughness based on roughness standards and displays the results in μm. The surface roughness tester has a resolution varying from 0.01 μm to 0.4 μm depending on the measurement range. The process parameters were selected as cutting speed, depth of cut, feed rate and the output response were selected as surface roughness. Thus, the range for the parameters was selected at three levels for the Taguchi analysis. Thus on the basis of the design of experimentation, the L9 orthogonal array was selected for different combinations.

![Experimentation Plates](image)

| Table 2. Selective Pilot Readings |
|----------------------------------|
| Spindle Speed | Depth of Cut | Feed Rate | Surface Roughness (Mean) |
|----------------|--------------|-----------|--------------------------|
| 1200           | 0.6          | 1000      | 0.478                    |
| 3000           | 0.2          | 2000      | 0.785                    |

By selecting a proper range of parameters, the pilot experimentations were performed. Selective results are as shown in table 2. Thus by analyzing the effect of the process parameters on the surface roughness by using the Taguchi analysis in Minitab, the mean effect curve and the interaction plots were analyzed and on this basis a range for the experimentations were selected as shown in table 3.
Table 3. Process Parameters and Levels

| Factors | Parameters                | Levels       |
|---------|---------------------------|--------------|
| A       | Spindle Speed             | L1 1200      |
|         | B                         | L2 2000      |
|         | C                         | L3 2500      |
| B       | Depth of Cut              | 0.2          |
|         |                           | 0.4          |
|         |                           | 0.6          |
| C       | Feed                      | 1000         |
|         |                           | 1500         |
|         |                           | 2000         |

4. Results and Discussion for the Experiments based on selected parameters

The parameters from the Taguchi Analysis and the parameters which had the best surface integrities were selected for further experimentation as shown in table 4. Thus, the experimental results, the interaction plot for surface roughness and the mean effect plots for means and S/N ratio were plotted and analysed as shown in fig. 3.

Table 4. Experimentation Result Analysis in Taguchi

| Sr. No. | Spindle Speed | Depth of Cut | Feed Rate | Ra1 | Ra2 | Ra3 | PSNRA2 | PMEAN2 |
|---------|---------------|--------------|-----------|-----|-----|-----|--------|--------|
| 1       | 1200          | 0.2          | 1000      | 6.580 | 6.523 | 4.850 | -15.4733 | 5.84034 |
| 2       | 1200          | 0.4          | 1500      | 4.210 | 4.169 | 4.250 | -12.3408 | 4.06567 |
| 3       | 1200          | 0.6          | 2000      | 3.810 | 3.910 | 3.854 | -12.0166 | 4.14599 |
| 4       | 2000          | 0.2          | 1500      | 2.890 | 2.713 | 2.854 | -9.9259  | 3.20285 |
| 5       | 2000          | 0.4          | 1000      | 3.007 | 2.430 | 3.125 | -7.7497  | 2.51827 |
| 6       | 2000          | 0.6          | 2000      | 2.105 | 2.215 | 1.985 | -6.9474  | 2.05354 |
| 7       | 2500          | 0.2          | 2000      | 3.570 | 2.570 | 3.145 | -9.1123  | 2.85514 |
| 8       | 2500          | 0.4          | 1000      | 1.985 | 1.875 | 2.105 | -7.5321  | 2.46805 |
| 9       | 2500          | 0.6          | 1500      | 2.590 | 2.587 | 2.445 | -7.3257  | 2.30081 |

Figure 3. Effects of process parameters on surface roughness (S/N Data)

The interaction plot for the parameters was plotted by using ANOVA which gives us the idea for studying the effect of the parameters on each other and thus it’s influence on the surface finish as shown in fig. 3 and 4 respectively. The better surface roughness was found at the depth of cut 0.6, feed rate 2000 and cutting speed 2500.
4.1 Analysis of the Results

For the optimization of results following two methods were used for finding the influence of the parameters on the surface integrity. Also the analysis of the tool life and the power consumption have done for the optimal results.

4.1.1 Analysis of the Results Using ANOVA

In order to study the significance of the process variables towards surface roughness, analysis of variance (ANOVA) was performed. It was found that feed rate and depth of cut are non-significant process parameters for surface roughness as shown in table 5 and 6 for S/N ratio and mean respectively. As surface roughness is ‘smaller the better’ type quality characteristic thus, the analysis was done using smaller the better conditions.

![Interaction Plot for means ra](image)

**Figure 4.** Interaction plot for Ra

| Table 5. Analysis of variance for S/N ratio |
|------------------------------------------|
| Source | DF | Seq SS | Adj SS | AdjMS | F  | P   |
| Spindle Speed | 3  | 197.267 | 197.267 | 65.756 | 15.52 | 0.003 |
| Depth of Cut | 3  | 29.524 | 29.524 | 9.841 | 2.32 | 0.175 |
| Feed Rate | 3  | 9.761 | 9.761 | 3.254 | 0.77 | 0.552 |
| Residual Error | 6  | 25.423 | 25.423 | 4.237 |
| Total | 15 | 261.975 |

DF- Degrees of freedom, SS- Sum of Squares, MS- Mean Square (Variance), F- Ratio of variance of a source to variance of error, P<0.05 – determines significance of a factor at 95% confidence level
Further, the response tables (Tables 7 and 8) show the average of each response characteristic (S/N data and means) for each level of each factor. The tables include ranks based on delta statistics, which compare the relative magnitude of effects. The delta statistic is the highest minus the lowest average for each factor. Minitab assigns ranks based on delta values; rank 1 to the highest delta value, rank 2 to the second highest, and so on. The ranks indicate the relative importance of each factor to the response. The ranks and the delta values show that spindle speed has the greatest effect on surface roughness and is followed by depth of cut and feed rate in the order. The spindle speed effects more on the surface roughness followed by depth of cut and feed rate.

### Table 7. Response Table for S/N ratio

| Level | Spindle Speed | Depth of Cut | Feed Rate |
|-------|---------------|--------------|-----------|
| 1     | -12.333       | -9.484       | -7.077    |
| 2     | -9.244        | -8.798       | -7.139    |
| 3     | -6.982        | -6.726       | -8.991    |
| 4     | -2.699        | -6.252       | -8.052    |
| Delta | 9.633         | 3.232        | 1.913     |
| Rank  | 1             | 2            | 3         |

### Table 8. Response Table for Means

| Level | Spindle Speed | Depth of Cut | Feed Rate |
|-------|---------------|--------------|-----------|
| 1     | 4.199         | 3.206        | 2.747     |
| 2     | 2.902         | 2.862        | 2.617     |
| 3     | 2.239         | 2.454        | 2.878     |
| 4     | 1.489         | 2.306        | 2.587     |
| Delta | 2.710         | 0.900        | 0.291     |
| Rank  | 1             | 2            | 3         |

### 4.1.2 Optimization of Parameters by GRA (Grey Relational Analysis) (Full Quantity Lubrication)

For the ‘smaller-the-better’ characteristic like surface roughness, the original sequence can be normalized as follows by the equation 1:

\[
xi^*(k) = \frac{maxi (k) - xi (k)}{maxi (k) - mini (k)} \\
\text{………………… 1}
\]

Where, \(xi^*(k)\) and \(xi (k)\) are the sequence after the data pre-processing and comparability sequence respectively.

- **Confirmation Test**

The regression equation obtained from Minitab is as shown in table 10. The percentage error between the actual and predicted values of the responses falls below 5%, which shows that the optimized value of CNC end milling process parameters obtained is good enough for achieving the target set during the experiment.
Table 9. GRA Analysis

| Experiment No. | Cutting speed (rpm) | Depth of cut (mm) | Feed Rate (mm/min) | Ra (μm) | Grade |
|----------------|---------------------|-------------------|--------------------|---------|-------|
| 1.             | 1200                | 0.2               | 1000               | 1.00    | 1     |
| 2.             | 1200                | 0.4               | 1500               | 0.8091  | 0.8091|
| 3.             | 1200                | 0.6               | 2000               | 0.7422  | 0.7422|
| 4.             | 2000                | 0.2               | 1500               | 0.6257  | 0.6257|
| 5.             | 2000                | 0.4               | 1000               | 0.5768  | 0.5768|
| 6.             | 2000                | 0.6               | 2500               | 0.6017  | 0.6017|
| 7.             | 2500                | 0.2               | 2000               | 0.5327  | 0.5327|
| 8.             | 2500                | 0.4               | 2500               | 0.5083  | 0.5083|
| 9.             | 2500                | 0.6               | 1000               | 0.4939  | 0.4939|

Table 10. Confirmation Results

| Unit          | Predicted | Experimental | Error |
|---------------|-----------|--------------|-------|
| Ra Mean (μm)  | 6.0801    | 5.82300      | 0.2571|

4.1.3 Analysis of the Cutting Forces Using Fuzzy Logic

The high cutting forces causes poor surface integrity, reduced tool life and increased power consumption. Therefore, analysis of the cutting force was done using fuzzy logic also. In this, the process parameters of the milling such as the spindle speed, feed, and depth of cut were taken as the input conditions and the cutting force was taken as the output parameter. For the input parameters, the membership functions were selected with a level of 6 for each input functions.

![Figure 5 (a)](image1)

Figure 5 (a). Effect of Depth of Cut and spindle speed on cutting forces and (b). Effect of Depth of Cut and feed on cutting forces.

The membership function was selected for the cutting speed with six levels and in the range of 1200 to 2500 rpm. For the depth of cut the membership function was selected for a range of 0.2 to 0.6 mm and the feed rate was selected with six levels and in the range of 1000 to 2000 mm/min. The output conditions were taken in the range of 1000 to 2000N as shown in fig. 5 (a) and (b). From the surface
graphs the effect of the parameters exhibited that for nominal speed the cutting forces are minimum and the best results are obtained at the optimized points where the cutting forces are also found and required minimum.

4.1.4 Effects on Tool Life and Surface Roughness

As shown in table 1, at cutting speed 1200 rpm, the tool life and surface roughness is found as 160.81 min and 4.055 respectively. Here, the tool life is improved to great extent but at the same the surface roughness is poor. Further, at the cutting speed of 2000 rpm the tool life and surface roughness is 142.38 min and 2.053 respectively. In this case, the tool life found better and surface roughness is minimum among all speeds. At cutting speed 2500 rpm the tool life and surface roughness is 111.24 min and 2.308 respectively. In this work, we found that the tool life is found as less which is not desirable and surface roughness is found better. Therefore, we may conclude that, spindle speed 2000 is optimum where the tool life is better and surface roughness is found as less. The table 12 depicts that, as the depth of cut and feed rate increases the MRR increases but at the same time power consumption also increases.

Table 1. Comparison of responses with different spindle speed

| Spindle Speed | Power Consumption (HP) | Tool Life (Min) | Surface Roughness (µm) | S/N Ratio |
|---------------|------------------------|----------------|------------------------|-----------|
| 1200          | 0.8317                 | 160.81         | 4.065                  | -12.34    |
| **2000**      | **1.1156**             | **142.38**     | **2.053**              | **-6.94** |
| 2500          | 1.2481                 | 111.24         | 2.308                  | -7.325    |

Table 12. Results for MRR and Power Consumption

| Spindle Speed (rpm) | DOC (mm) | Feed Rate (mm/min) | MRR (IPM) | Power Consumed (HP) |
|---------------------|----------|--------------------|-----------|---------------------|
| 1200                | 0.2      | 1000               | 0.2453    | 0.2787              |
| 1200                | 0.4      | 1500               | 0.7319    | 0.8317              |
| **1200**            | **0.6**  | **2000**           | **1.4649**| **1.6641**          |
| 2000                | 0.2      | 1500               | 0.3661    | 0.4160              |
| 2000                | 0.4      | 1000               | 0.4879    | 0.5544              |
| **2000**            | **0.6**  | **2000**           | **1.4640**| **1.1156**          |
| 2500                | 0.2      | 2000               | 0.4882    | 0.5547              |
| 2500                | 0.4      | 1000               | 0.4879    | 0.5544              |
| **2500**            | **0.6**  | **1500**           | **1.0983**| **1.2481**          |

As shown in table 12, at the speed of 1200 rpm, DOC 0.6 and feed rate 2000, the MRR is found as 1.4649 IPM with corresponding power consumption of 1.6641 HP. Similarly, at speed 2000 rpm, DOC 0.6 and feed rate 2000 the MRR and corresponding power consumption found constant i.e. 1.4649 IPM and 1.6641 HP respectively. Further, at speed 2500 rpm, same depth of cut of 0.6 and feed rate 1500 the MRR found is 1.0983 IPM with corresponding power consumption of 1.2481 HP. From these observations, it may be conclude that, the higher MRR is obtained at speed 2000 rpm with minimum power consumption. However, at speed 1200 rpm the power consumption is minimum with highest tool life but, at the same time high surface roughness of 4.065 µm is obtained, which is not desirable. The high surface integrity and high tool life obtained at spindle speed of 2000 rpm with comparatively lower power consumption of 1.1156. Further, at the highest spindle speed of 2500 causes highest power consumption among all, lowest tool life among all and a better surface roughness were observed.
5. Conclusions
P20 steel has been investigated for the end milling process by using CNC machine tool. The optimization of the process parameters, the tool life and power consumption based on the maximization of surface roughness was carried out with notable observations as:

- The high surface integrity and high tool life was observed at spindle speed of 2000 rpm.
- The high MRR was found at speed of 2000 rpm with depth of cut 0.6 and feed rate 2000 mm/min.
- High energy conservation was observed at speed 2000 rpm.
- As the spindle speed was increased by 66.67 times, the surface roughness was reduces by 49.93% which is almost half of the previous literature values.
- Among two best combination of cutting parameters, cutting forces reduced by 0.263 times with one of combination.

References
[1] Damir Grguraš, Matjaž Kern, Franci Pušavec 2018 Suitability of the full body ceramic end milling tools for high speed machining of nickel based alloy Inconel 718 Procedia CIRP 77 630-633
[2] Elebestawi M.A, T.I. EL-Wardany, DI Y. and Min T. 1993 Performance of whisker reinforced ceramic tools in milling nickel- based alloy CIRP Annals 42(1) 99-102
[3] Çelik A, Alağaç MS, Turan S, Kara A, Kara F. 2017 Wear behavior of solid SiAlON milling tools during high speed milling of Inconel 718 Wear 378–379 58–67
[4] Vinothkumar Sivalingam, Jie Sun, Bin Yang, Kai Liu, Ramesh Raju 2018 Machining performance and tool wear analysis on cryogenic treated insert during end milling of Ti-6Al-4V alloy Journal of Manufacturing Processes 36 188-196
[5] S. Ravi Teja, N.C. Swapna, G.P. Chaitanya, C. Vishnu Teja, Bhavana, Ashishtewari, S. Saikumar 2018 Machinability studies of aerospace steel using hot end milling Materials Today Proceeding 5 27051-057
[6] Xiaona Zhou, Fei Liu 2015 An energy-consumption model for establishing energy-consumption allowance of workpiece in machine system Journal of Cleaner Production 135 1580-090
[7] Sunil Dambhare, Samir Deskmukh 2016 Sustainability Issues in Turning Process: A Study in Indian Machining Industry 12th Global Conference on Sustainable Machining Procedia CRIP 26 379-384
[8] R. Suresh, S. Basavarajappa 2012 Some studies on hard turning of AISI 4340 steel using multilayer coated carbide tool Measurement 45 1872-84
[9] Rajesh Kumar Bhushan 2013 Optimization of cutting parameters for minimizing power consumption and maximizing tool life during machining of Al alloy SiC particle composites Journal of Cleaner Production 39 242-254
[10] Guoliang Liu, Chuanzhen Huang 2016 Surface integrity and fatigue performance of 17-4PH stainless steel after cutting operation Surface and Coating Technology 307 182-189