Optimization of one direction tool path orientation for pocket milling of Ti-6Al-4V using taguchi based grey relational analysis

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Abstract. In pocket milling, a need for optimization of output quality characteristics is necessary for difficult to machine materials such as Ti-6Al-4V due to its applications in dies, molds, aerospace and mechanical industries. This paper shows the incorporation of tool path orientation as a process parameter along with spindle speed, feed rate and depth of cut to improve the output quality characteristics. Optimization was accomplished by varying the one direction tool path orientation together with machining parameters using Taguchi based Grey Relational analysis. The output quality characteristics determined are radial tool deflection, surface roughness and material removal rate (MRR). The optimum combination of process parameters obtained from the grey relational analysis was then validated by performing confirmation tests.

Keywords: Grey Relational Analysis; One direction; Pocket Milling; Surface Roughness; Taguchi Method; Tool deflection; Tool Path, One direction path orientation. Signal to Noise Ratio.

1. Introduction

Milling is a material removal process which involves feeding the work piece to a rotating tool which has multiple cutting edges. It is one of the most widely used material removal processes when compared to the other machining processes. There are various types of milling processes namely slotting, pocket milling, gear milling, thread milling, profile milling, helical milling, plain milling, side milling, face milling, end milling and so on. Pocket milling is a machining process which aims to clear out a pre-defined contour completely [1]. Roughing operations are said to take approximately 50% of the machining time which indicates that the time consumption is large when compared to the finishing processes [2]. This asserts the need to optimize the pocketing operation. The path followed by the cutting tool to produce the desired geometry of the contour present on the workpiece is called a tool path. The cutting tool path strategy also have an influence on important parameters such as cutting forces, length of tool path and surface roughness[3]. The optimization of the tool path strategy and the process parameters here in turn lead to benefits in the industry predominantly improving the machining time, quality of products and increased tool life which leads to reduced costs.
Among the various optimization techniques, the Taguchi method and Grey Relational Analysis are the most commonly used techniques used to optimize the tool path strategies and the process parameters. Extensive application of the given techniques has been used by various researchers to optimize the output characteristics of the selected process. Yusuf et al. used this technique to optimize surface roughness as an output characteristic for CNC end mill cutters and determined that the spindle speed was the most important control factors among the other process parameters such as type of end milling tool, depth of cut, spindle speed and feed rate and stated the noise factor as coolant pressure and patterns of cut [4]. Sukumar et al. determined the optimum combination of influential factors for surface roughness by using a set of input characteristics such as speed, feed and depth of cut through Taguchi method [5]. Choubey et al. also worked with Taguchi design and compared it with the ANOVA analysis for the speed, feed and depth of cut and determined that the feed and spindle speed was important for the variation in material removal rate and surface finish respectively [6]. Khan et al. measured the quality improvement by using the surface roughness and diameter error where the analysis determined that the cutting speed was the most influencing factor on the quality improvement with a percentage of 82.4% [7]. The increased cutting forces leads to the tool deflection which causes errors in machining which should be corrected [8]. Compensation techniques to reduce the tool deflection have been introduced by Dow et al. which has helped to solve the problem to a minimal extent due to the dependency on tool and work piece location [9]. However, further optimization of tool deflection to enhance the quality of products by minimizing errors in the dimensions will result in reduced machining costs which also must be considered. Kwak also used Taguchi method to drastically decrease the number of experiments to model the response functions of the surface grinding process compared to other conventional processes [10]. Kivak describes the Taguchi method and regression analysis that have been applied to evaluate the machinability of Hadfield steel with PVD TiAlN and CVD TiCN/A1203-coated carbide inserts under dry milling conditions. It was reported that the feed rate is the factor of highest importance for the variation in surface roughness and cutting speed which is critical for the flank wear of the tool [11]. The effect of cutter path strategies on surface roughness of pocket milling on 1.2738 steel using the Taguchi method was investigated by Gologlu et al. It was inferred that the feed rate was influential in spiral and zig strategies whereas depth of cut was influential in zigzag strategies [12]. Kuram et al. used GRA for the multi objective optimization of Al 7075 using a ball nose end mill for micro milling. It was suggested that the feed per tooth, spindle speed and depth of cut are the optimum combinations to reduce tool wear and surface roughness of the machining process [13]. Maiyar et al. deduced through grey relational analysis that a suitable combination of cutting velocity, feed rate and depth of cut improved the MRR and surface roughness significantly [14]. Lu et al. compared grey relational analysis with the principal component analysis where the conclusion stated that the grey relational analysis proved better compared to principal component analysis for multi objective optimization [15]. Prabhu et al. also used grey relational analysis and fuzzy logic for electro discharge machining of single walled carbon nanotubes where it was discovered that grey relational analysis gave better results compared to initial experimental values [16]. From the reviewed studies, insights into the effects of one direction tool path orientation on Tool Deflection, Surface Roughness and Material Removal Rate in Pocket Milling of Ti-6Al-4V were not explicitly documented. So, in this work one direction tool path orientation is selected to study the effects of MRR, surface roughness and tool deflection by varying the process parameters affecting the quality characteristics was found. The results were validated using a set of confirmation tests from which the significance of one direction tool path orientation was evaluated.

2. Experimental Work

2.1 Work piece and Tool Details

| Table 1. Chemical Composition of Ti-6Al-4V |
Ti-6Al-4V (Grade 5 titanium alloy) was chosen as the work piece material. Some of the characteristic features of the alloy include high strength, light weight, formability and corrosion resistance which have made it applicable for many industries. Table 1 and Table 2 depict the chemical composition and properties of Ti-6Al-4V respectively. A four flute flat end milling tool of diameter 6 mm made of tungsten carbide material with a helix angle of 30° is used for the experiment. The shank diameter is 6 mm with a cutting edge and overall length of 14 and 50 mm respectively. A total of 9 tools for each of the trials are used for performing the experiments.

Table 2. Properties of Ti-6Al-4V

| Property                              | Value |
|---------------------------------------|-------|
| Density (g/cm³)                       | 4.47  |
| Yield Strength (MPa)                  | 800   |
| Elongation (%)                        | 14    |
| Rockwell Hardness (C scale)           | C36   |

2.2 Design of Experiments

The process parameters selected to conduct this experiment are spindle speed, depth of cut and feed rate. One direction tool path is also chosen as an important process parameter. The tool cuts within the pocket profile were taken in only one direction. Table 3 indicates the level of process parameters and the values considered for the study. The output responses measured are surface roughness, radial tool deflection and material removal rate.

An L9 orthogonal array was chosen for 4 factors and 3 levels with the primary intention of reducing the number of experiments.

The Minitab 16 software was used to carry out the design of experiments. Table 4 illustrates the final DOE using the L9 orthogonal array.
### Table 4. Design of Experiments

| Experiment Number | One direction Tool Path (°) | Spindle Speed (rpm) | Feed Rate (mm/min) | Depth of Cut (mm) |
|-------------------|-----------------------------|---------------------|--------------------|------------------|
| 1                 | 0                           | 2000                | 1000               | 0.2              |
| 2                 | 0                           | 2300                | 1200               | 0.3              |
| 3                 | 0                           | 2600                | 1400               | 0.4              |
| 4                 | 30                          | 2000                | 1200               | 0.4              |
| 5                 | 30                          | 2300                | 1400               | 0.2              |
| 6                 | 30                          | 2600                | 1000               | 0.3              |
| 7                 | 60                          | 2000                | 1400               | 0.3              |
| 8                 | 60                          | 2300                | 1000               | 0.4              |
| 9                 | 60                          | 2600                | 1200               | 0.2              |

#### 3. Experimental Details

##### 3.1 Tool Path Generation

The tool path generation of one direction tool path along with the different orientation for the set of trials were accomplished by using MASTERCAM X6 software. Other cutting parameters were provided as an input to the CAM software from which the tool path has been simulated and the NC code were acquired.
3.2 Pocket Milling Experiment

The components were machined using a 3-axis VMC with the suggested combination of input parameters obtained from the L9 orthogonal array using Taguchi method. The maximum spindle speed and feed rate of the VMC was maintained as 8000 rpm and 10000 mm/min respectively. The machine tool controller for this VMC is the Sinumerik 828d basic M controller. The maximum traverse length is 450 mm and 350 mm in the X and Y axes respectively. The size of the pocket is taken as 30x30 mm. Figure 1 shows the experimental setup of pocket milling which was conducted under dry condition. The coolant used is compressed air which is normally used for medium duty machining conditions. Figure 2 shows the machined specimen of all the 9 experiments conducted on the VMC.

![Figure 1. Experimental Setup](image)

![Figure 2. Machined specimen (0° below, 30° middle and 60° on Top)](image)

3.3 Output Quality Characteristic Measurement

The output quality characteristics that are considered for the given experiment are material removal
rate, surface roughness and radial tool deflection. The tool deflections for the given set of experiments were measured by using pre-setter. The Zoller Smile 620 pre-setter was used for determining the tool deflection for the set of trials in the given experiment. The pre-setter has a measuring range of 420 mm and 210 mm in the Z and X axes respectively. A snap gauge of 620 mm diameter is also included in this setup for tool wear measurement. The field of view for the camera and lighting system is 7×6 mm with 12 LED's of red color for cutting edge inspection. The camera chip set is of CCD monochrome type. Figure 3 shows Zoller tool presetter for deflection measurement.

![Zoller Tool Pre setter for deflection measurement](image)

The surface roughness of the machined components is measured using the Carl Zeiss Surfcom 1400G Surface Roughness Tester. The surface roughness tester is equipped with a diamond stylus of 2µm radius capable of measuring the surface roughness up to 4mm of measuring length. The surface roughness in the axial direction of the machined surface is measured for all of the 9 machined specimens. The material removal rate is calculated based on the cycle time and the work piece weight measured before and after the machining process. Eq. (1) is used to determine the material removal rate for the given experiment [13].

\[
\text{MRR} = \frac{\text{Unmachined - Post machining weight}}{\text{Cycle Time} \times \text{Density}}
\]  

(1)

The radial tool deflection, surface roughness and material removal rate are further determined using the specific setup mentioned. Table 5 shows the measured output quality responses.

| Experiment Number | Material Removal Rate(mm³/min) | Surface Roughness(Ra) (µm) | Radial Tool Deflection(mm) |
|-------------------|--------------------------------|-----------------------------|-----------------------------|
| 1                 | 210.7635                       | 0.3684                      | 0.012                       |
| 2                 | 240.8465                       | 0.4827                      | 0.017                       |
4. Results and Discussions

4.1 Signal to Noise Ratios

The measured value from the experiments are converted into signal to noise ratios to determine whether the given experiment is adding value to the machining process or hindering the desired results. There are 2 cases that are normally used to determine the signal to noise ratios based on the objective function or the function which needs to be maximized or minimized. The 2 cases are smaller the better and larger the better. Eq. (2) and Eq. (3) indicates the formulae required to calculate the signal to noise ratios for the above cases respectively [6]. The output quality parameters such as surface roughness and tool deflection must be reduced which affirms the use of the smaller the better case. The MRR or material removal rate must be increased and the larger the better case is applied for this case. Table 6 shows the entire signal to noise ratios for the set of responses measured.

\[
\frac{S}{N} = -10\log \frac{1}{n} \left( \Sigma y^2 \right) \tag{2}
\]

\[
\frac{S}{N} = -10\log \frac{1}{n} \left( \Sigma \frac{1}{y^2} \right) \tag{3}
\]
Table 6. Signal to Noise Ratios

| Experiment Number | Material Removal Rate(dB) | Surface Roughness(dB) | Radial Tool Deflection(dB) |
|-------------------|---------------------------|-----------------------|---------------------------|
| 1                 | 46.47591                  | 8.673608              | 38.41638                  |
| 2                 | 47.63481                  | 6.326454              | 35.39102                  |
| 3                 | 41.82807                  | 11.89307              | 30.75204                  |
| 4                 | 43.10653                  | 8.647711              | 37.72113                  |
| 5                 | 50.6489                   | 6.263701              | 35.9176                   |
| 6                 | 49.70516                  | 5.195905              | 34.42493                  |
| 7                 | 44.09365                  | 4.464524              | 36.47817                  |
| 8                 | 47.24971                  | 6.085114              | 30.17277                  |
| 9                 | 48.25527                  | 6.957008              | 35.9176                   |

Figure 4, Figure 5 and Figure 6 show the full interaction plot matrix of the process parameters with the three responses measured namely tool deflection, surface roughness and material removal rate. The interaction plot for surface roughness clearly depicts that at 0° one direction tool path orientation, 2600 rpm spindle speed, 1400 mm/min feed rate and 0.4 mm depth of cut, the surface finish of the machined work pieces are found to be increasing. From this it is suggested that these are the optimum combination of input parameters at 0° one direction tool path for surface roughness.

The surface finish is due to the fact that the combination of high feed rate and spindle speed reduces the marks caused on the work piece by the tool. Similarly, the interaction plot for MRR also depicts the variation in the material removal rate based on the one direction tool path orientation angles. The interaction plot for MRR also illustrates that specifically at an angle of 0°, the higher depth of cuts is less significant when compared to the spindle speed. This behavior describes the significance of tool path orientation on the material removal rate on the machining process for material removal rate. On the contrary, the interaction plot for radial deflection shows that the depth of cut has a higher influence on the experiment which can be realized based on the fact that large depth of cuts lead to increased cutting forces which in turn cause tool deflections.
Figure 4. Interaction Plot Matrix for Surface Roughness

Figure 5. Interaction Plot Matrix for Material Removal Rate
4.2 Grey Relational Analysis

The GRA is a procedure which is used to determine and clarify relationships between multiple responses. The grey relational analysis contains 3 steps namely grey relational generation which normalizes outputs, grey relational coefficients which give coefficients based on the generated values and a grey relational grade which grades each of the coefficients to prioritize the experiments to be considered. Equation (4) and Equation (5) are used for grey relational generation based on the smaller the better and larger the better case respectively [14].

\[
T_i(k) = \frac{\text{max}_i(y_i(k)) - y_i(k)}{\text{max}_i(y_i(k)) - \text{min}_i(y_i(k))}
\] (4)

\[
T_i(k) = \frac{y_i(k) - \text{min}_i(y_i(k))}{\text{max}_i(y_i(k)) - \text{min}_i(y_i(k))}
\] (5)

Here, \(T_i(k)\) is the value after grey relational generation, \(\text{min}_i(y_i(k))\) is the smallest value among the specific output parameter and \(\text{max}_i(y_i(k))\) is the largest value among the output parameters. Equation (6) is used to calculate the grey relational coefficient from which the grading stage of the grey relational analysis is carried out

\[
\text{Grey Relational Coefficient} = \frac{\Delta_{min} + \Psi \Delta_{max}}{(1 - y_i(k)) + \Psi \Delta_{max}}
\] (6)
In the above-mentioned equation, $\Delta_{\text{min}}$ is the minimum value and $\Delta_{\text{max}}$ is the maximum value. The normalized S/N ratio is between zero to one ($0 < \Psi < 1$). The value of $\Psi$ is assumed as 0.5 for these set of trials. Table 7 shows the normalized values of the S/N ratios required to serve the purpose of grey relational generation. Equation (7) determines the grey relational grade $y_i$ for each of the trials where $n$ is the number of responses and $k$ is the value corresponding to the referred response [16].

$$y_i = \frac{1}{n} \sum (k)$$

Table 8 elucidates the grey relational coefficients and the respective grey relational grade with the corresponding ranks based on higher grey relational grades. The average grey relational grades are calculated so as to obtain the influence of each control factors on their levels after machining. The difference in the maximum to minimum values signifies the influence in the control factor on the particular level of experiments. Table 9 depicts the average grey relational grades with the difference in maximum and minimum values of average grade for the respective control factors. Figure 7 represents the main effects plot indicating the optimum set of process parameters from which it is observed that the optimal process parameters are at 60° orientation, spindle speed of 2300 rpm, feed rate of 1000 mm/min and depth of cut of 0.3 mm.

Table 7. Normalized Values from Grey Relational Generation

| Experiment Number | MRR    | Surface Roughness | Radial Tool Deflection |
|-------------------|--------|-------------------|------------------------|
| 1                 | 0.52692| 0.43339           | 0.00000                |
| 2                 | 0.65830| 0.74935           | 0.36699                |
| 3                 | 0.0000 | 0.00000           | 0.92973                |
| 4                 | 0.14494| 0.43687           | 0.08434                |
| 5                 | 1.0000 | 0.75780           | 0.30312                |
| 6                 | 0.89301| 0.90155           | 0.48419                |
| 7                 | 0.25685| 1.00000           | 0.23512                |
| 8                 | 0.61464| 0.78184           | 1.00000                |
| 9                 | 0.72864| 0.66447           | 0.30312                |
**Table 8.** Grey relational coefficients and grades with ranking

| Experiment Number | MRR    | Surface Roughness | Radial Tool Deflection |
|-------------------|--------|-------------------|------------------------|
| 1                 | 0.51383| 0.468775          | 0.333333               |
| 2                 | 0.59403| 0.666094          | 0.441304               |
| 3                 | 0.33333| 0.333333          | 0.876779               |
| 4                 | 0.36898| 0.470312          | 0.353191               |
| 5                 | 1.00000| 0.673675          | 0.417752               |
| 6                 | 0.82373| 0.835484          | 0.492217               |
| 7                 | 0.40220| 1.000000          | 0.395293               |
| 8                 | 0.56474| 0.696227          | 1.000000               |
| 9                 | 0.64820| 0.598424          | 0.417752               |

**Table 9.** Average Grey Relational Grade

| Parameter                  | Level 1 | Level 2 | Max-Min     | Rank |
|----------------------------|---------|---------|-------------|------|
| One direction tool path (°) | 0.506758| 0.603928| 0.183231    | 2    |
| Spindle Speed (rpm)        | 0.478437| 0.672648| 0.194211    | 1    |
| Feed Rate (mm/min)         | 0.629815| 0.506478| 0.123337    | 3    |
| DOC (mm)                   | 0.563528| 0.627819| 0.072607    | 4    |

Average Grey Relational Grade of all levels = 0.586140
5. Confirmation Test

The confirmation test is carried out by using the optimum result obtained from the GRA. Then the various responses are measured and compared. The test was done with tool having four flute carbide end mill of 6 mm, tool path orientation at 60 degrees, spindle speed of 2300 rpm, 1000 mm/min feed rate and a depth of cut of 0.3 mm. Table 10 shows the results of the average values of three confirmation tests conducted with the optimum parameters.

![Main Effects Plot](image)

Figure 7. Main Effects Plot indicating optimum set of process parameters.

| Table 10. Confirmation Test |
|-----------------------------|
| **Response** | **Initial Parameters at Level 1** | **Optimum Parameters** |
| MRR(mm$^3$/min) | 210.7635 | 280.6473 |
| Surface Roughness(Ra) ($\mu$m) | 0.3684 | 0.2625 |
| Radial Tool Deflection (mm) | 0.012 | 0.010 |
| Grey Relational Grade | 0.43864 | 0.46620 |
6. Conclusion

This paper presents an application of grey relational analysis for optimizing the process parameters of rough cutting process in pocket operation on Ti-6Al-4V alloy using 6mm end mill cutter. From the study the following conclusions are arrived. The optimum process parameters in rough cutting process of Ti-6Al-4V alloy using pocket milling operation was found to be 60 degrees tool path orientation, 2300 rpm spindle speed, 1000 mm/min feed rate and 0.3 mm. of depth of cut. Based on the Average Grey Relational Grade the tool path orientation and the Spindle speed are found to be the two most significant process parameters followed by feed rate and depth of cut. It should be noted that the optimum, results can only be applied for a process specified as rough cutting in pocket milling. The comparison made with the confirmation test values with the initials process parameter values showed an improvement in grey relational grade of 0.02756.

7. References

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