AN OPTIMIZATION STRATEGY TO REDUCE SURFACE ROUGHNESS, FLANK WEAR AND TOOL VIBRATION IN MICRO MILLING OF TI-6AL-4V ALLOY

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Abstract

The present work is aimed to investigate the influence of process parameters namely cutting speed, feed and uncut chip thickness on tool life in micro milling of Ti-6Al-4V alloy. Twenty Seven experiments have been planned as per full factorial design with three levels of each parameter using carbide end mill cutters. Surface roughness and vibration amplitude are considered as responses to evaluate the tool life and to identify significance of input process parameters. In this study, a non-contact sensor, Laser Doppler Vibrometer (LDV) was used to measure the vibration of tool in terms of Acousto Optic Emission (AOE) signals. A high-speed Fast Fourier Transform (FFT) analyser was used to transform the acousto optic emission signals into useful signals like vibration amplitude. In the analysis of surface roughness and amplitude of vibration, optimum cutting parameters were found as 5000 r.p.m. of spindle speed, 40 mm/min of feed rate and 25.6 µm of uncut chip thickness.

Keywords: Surface Roughness, Micro Milling, Tool wear, Taguchi, LDV, Multi Response Optimization

I. Introduction

Micro-machining is an alternative to standard methods of micro manufacturing owing to its applicability to a wide range of materials, cost and versatility of the process. In micro cutting process, the manufactured components and characteristics usually belong to mesoscale, and the final geometric accuracy and
surface quality are affected by many factors. In micro machining of titanium alloys, performance characteristics like surface roughness, tool vibration and tool wear will determine overall performance of the process. Objective of this work is to investigate the effect of process parameters on individual performance characteristics and overall performance of the process. Fabio et al. [III] developed a mechanistic cutting force model in micro-milling of aluminium alloy by considering homogeneous grain properties. The experiments were performed with different feed rates and cutting velocities to analyse cutting forces. It was observed that cutting speed has more influence than feed per tooth on specific cutting force and the same was confirmed by the mechanistic model results.

James et al. [V] revealed that in micro milling operation deviations and surface quality can be controlled by the help of acoustic emission (AE). Micro milling is performed to prepare the components with a sub millimetre waveguide to obtain the desired surface quality and geometrical accuracy. Time frequency analysis (TFT) is used to convert AOE more effective signal features (SF). The obtained information is correlated against the measured geometrical deviations and the onset of catastrophic tool wear. Influence of tool path on surface quality and wear in micro milling of Ti-6Al-4V alloy was investigated by Emel et al. [II]. Micro milling experiments were performed by using high-speed spindle attachment connected to main spindle of standard machine tool under different tool paths. The experimental studies are categorized in two stages. In the first stage, the effect of spindle speed was examined under various tool paths at low and high feed rates. In the second stage, the effect of feed rate on machining performance was investigated under different tool paths. Based on their study, the optimum cutting conditions were determined using high-speed spindle attachment under various tool paths. Micro milling is one of the micro machining processes extensively used. It is kinematically similar to conventional milling process, however, differs in chip formation mechanism and uncut chip thickness modeling because of low cutting edge radius and less feed per tooth [X].

Vibration has a significant effect on cutting conditions and machining parameter selection. Spindle speed, feed rate and axial depth of cut influence on vibration during machining was studied by many researchers extensively whereas radial depth of cut effect on vibration studies were limited. Radial depth of cut alters the cutting teeth action and subsequently influences vibration generation during machining [IV].

Samad et al. [VIII] investigated the effect of tool wear on micro milling forces and surface roughness. Results reveal that, machining with worn end mills alters the tool wear patterns and forces induced. Tool wear caused tool deflection as well as tool breakage. The finite element model-based tool deflection and tool breakage predictions were compared with experimental results and good agreement observed among both the values. Rosemar et al. [VII] analyzed the behavior of Poly Crystalline Diamond (PCD) tools in machining of Ti–6Al–4V alloy at high speed conditions with high pressure coolant supply. Tool performance under different tribological conditions and pattern of wear mechanisms were examined. Increase in coolant pressure results enhancement in tool life and reduction of adhesion tendency.
II. Response Surface Methodology (RSM)

Response Surface Methodology (RSM) is one type of modeling tool to develop mathematical relation between input parameters and output responses. RSM technique consists a regression surface fitting to develop an appropriate approximation model between the response ‘Y’ and independent variables \( \{X_1, X_2, \ldots X_N\} \) and it can be expressed in the form of equation 1.

\[
Y = f(X_1, X_2, X_3, \ldots , X_n) \pm e_r
\]

Where \( Y \) is response function which is an unknown and \( e_r \) is other sources of variability not accomplished for \( Y \). Usually, it covers the effect of measurement error in response, background noise and so on.

Bhuvnesh et al. [I] used RSM to investigate the effect of cutting speed, depth of cut, feed rate and nose angle on surface roughness in milling of AISI 1019 steel with carbide inserts as cutting tool material. Cutting speed, feed rate and nose radius were found to be significant on surface roughness. Subramanian et al. [IX] applied RSM technique to develop statistical model to identify the influence of tool geometry, cutting speed, feed rate and depth of cut on cutter vibration during milling of Al 7075-T6 alloy. Amplitude of cutter vibration was predicted using statistical model developed and results revealed that predicted values were close to experimental values.

In the present work, 27 experiments were performed on Ti-6Al-4V alloy. Surface roughness, vibration amplitude and tool wear were measured with the variation of input process parameters and RSM technique was used with Design Expert software to identify interaction effects and significant parameters.

III. Work Piece Material and Mill Cutter

In the present investigation, micro milling characteristics was investigated on Ti-6Al-4V alloy. Among the Titanium alloys usage in various applications, Ti-6Al-4V alloy contributes major percentage around 60%. It possesses good corrosion resistance, high specific strength and bio compatible characteristic. Hence, Ti-6Al-4V is widely used in Marine engine parts, Aircraft components, and Medical and Chemical applications. The Chemical composition of Ti-6Al-4V alloy is illustrated in Table 1.

| Element | Al  | V   | C   | N   | O   | H   | Fe  | Ti  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| %       | 6.75| 4.5 | 0.08| 0.5 | 0.2 | 0.0125 | 0.3 | Balance |

Tungsten carbide end mill cutters are used for the experimentation. The selected end mill cutter specifications are, shank diameter 8 mm, flute diameter 0.9 mm, helix angle 35°, flute length 1.8 mm and total length 50 mm.
IV. Experimentation

In the present work, 3 levels of spindle speed, feed rate and uncut chip thickness were taken as process parameters for the micro-milling as shown in table 2. As per full factorial design, twenty seven experiments were performed on Ti-6Al-4V alloy using tungsten carbide mill cutter. The line diagram of micro-milling set up is shown in fig.1. The following steps were followed during the experimentation:

i. Each experiment was started with different input process parameters as shown in the table 3.

ii. A size of 100 x 100 mm Ti-6Al-4V alloy workpiece was rigidly fixed on the machine table and mill cutter mounted on spindle as depicted in the fig.2.

iii. A LDV was placed in front of the machine to measure mill cutter vibration amplitude.

iv. After each pass, tool flank wear and surface roughness (Ra and Rq) of machined surface were measured using machine vision system and Talysurf respectively.
Table 2: Input Process parameters and their levels

| Factors                  | Units | Designation | Level 1 | Level 2 | Level 3 |
|--------------------------|-------|-------------|---------|---------|---------|
| Spindle speed (S S)      | rpm   | A           | 3000    | 4000    | 5000    |
| Feed rate (F)            | mm/min| B           | 40      | 50      | 60      |
| Uncut chip thickness (T_U)| µm    | C           | 25      | 30      | 35      |

V. Results and Discussion

In order to identify optimum process parameters in micro milling of Ti-6Al-4V alloy, 27 experiments were performed on CNC machine with Tungsten carbide end mill cutters. All the milling experiments were carried out in dry working condition. In this study, LDV was used for online acquisition of cutter vibration data in the form of AOE signals as shown in fig.3. FFT was used to convert the AOE signals into frequency domain with different frequency zones to find out peak vibration amplitude.

Table 3: 27 Experiments input parameters and output characteristics

| Exp. No. | DOE | Surface Roughness (Ra) | Tool Wear VB | Vibration Amplitude |
|----------|-----|------------------------|--------------|---------------------|
| S S      | F   | T_U                   |              |                     |
|          |     |                        |              |                     |
| 1        | 3000| 40                    | 25           | 0.135               | 0.43       | 37.4     |
| 2        | 3000| 40                    | 30           | 0.09                | 0.44       | 36.1     |
| 3        | 3000| 40                    | 35           | 0.135               | 0.39       | 35.1     |
| 4        | 3000| 50                    | 25           | 0.25                | 0.34       | 38.3     |
| 5        | 3000| 50                    | 30           | 0.185               | 0.37       | 35.4     |
| 6        | 3000| 50                    | 35           | 0.085               | 0.45       | 30.7     |
| 7        | 3000| 60                    | 25           | 0.295               | 0.33       | 38.7     |
| 8        | 3000| 60                    | 30           | 0.18                | 0.29       | 28.5     |
| 9        | 3000| 60                    | 35           | 0.095               | 0.43       | 26.9     |
| 10       | 4000| 40                    | 25           | 0.115               | 0.40       | 31.0     |
| 11       | 4000| 40                    | 30           | 0.5                 | 0.26       | 30.8     |
|     |     |     |     |     |     |
|-----|-----|-----|-----|-----|-----|
| 12  | 4000| 40  | 35  | 0.455| 0.26 | 30.1|
| 13  | 4000| 50  | 25  | 0.38 | 0.30 | 29.2|
| 14  | 4000| 50  | 30  | 0.465| 0.32 | 33.8|
| 15  | 4000| 50  | 35  | 0.35 | 0.31 | 43.0|
| 16  | 4000| 60  | 25  | 0.175| 0.57 | 36.7|
| 17  | 4000| 60  | 30  | 0.27 | 0.42 | 38.7|
| 18  | 4000| 60  | 35  | 0.12 | 0.42 | 40.2|
| 19  | 5000| 40  | 25  | 0.085| 0.37 | 29.5|
| 20  | 5000| 40  | 30  | 0.155| 0.35 | 31.6|
| 21  | 5000| 40  | 35  | 0.395| 0.29 | 31.3|
| 22  | 5000| 50  | 25  | 0.17 | 0.36 | 28.8|
| 23  | 5000| 50  | 30  | 0.18 | 0.35 | 32.1|
| 24  | 5000| 50  | 35  | 0.36 | 0.28 | 29.8|
| 25  | 5000| 60  | 25  | 0.17 | 0.41 | 29.2|
| 26  | 5000| 60  | 30  | 0.115| 0.38 | 28.5|
| 27  | 5000| 60  | 35  | 0.12 | 0.34 | 28.5|

**Table 4: Analysis of Variance for Surface Roughness**

| Source | DF | Adj SS   | Adj MS   | F-Value | P-Value | % Contribution |
|--------|----|----------|----------|---------|---------|----------------|
| SS     | 2  | 0.117067 | 0.058533 | 4.40    | 0.026   | 49.55          |
| F      | 2  | 0.044017 | 0.022008 | 1.66    | 0.216   | 18.63          |
| T_U    | 2  | 0.009282 | 0.004619 | 0.35    | 0.711   | 3.92           |
| Error  | 10 | 0.065928 | 0.013296 |         |         |                |
| Total  | 16 | 0.236250 |          |         |         | 100            |

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95% confidence level is adopted to obtain the ANOVA results. Table 4 illustrates ANOVA results of surface roughness in micro milling process of Ti-6Al-4V alloy. Each individual cutting parameters effect on surface roughness is also estimated. As per the ANOVA results spindle speed contribution is highest among other parameters (49.55%) on surface roughness.

### Table 5: Analysis of Variance for Tool wear

| Source | DF | Adj SS  | Adj MS  | F-Value | P-Value | % Contribution |
|--------|----|---------|---------|---------|---------|---------------|
| SS     | 2  | 0.016541| 0.003270| 4.69    | 0.015   | 29.39         |
| F      | 2  | 0.016007| 0.008004| 5.68    | 0.012   | 28.44         |
| T_U    | 2  | 0.008319| 0.004159| 0.87    | 0.433   | 14.78         |
| Error  | 10 | 0.015407| 0.004770|         |         | 27.39         |
| Total  | 16 | 0.056274|         |         |         | 100           |

In the ANOVA, at a confidence level of 95%, the experimental results were evaluated as shown in Table 5. ANOVA also determined the contribution of individual cutting parameters on the Tool Wear. According to the ANOVA for S/N ratio of tool wear, the spindle speed and feed were showing approximately equal contributions of 29.39% and 28.44%.

### Table 6: Analysis of Variance for Amplitude of cutter vibration.

| Source | DF | Adj SS  | Adj MS  | F-Value | P-Value | % Contribution |
|--------|----|---------|---------|---------|---------|---------------|
| SS     | 2  | 126.794 | 63.3970 | 4.50    | 0.040   | 65.52         |
| F      | 2  | 3.825   | 1.9126  | 0.11    | 0.900   | 1.97          |
| T_U    | 2  | 0.783   | 0.3915  | 0.02    | 0.979   | 0.42          |
| Error  | 10 | 62.103  | 18.1051 |         |         | 32.09         |
| Total  | 16 | 193.505 |         |         |         | 100           |

In the ANOVA, at a confidence level of 95%, the experimental results were evaluated as shown in Table 6. ANOVA also determined the contribution of individual cutting parameters on the Vibration Amplitude. According to the ANOVA for S/N ratio of amplitude, the spindle speed is showing more contribution of 65.52%.
Fig. 4: (a) Effect of feed and spindle speed on surface roughness, (b) Effect of uncut chip thickness and spindle speed on surface roughness, (c) Effect of uncut chip thickness and feed on surface roughness.

Figs. 4 (a), (b) and (c) are the three dimensional plots depict the effect of process parameters on surface roughness. Fig. 4 (a) shows that the surface roughness increases with the enhancement of spindle speed up to 4000 RPM and further decreases, and similar effect is reported with the feed rate (up to a feed rate of 50 mm/min). Fig. 4 (b) illustrates that the surface roughness increases with the enhancement of uncut chip thickness and decreases with increase of spindle speed. Fig. 4 (c) depicts that the surface roughness increases with the raise of feed rate and decreases with the increase of uncut chip thickness.

Fig. 5: (a) Effect of feed and spindle speed on tool wear, (b) Effect of uncut chip thickness and spindle speed on tool wear, (c) Effect of uncut chip thickness and feed on tool wear.

Figs. 5 (a), (b) and (c) are the three dimensional plots shows the effect of process parameters on the Tool wear. Fig. 5 (a) shows that the Tool wear increases with rise of feed rate and decreases with increase of spindle speed. Fig. 5 (b) depicts that the Tool wear decreases with increase of uncut chip thickness and increases with rise of spindle speed. Fig. 5 (c) shows that the Tool wear increases with enhancement of feed rate and uncut chip thickness.

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Fig. 6: (a) Effect of feed and spindle speed on vibration amplitude, (b) Effect of uncut chip thickness and spindle speed on vibration amplitude, (c) Effect of uncut chip thickness and feed on vibration amplitude.

Fig. 6 (a), (b) and (c) are the three dimensional plots shows the effect of process parameters on the Vibration Amplitude. Fig.6 (a) shows that the Vibration Amplitude increases with rise of feed rate and decreases with increase of spindle speed. Fig.6 (b) shows that the Vibration Amplitude increases with increase of uncut chip thickness and decreases with increase of spindle speed. Fig. 6 (c) shows that the Vibration Amplitude does not effected by feed rate and uncut chip thickness.

Fig. 7: Multi objective functions for surface roughness, flank wear and vibration amplitude

In the present study, a multi response optimization technique was used to optimize the process parameters for less surface roughness, flank wear and vibration amplitude. Rajesh [VI] revealed that multi response optimization overcomes conflicts arise in single response optimization. Desirability function is an important function in optimization to estimate acceptance of the optimized values [VI]. Desirability value of the optimization is calculated with a gradient algorithm between 0 and 1.
Optimization of process parameters was carried out for minimization of surface roughness, tool wear and vibration amplitude. According to fig.7, optimum cutting parameters were found as 5000 r.p.m. of spindle speed, 40 mm/min of feed rate and 25.6 µm of uncut chip thickness. Desirability values were found to be 0.99105, 0.95303 and 1.0 for surface roughness, tool wear and vibration amplitude respectively. The desirability value which are close to 1 indicates accept of optimization [XI]. Minitab 18 software was used for optimization of process parameters.

VI. Conclusions

Experiments were performed on Ti-6Al-4V alloy to investigate the effect of spindle speed, feed rate and uncut chip thickness on surface roughness, tool wear and vibration amplitude. The following conclusions can be drawn from this investigation.

1. ANOVA conforms that the mathematical models of surface roughness, tool wear and vibration amplitude was well fitted to experimental data.
2. Surface roughness increases with increase of spindle speed and uncut chip thickness but the effect of feed on the surface roughness found to be less. The tool wear increases with increase of feed and decreases with increase of uncut chip thickness.
3. Vibration Amplitude increases with increase of feed and chip thickness but decreases with increase in spindle speed.
4. Optimization of process parameters was carried out for minimization of surface roughness, tool wear and vibration amplitude. Optimum cutting parameters were found as 5000 rpm of spindle speed, 40 mm/min of feed and 25.6 µm of helix angle.

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