

# Micromilling of Ti-6Al-4V Titanium Alloy Using Ball-end Tool

T Pratap<sup>1\*</sup> and K Patra<sup>2</sup>

<sup>1,2</sup> Micro-fabrication Lab, Department of Mechanical Engineering, Indian Institute of Technology Patna, Bihta, Patna-801103, Bihar, India

\* tejpratap.pme13@iitp.ac.in

**Abstract.** The present work experimentally investigates the characteristics of micromilling of Ti-6Al-4V workpiece using ball-end tool. Micromilling were performed using 400  $\mu\text{m}$  ball-end milling tool with the consideration of effective tool diameter. The effective tool diameter in ball-end milling is different from flat-end milling due to variation in cutting zone with axial depth of cut which accounts actual cutting speed and feed the machining. Process input variables includes cutting speed, feed per tooth and axial depth of cut, each with three levels, whereas cutting forces and surface roughness as process responses. Response surface methodology (RSM) based quadratic regression analysis was utilized to develop the correlation between process inputs and responses. Experimental results of present study on micromilling of Ti-6Al-4V using ball-end tool showed that axial depth of cut and feed per tooth could significantly influence the cutting forces and surface roughness. However, present study shows cutting speed has least effect on process responses. Finally, suitable set of process variables were proposed based multi objective optimization approach to obtain minimum cutting forces and surface roughness which were also validated with conformation test results.

## 1. Introduction

The applications of highly precise complex three-dimensional micro-features have grown over the years to enhance the performances of micro-fluidic devices, electronic chips, biomedical devices, aerospace components, optical lens, etc [1, 2]. Effective techniques to fabricate these micro-features are highly dependent on the applications, the materials to be used and the geometrical complexity [2]. However, with the ease of material processing, applicability on wide range of materials processing, higher material removal rate (MRR), operational flexibility, good accuracy, etc., tool based micromachining is considered as a effective technique among available micro-fabrication techniques for mass production of such micro-features [1-3]. Micromilling is one of the better choice among tool based processes for producing such complex features with three dimensional geometries and its applicability even enhanced by the selection of ball-end milling tool. Because of its hemispherical geometry it provides additional ability to produce complex edge free surfaces, good finish, fewer burrs, mold cavities and various surface-textures which is highly demanding nowadays [1-5].

Ti-6Al-4V titanium alloy is an extensively applied material in biomedical implants, automotive suspensions and several aerospace equipment for its superior physical and chemical properties like higher specific strength, non-toxic nature, biocompatibility and good fatigue and corrosion resistance



even at extremely high temperatures [3, 6-7]. However, Ti-6Al-4V machining is challenging due to its unfavourable machining natures like: lack of elastic modulus, low heat conductivity, etc., which promotes higher temperature generation leading to influence in reactivity with tool material, promotes tool wear and failure, etc. [6-9]. In addition to these factors, scaling of micro-tools (Size effect) added further challenges in machining [7, 10]. Moreover, downscaling of the tool size increases aspect ratio, which leads to breakage of the tool even for very small discrepancy in tool overhang [7, 10, 11].

Along with the aforementioned micromilling issues, selection of ball-end milling tool produces ball tip rubbing due to variation in cutting speed along hemispherical portion (zero at the ball tip to highest at extreme of tool workpiece contact). The rubbing phenomenon will be more predominant for smaller axial depth of cut, which is generally required for hard and brittle materials [11, 12]. It significantly affects the chip formation mechanics that causes variation in cutting forces, surface quality and reduced tool life. To overcome its adverse effect, inclined milling is generally preferred which reduces the actual cutting time and allows the proper cooling, thus, decreases the rise in temperature and tool wear [12, 13]. However, tool inclination changes the machined profile which significantly affects the application and used based on the requirement. Berestovskyi *et al.* [11] showed how profile of the machined micro channel varied with the flute length of micro ball-end milling tool. Arif *et al.* [12] also reported that surface profile varies with any discrepancy in workpiece flatness or uneven mounting with ball-end tool. Qui *et al.* [13] observed the behaviour of ball-end tool inclination on surface finish and cutting forces in milling of quartz glass. Another challenging issue with micromilling is burr formation control, which reduces the quality and functionality [14]. However, from the literature it was found that smaller size top burr was produced by selection of ball-end milling tool compared to flat-end milling tool due to the burr suppressed by ball-end tool [15].

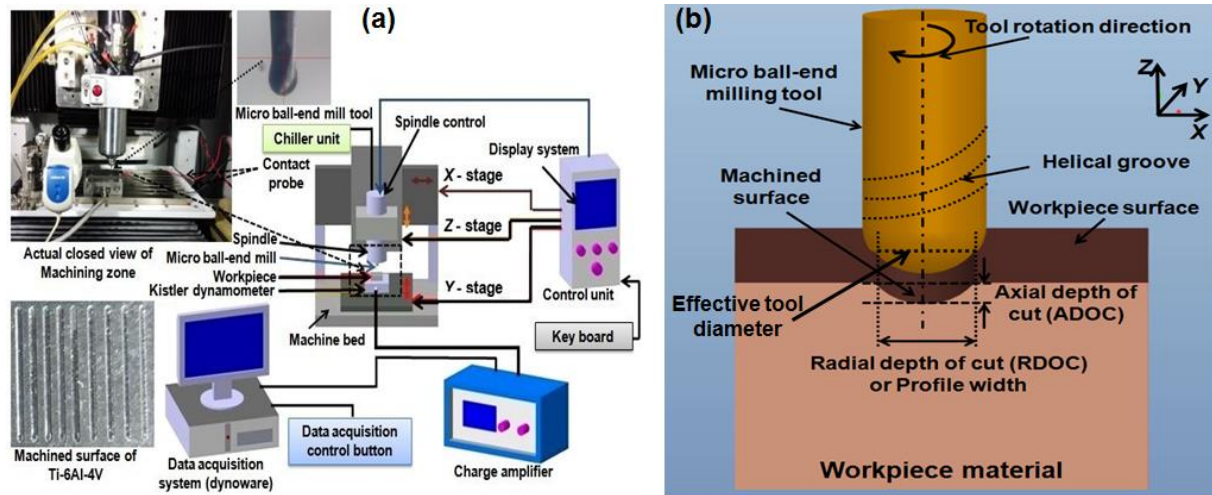
However, from literature, it was found that selection of suitable surface profile depends upon the application and to fabricate such profiles required proper selection of tool geometry and its position with respect to workpiece. It was also observed that, by the consideration of effective tool diameter of ball-end milling tool, micromilling performance characteristics such as; cutting forces, surface roughness, machined surface profile, burr formation are not optimized. This change in effective tool diameter is due to the variation in axial depth. Therefore, contrary to micro-flat-end milling where cutting speed does not vary with cutting depth at a particular spindle rotation, effective cutting speed of micro-ball-end tool varies with the axial direction cutting depth. Therefore, the present work targets the experimental investigation of micromilling of Ti-6Al-4V using ball-end tool considering effective tool diameter. Process responses are observed in terms of cutting forces and surface roughness whereas process inputs are cutting speed ( $V$ ), feed per tooth ( $f_t$ ) and axial depth of cut ( $ADOC$ ). Process responses are predicted using quadratic regression models and RSM based plots are utilized to describe the parametric effects on individual response. Finally, multi-objective optimization has been performed by desirability function approach to select the optimal combination.

## 2. Experimental methodology

### 2.1. Experimental details

Test samples were fixed on the top surface of dynamometer and facing is performed using flat-end milling at micromachining centre (DT-110, Mikrottools Pte. Ltd.). It reduce the chance of any flatness error which is further ensured by the use of contact probe. After the face milling, fresh solid carbide two fluted micro ball-end milling tool of diameter 400  $\mu\text{m}$  is used to perform the experiments under dry condition with three repetitions considering effective tool diameter as shown in the figure 1. Positional accuracy of  $\pm 1 \mu\text{m}$  per 100 mm of travel is achieved by its programmable multi axis controller. The cutting forces ( $F_x$ ,  $F_y$  and  $F_z$ ) are acquired in time domain using piezo electric dynamometer (MiniDyn Type 9256C2) at sampling rate of 50 kHz and average of three experimental root mean square (RMS) values are considered for further analysis. Unwanted chips and wear debris of the tool presented are ultrasonically cleaned under acetone solution and dried with compressed air. Surface roughness ( $R_a$ ) was measured by digital type surface analyzer (Mitutoyo, SJ-400) at three

different locations along the slot base and average value has been reported. Machined surface profile was also investigated by zeta-20, 3D optical profiler at three different locations to see the consistency of the machined surface profile.



**Figure 1.** (a) Experimental setup used for micromilling of Ti-6Al-4V (b) Schematic representation of effective tool diameter in ball-end milling tool for given axial depth of cut

### 2.2. Effective diameter calculation and modified process inputs

Effective tool diameter ( $D_e$ ) are calculated based on tool geometry and  $ADOC$  using the equation (1). This effective diameter is used to calculate spindle speed ( $N$ ) for designed value of cutting speed ( $V$ ) by equation (2) and finally, modified spindle speed is multiplied by selected feed per tooth ( $f_t$ ) to achieve actual feed rate as per equation (3).

$$D_e = 2\sqrt{R^2 - (R - ADOC)^2} \quad (1)$$

$$V = \pi D_e N \quad (2)$$

$$f = z f_t N \quad (3)$$

where,  $D_e$  = effective tool diameter ( $\mu\text{m}$ )

$R$  = radius of ball end tool ( $\mu\text{m}$ )

$ADOC$  = axial depth of cut in ( $\mu\text{m}$ )

$V$  = cutting speed (m/min)

$N$  = modified spindle speed in rpm

$f$  = feed rate (mm/min)

$z$  = number of tooth and

$f_t$  = feed per tooth ( $\mu\text{m}/\text{tooth}$ )

### 2.3. Design of Experiments (DOE) and process responses

To select suitable process variables, experiments are designed by DOE with three factor ( $V$ ,  $f_t$  and  $ADOC$ ) and three levels. Process responses for the given set of experiments are measured as cutting forces  $F_x$ ,  $F_y$  and  $F_z$  along tangential, feed and thrust direction, respectively, and surface roughness ( $R_a$ ) along the slot base as shown in Table 1. RSM based quadratic regression expressions are also developed to relate the process input to each of the response and compared with experimental results to check the maximum possible error present in the developed model. Design-Expert 9 software

package (Stat-Ease Inc., USA) has been utilized to plot response surface which provides the idea of influencing factor for the given sets of experiments.

**Table 1.** Experimental outcomes of micromilling of Ti-6Al-4V using ball-end milling tool

Process inputs with their assigned levels				Process responses			
Cutting condition	$V$ (m/min)	$f_t$ ( $\mu\text{m/tooth}$ )	$ADOC$ ( $\mu\text{m}$ )	$F_x$ (N)	$F_y$ (N)	$F_z$ (N)	$R_a$ ( $\mu\text{m}$ )
1	8	0.5	10	0.2081	0.3356	1.7112	0.321
2	8	1.5	20	0.4511	0.6010	2.1386	0.192
3	8	2.5	30	0.8308	0.9142	2.5735	0.167
4	16	1.5	30	0.6016	0.7937	2.3484	0.159
5	16	2.5	10	0.6873	0.6904	2.1735	0.191
6	16	0.5	20	0.3606	0.5989	1.8772	0.269
7	24	2.5	20	0.7761	0.7797	2.2329	0.174
8	24	0.5	30	0.5526	0.7863	2.1829	0.177
9	24	1.5	10	0.3822	0.5193	1.9772	0.262

### 3. Experimental results and discussions

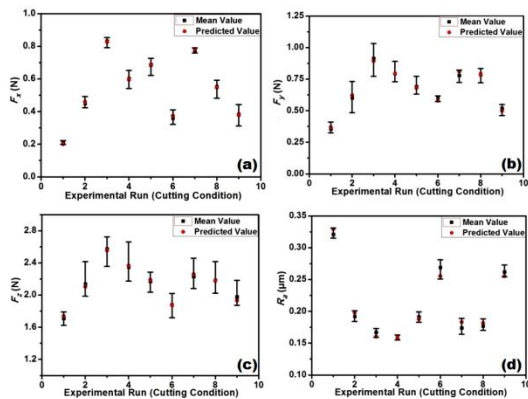
Quadratic regression expressions of the predicted cutting forces and surface roughness are given in equation (4), (5), (6) and (7), respectively. Predicted results of each of the response are compared with the experimental results and shown in figure 2 (a-d). Observation also indicates that predicted values are well suited with the error bar plot for all the responses. From the all proposed mathematical expression, it was observed that cutting velocity ( $V$ ) term have very smallest co-efficient and hence, less contribute to the prediction of given responses. Therefore, influences of the significant process inputs  $f_t$  and  $ADOC$  on the process responses  $F_x$ ,  $F_y$ ,  $F_z$  and  $R_a$  are described with the help of three dimensional response surface plots shown in figure 3 (a-d). figure 3 (a) and (b) show the variation of  $F_x$  and  $F_y$  with  $ADOC$  and  $f_t$ , respectively. Response surfaces in both plots indicate that with increase in  $ADOC$  and  $f_t$  both tangential force ( $F_x$ ) and feed force ( $F_y$ ) increases. The increase in force is due to the increase in effective chip area with increasing value of  $ADOC$  and  $f_t$ . Contrary to micro-flat-end milling, thrust force ( $F_z$ ) in micro-ball-end milling is one order more than tangential and feed forces due to rubbing of the ball-end of the tool with respect to workpiece. Figure 3 (c) shows that thrust force ( $F_z$ ) increases with increasing  $ADOC$  and  $f_t$  caused by increase in effective cutting zone. The variation in effective tool diameter by the change in  $ADOC$  is the major contributor for the variation in cutting zone. Response surface plot shown in figure 3 (d) shows that with increase in  $f_t$  and  $ADOC$  surface roughness decreases. It shows that with the increase in  $f_t$  and  $ADOC$ , ploughing and rubbing effect reduces and results the smoother surface [6, 10-12]. Similarly for low axial depth of cut, rubbing effect is more dominant than cutting and it leads to more roughness of the workpiece surface.

$$F_x = +0.00784 + 0.00234 V - 0.00493 f_t + 0.01722 ADOC - 0.00362 f_t ADOC + 0.09095 f_t^2 \quad (4)$$

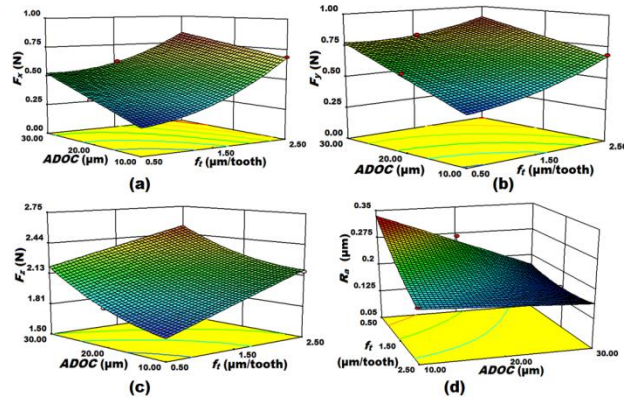
$$F_y = +0.12768 + 0.00198 V + 0.03842 f_t + 0.02146 ADOC - 0.00399 f_t ADOC + 0.04952 f_t^2 \quad (5)$$

$$F_z = +1.61994 - 0.0028 V + 0.27091 f_t - 0.00536 ADOC - 0.00347 f_t ADOC + 0.00078 ADOC^2 \quad (6)$$

$$R_a = +0.47233 + 0.00076 V - 0.14487 f_t - 0.00971 ADOC + 0.00346 f_t ADOC + 0.01217 f_t^2 \quad (7)$$

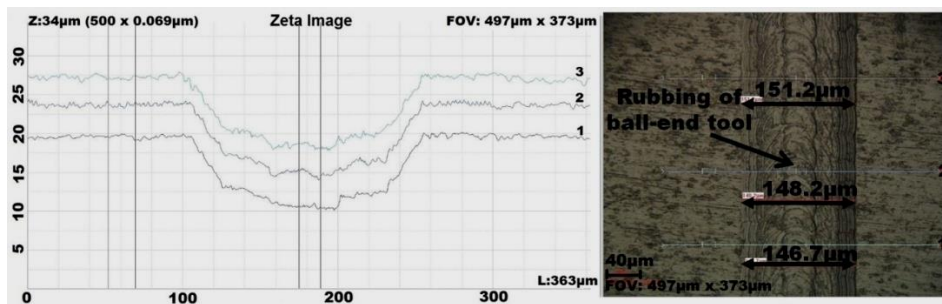


**Figure 2.** Predicted and experimental values with error bar (a)  $F_x$  (b)  $F_y$  (c)  $F_z$  and (d)  $R_a$



**Figure 3.** Effects of  $ADOC$  and  $f_t$  on cutting performances (a)  $F_x$  (b)  $F_y$  (c)  $F_z$  and (d)  $R_a$

Machined surface profile variations are also investigated by measuring surface profile at three locations along the length for all the channels to check the accuracy of the produced surface. Figure 4 shows the machined surface profile variation along with their respective three dimensional views. It can be observed from the machined surface profiles that cross-sectional features are almost similar in nature with minor variation and there is almost no burr on the top surface of the workpiece. This shows that micro-ball-end mill is capable to produce surfaces of repeatable profiles along with minimum top burr. Ball-tip rubbing zone along the centre line are also observed which significantly effects on the surface roughness as observed in the experimental results.



**Figure 4.** Machined surface profile measurement using Zeta-20 optical profiler for cutting condition:  $V = 8 \text{ m/min}$ ,  $f_t = 0.5 \text{ } \mu\text{m/tooth}$  and  $ADOC = 10 \text{ } \mu\text{m}$

From the response surface analysis we have also found that cutting forces increases with increase in  $f_t$  and  $ADOC$  while surface roughness reduces. As the nature of cutting forces and surface roughness are reverse in nature, there should be a compromise to fulfil the condition of minimum cutting forces along with smother surface quality. This can be performed by multi-objective optimization using desirability function approach of Design-Expert 9 software package. The constraints of the process inputs are selected within the performed range and process response are of minimization type. From the set of optimized solution, minimum cutting forces ( $F_x$ ,  $F_y$  and  $F_z$ ) are obtained at  $V = 8 \text{ m/min}$ ,  $f_t = 1.34 \text{ } \mu\text{m/tooth}$  and  $ADOC = 10.79 \text{ } \mu\text{m}$ . However, for minimum surface finish ( $R_a$ ) optimum condition is obtained at  $V = 8 \text{ m/min}$ ,  $f_t = 1.28 \text{ } \mu\text{m/tooth}$  and  $ADOC = 12.62 \text{ } \mu\text{m}$ . To validate the optimized results, fresh experiments were conducted at  $V = 8 \text{ m/min}$ ,  $f_t = 1.34 \text{ } \mu\text{m/tooth}$  and  $ADOC = 10.79 \text{ } \mu\text{m}$  and compared with the predicted optimized results. The maximum error for cutting forces ( $F_x$ ,  $F_y$  and  $F_z$ ) are found to be 4.02%, 2.49% and 2.09%, respectively, whereas for surface roughness ( $R_a$ ) maximum error is 4.71%.

#### 4. Conclusions

The present work, effects of process inputs on the cutting forces ( $F_x$ ,  $F_y$  and  $F_z$ ) and surface roughness ( $R_a$ ) have been investigated through micromilling of Ti-6Al-4V using ball-end milling tool considering effective tool diameter. Research findings are concluded with the following points.

- For axial depth of cut ( $ADOC$ ) below tool radius, cutting speed ( $V$ ) and profile width changes accordingly due to variation in effective tool diameter ( $D_e$ ). To maintain constant  $V$  and  $f_t$ ,  $N$  and  $f$  must be modify.
- Based on the developed response surface plots, it is observed that  $f_t$  and  $ADOC$  significantly influence the cutting forces and surface roughness, whereas they are found to of opposite in nature. The selected range of cutting speed ( $V$ ) is least significant for given responses.
- Machined profile is found to be similar in nature.
- Micromilling with ball-end tool is capable to reduce the top burr which is a major challenge with flat-end tool. However, rubbing of ball-end tip has also been observed along slot base.
- The validation experiments results are found to be comparable with optimized predicted values.

## References

- [1] Kumar SPL, Jerald J, Kumanan S and Prabakaran R 2014 A review on current research aspect in tool-based micromachining processes *Materials and Manufacturing Processes* **29** 1291-1337.
- [2] Camara MA, Rubio JCC, Abrao AM and Davim JP 2012 State of the art on micromilling of materials, a review *Journal of Materials Science & Technology* **28(8)** 673-685.
- [3] Mamedov A and Lazoglu I 2015 Micro ball-end milling of freeform titanium parts *Advances in Manufacturing* **3(4)** 263-268.
- [4] Özel T and Liu X 2009 Investigations on mechanics-based process planning of micro-end milling in machining mold cavities *Materials and Manufacturing Processes* **24(12)** 1274-1281.
- [5] Baburaj M, Ghosh A and Shunmugam MS 2016 CAD based simulation of ball end mill manufacturing *Computer-Aided Design and Applications* doi: 10.1080/16864360.2016.1199754
- [6] Hassanpour H, Sadeghi MH, Rezaei H and Rasti A 2016 Experimental study of cutting force, microhardness, surface roughness, and burr size on micromilling of Ti6Al4V in minimum quantity lubrication *Materials and Manufacturing Processes* doi: 10.1080/10426914.2015.1117629
- [7] Pratap T, Patra K and Dyakonov AA 2015 Modeling cutting force in micro-milling of Ti-6Al-4V titanium alloy *Procedia Engineering* **129** 134-139.
- [8] Garcia U and Ribeiro MV 2016 Ti6Al4V titanium alloy end milling with minimum quantity of fluid technique use *Materials and Manufacturing Processes* **31(7)** 905-918.
- [9] Davim JP 2014 *Machining of titanium alloys* Springer, Heidelberg.
- [10] Oliveira FBD, Rodrigues AR, Coelho RT and Souza AFD 2015 Size effect and minimum chip thickness in micromilling *International Journal of Machine Tools & Manufacture* **89** 39-54.
- [11] Berestovskyi D, Hung WNP and Lomeli P 2014 Surface finish of ball-end milled microchannels *Transaction ASME Journal of Micro-Nano Manufacturing* **2** 041005-1-10.
- [12] Arif M, Rahman M and San WY 2012 An experimental investigation into micro ball-end milling of silicon *Journal of Manufacturing Processes* **14** 52-61.
- [13] Qiu Y, Gu ML, Zhang FG and Wei Z 2014 Influence of tool inclination on micro-ball-end milling of quartz glass *Materials and Manufacturing Processes* **29(11-12)** 1436-1440.
- [14] Aurich JC, Dornfeld D, Arrazola PJ, Franke V, Leitz L and Min S 2009 Burrs-analysis, control and removal *CIRP Annals – Manufacturing Technology* **58** 519-542.
- [15] Chen MJ, Ni HB, Wang ZJ and Jiang Y 2012 Research on the modeling of burr formation process in micro-ball end milling operation on Ti-6Al-4V *The International Journal of Advanced Manufacturing Technology* **62** 901-912.