Multiobjective Optimization in Micromachining of Aluminum (Al 7075) using Taguchi Technique

V.S.Kathavate and A.S.Adikine

Abstract— In present scenario, the demand for precise micro components in the field of aerospace, mechanical, optics, electronics and biotechnology is increasing. This current work aims for optimization in micromilling of Al 7075 material using Taguchi robust technique. This work is carried out under three stages; experimental work, modelling and multiobjective optimization. Initially, micromilling experiments are carried out by constructing taguchi L_9 orthogonal array keeping spindle speed, feed rate and depth of cut as controlled process variables, while results are analyzed using MINITAB 15 software for the responses Metal removing rate and Surface roughness. Regression Model replicating MRR and Surface roughness is created. To optimize all responses, Taguchi signal to noise ratio is used. Finally, analysis of variance (ANOVA) is done and multiobjective optimization results are predicted. It was found that for the optimized conditions of MRR and surface roughness spindle speed should be kept 2600 rpm, feed rate 600 mm/min and depth of cut should be in the range of 0.07 mm. From ANOVA it can be anticipated that feed rate is the most influencing factor which contributes 65% followed by spindle speed 18% and depth of cut 10%. It can be said that metal removing rate is adversely affected by feed rate while surface roughness is influenced by spindle speed.

Key Words— Depth of Cut (DoC), feed rate, Metal removing rate (MRR), Micromachining, Multiobjective optimization, Signal to Noise (S/N), Spindle speed, Surface roughness, Taguchi method.

I. INTRODUCTION

Increase in demand for the micro products with precise machining and superior surface finishing is gaining more significance and has versatile impact on national security, defence, energy, healthcare and domestic manufacturing base [1]. Non-traditional fabrication methods such as laser machining, focused ion beam machining, electrochemical machining and electro discharge machining (EDM) are used to produce micro components, but these methods have limited potential due to the limited work piece material selection, poor productivity and high cost[2]. But micromachining process such as micro-milling, micro-drilling and micro-grinding are gaining more importance over nontraditional machining process [3]. So, it is capable

of producing 2- dimensional surfaces with third dimension ($2\frac{1}{2}D$).

Micromachining of any metal often consists of using miniature cutting tool which may derived from macro tool[4]. Tools used for turning, milling and drilling in micromachining are very small in diameter upto $10\mu m$. Complex structures with high aspect ratios and tedious geometries can be suitably produced by micromilling process. Surface roughness may be increased due to elastic recovery and minimum chip thickness provided that chip thickness should be less than cutting edge radius of micro tool. Ali and Ong used focussed ion beam sputtering for the fabrication of microtools[5]. Polycrystalline diamond micro hexagonal tool was fabricated by Cheng et. al. using wire electrical discharge machining process[6]. Suzuki et.al. had developed the micro tool made of polycrystal diamond[7].

Micro machinability of copper 101 was reported by Sinan Filiz et.al.[4]. Whereas, G. Bissacco et.al. investigated the micro milling of hardened tool steel[8]. From the variety of materials such as polymer [9], steel, aluminum, tungsten carbide [10], brass [11] and silicon [12] manufacturing of complex shapes such as two dimensional and three dimensional structures are possible using micromilling. Though there is moderate research on micro milling of steel, copper and composites, very few carried the experimentation on aluminum.

There are various process parameters which have direct influence on micro milling performance. Cutting forces, tool inclination angle, spindle speed, feed rate and depth of cut are few of them. Most of the researchers have optimized process parameters and their influence by various methods like response surface methodology (RSM), central composite design (CCD), full factorial and fractional factorial. Few of them were decided to go with Taguchi method.

Taguchi technique is one of the most suitable and advanced technique for optimizing process parameters in machining process in current scenario. It consists of specially constructed orthogonal arrays (L_8 , L_9 , L_{18} and L_{27}) and gives much reduced variance. It gives the idea about what optimal settings of process parameters affect the responses in the particular process. Using Taguchi method, one can reduce its number of experimentations by huge margin, like if anyone has 13 process parameters and there 3 respective levels then instead of going for (3^{13}) experiments, able to get the similar results in 27 experiments (L_{27} array).

So, here in this work, the effects of process

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parameters spindle speed, feed rate and depth of cut were studied using taguchi robust technique and design was optimized for surface responses like metal removing rate (MRR) and surface roughness using multiobjective optimization. Signal to Noise ratios were calculated for best suitable design. Regression model was created for predicting the accuracy and confirmation of results.

II. EXPERIMENTAL

A. Material

The micromilling tests were conducted on Aluminum material of grade (Al 7075) and having dimensions 60mm × 35mm × 20mm. Initially the desired dimension parts of Al (7075) were machined by surface grinding. Surface roughness was maintained upto 1 µm. Vickers hardness of the material was determined using diamond indenter and found to be around 130. The chemical composition of Aluminum (Al 7075) was determined by energy dispersive spectroscopy (EDAX) (Table 1);

TABLE 1: Chemical Composition of Al 7075

Element	wt % Composition
Aluminum (Al)	88.3
Zinc (Zn)	4.8
Silicon (Si)	0.84
Manganese (Mn)	0.34
Lithium (Li)	0.0002

Tool for machining purpose was selected in accordance with material specifications and according to machine performance. A flat end milling cutter of 2 mm diameter was selected for carrying out the experiment which was having a 40 mm end mill length and 5 mm shank diameter. The static run out of the tool from the spindle axis was 7 µm. All the micro milling experiments were carried out on the machine of Heartford (E-2 series) VMC milling machine (figure 1). While machining was done on the area 30 mm × 15 mm surface with 1.5 mm depth.

Fig. 1. Micro milling of Al 7075

B. Selection of Process Variables

Input controlled variables Spindle speed (rpm), feed rate (mm/min) and Depth of cut (mm) were designed according to the trial and error basis method that the material can withstand with and according machine specifications so as to achieve optimum values of Metal removing rate and Surface Roughness (Table 2);

TABLE 2: Process Parameters and their levels

Code	Process parameters	Level 1	Level 2	Level 3
A	Spindle Speed (rpm)	2200	2600	3000
B	Feed Rate (mm/min)	400	500	600
C	Depth of Cut (mm)	0.05	0.07	0.09

C. Construction of Taguchi L₉ Orthogonal Array

Taguchi method consists of specially constructed Taguchi orthogonal arrays. These orthogonal arrays are the outcome (matrix) of the equation (**Levels** ^{Process Variables}). Now, here we have 3 process variables with their 3 levels. So, Taguchi L₉ orthogonal array was created and experiments were run according array (Table 3). For the sake of repeatability and precision measurements, each experiment was conducted twice.

TABLE 3: Taguchi L₉ Orthogonal Array

Experiment	Spindle	Feed	Depth of
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

III. RESULTS AND DISCUSSION

There are various factors which influences during micro milling operations such as tool wear, cutting forces and microstructure of the work piece. The main purpose of this work was to optimize the surface responses like metal removing rate and surface roughness.

A. Measurements

Measurements for the metal removing rate in gm/min was carried out using the governing equation, the difference between mass of the workpiece after machining and mass of the workpiece before machining per unit machining time. Here in micromilling experiments the machining time was kept constant upto 18 mins (Table 4);

$$MRR = \frac{m_a - m_b}{T} \quad (\text{gm/min})$$

Where, m_a = Mass of the workpiece after machining

m_b = Mass of the workpiece before machining

T = Machining time (18 mins)

TABLE 4: Mass difference between workpiece

Sr.No.	Mass before machining (gm)	Mass after machining (gm)
1	140.50	122.63
2	142.52	126.76
3	140.38	125.63
4	140.76	127.48
5	142.90	129.80
6	143.62	127.10
7	141.45	124.22
8	140.50	123.28
9	140.50	122.30

Surface roughness is one of the influencing parameter in production process which determines the quality of finished products. Surface roughness was measured in the direction of feed by the Taylor Hobson Make Surface Finish Tester, Seltronic 3 with offline and real time monitoring condition. The profilometer was calibrated with a standard calibration block. Average surface roughness (Ra) was selected as a roughness parameter. The measurement of Ra was repeated ten times and average values of these measurements were taken into consideration to make further analysis (Table 5);

TABLE 5: Surface roughness's of the machined workpiece

Sr.No.	Surface roughness (μm)
1	0.40
2	0.37
3	0.48
4	0.52
5	0.28
6	1.10
7	0.65
8	0.38
9	0.46

TABLE 6: Final result matrix

Sr.No.	Spindle speed	Feed rate	Depth of cut	MRR	Surface Roughness (μm)
1	2200	400	0.05	0.992	0.27
2	2200	500	0.07	0.875	0.37
3	2200	600	0.09	0.819	0.48
4	2600	400	0.07	0.737	0.52
5	2600	500	0.09	0.561	0.28
6	2600	600	0.05	0.584	1.10
7	3000	400	0.09	0.957	0.30
8	3000	500	0.05	0.956	0.38
9	3000	600	0.07	1.010	0.46

B. Regression Analysis

Regression analysis for metal removing rate

Regression analysis for metal removing rate was done in MINITAB 15 software and regression model was generated. The model predicting metal removing rate gives nearly same results as they were calculated manually in Table 6. The regression equation is

$$MRR = 0.901 + 0.000107 A - 0.000347 B - 1.73 C$$

TABLE 7: Regression analysis for metal removing rate

Predictor	Coefficient	SE Coef.	T	P
Constant	0.9012	0.6334	1.38	0.225
Spindle Speed	0.0001067	0.0001793	0.60	0.578
Feed Rate	-0.0003465	0.0007529	-0.46	0.665
Depth of Cut	-1.726	3.849	-0.45	0.673

Weighted analysis using weights in MRR,

$$S = 0.169455 \quad R\text{-Sq} = 93.6\% \quad R\text{-Sq (adj)} = 90.0\%$$

$$PRESS = 0.654909 \quad R\text{-Sq (pred)} = 0.00\%$$

The parameter R-sq describes the amount of variation observed in metal removing rate and is explained by the input factors. R-sq= 93.6% indicates that the model is able to predict the response with high accuracy and more precisely (Table 7). Adjusted R-sq is modified R-sq that has been adjusted for the no. of terms in the model. If unnecessary terms are included in the model, R-sq can be artificially high, but adjusted R-sq (90.00%) may get smaller. The standard deviation of error in the modelling, S=0.169455. Predicted model and actual metal removing rates are the fitted to regression line. It was found that all the observations agreements with governing single trend line (figure 2).

Fig. 2. Residual plots for metal removing rate

While, histogram with standardized residual suggests that, the skewness is minimum and all the residuals follow the minimum to maximum range of (-1.80 to +1.40), which again confirms the obtained results were accurate and more precise. Analysis of Variance (ANOVA) results suggest the influence of all the process parameters on the performance of micromilling operation (Table 8).

TABLE 8: Analysis of Variance for metal removing rate

Source	DF	SS	MS	F	P
Spindle Speed	2	0.18902	0.945	0.25	0.859
Feed Rate	2	0.65672	0.3234		
Depth of Cut	2	0.07577	0.038		
Residual error	2	0.07849	0.03925		
Total	8	1			

Influence of depth of cut on MRR is more about 65.67%, spindle speed contributes 18.90% followed by depth of cut 7.5%. Interval plot of MRR influenced by factor spindle speed suggests the optimal speed of 2600 rpm to 3000 rpm is suitable for achieving maximum metal removing rate (figure 3). Experimental validation with model was in agreement with each other being shown in (figure 4).

Fig. 3. Interval plot for MRR vs Spindle speed

Fig. 4. Comparative study for metal removing rate

Regression analysis for Surface roughness

Being as one of the response factor, regression analysis was done for surface roughness using MINITAB 15 software. The model generated for surface roughness is given by,

$$SF = 0.45 + 0.00011 A - 0.000783 B - 0.145 C$$

TABLE 9: Regression analysis for surface roughness

Predictor	Coefficient	SE Coef.	T	P
Constant	0.4520	0.645	1.68	0.230
Spindle Speed	0.0001099	0.0010989	0.78	0.59
Feed Rate	-0.00078299	0.0007829	-0.58	0.690
Depth of Cut	-0.14502	2.59	-0.85	0.64

Weighted analysis using weights in Surface roughness,

$$S = 0.28546 \quad R\text{-Sq} = 95.4\% \quad R\text{-Sq (adj)} = 87.8\%$$

$$\text{PRESS} = 0.689 \quad R\text{-Sq (pred)} = 0.00\%$$

The parameter R-sq gives the idea about the amount of variation observed in surface roughness and is explained by the input factors. R-sq= 95.4% generalises that the model is able to predict the response with high accuracy (Table 8). Adjusted R-sq is modified R-sq that has been adjusted for the no. of terms in the model. If unnecessary terms are included in the model, R-sq can be artificially high, but adjusted R-sq (87.8%) may get smaller. The standard deviation of error in the modelling, $S=0.28546$. Predicted model and actual surface roughness are the fitted to regression line. It was found that all the observations agreements with governing single trend line (figure 5).

Fig. 5. Residual plots for Surface roughness

Analysis of Variance (ANOVA) results suggest the contribution of all the process parameters on the performance of micromilling operation (Table 10).

Table 10 Analysis of Variance for surface roughness

Source	DF	SS	MS	F	P
Spindle Speed	2	0.4455	0.2228	0.20	0.960
Feed Rate	2	0.1988	0.9544		
Depth of Cut	2	0.2856	0.1428		
Residual error	2	0.0701	0.035055		
Total	8	1			

Spindle speed has the greater influence on surface roughness 44.5%, followed by depth of cut 28.56% and feed rate 20%. This was also explained by figure 6 and measured value and predicted values of surface roughness was nearly same (figure 7);

Fig. 6. Interval plot of surface roughness

Fig. 7. Comparative study for surface roughness

Signal to noise ratio has the greater significance in optimization process and it helps to identify control factors that reduce variability in a product or process by minimizing the effects of uncontrollable factors (noise factors). Noise factors cannot be controlled during production or product use, but can be controlled during experimentation. The signal-to-noise ratio measures how the response varies relative to the nominal or target value under different noise conditions. Depending on goal of experimentation, choice to choose Signal to Noise ratio is available.

Fig. 8. S/N ratio for MRR and surface roughness

In this work, the sole aim was to reduce surface roughness and to achieve maximum metal removing rate.

So, keeping all the constraints in minds and that of signal should be always maximum than that of noise, S/N ratio were taken as maximum the better. So it reveals the spindle speed of 2600 rpm, with feed rate of 600 mm/min and depth of cut 0.07 mm gives targeted responses.

C. Multiobjective Optimization

The main aim of this work is to achieve maximum metal removing rate and minimum surface roughness. Hence these are opposite responses so the multiobjective optimization needs to be carried out. In multiobjective optimization, the two opposite responses MRR and surface roughness have optimized simultaneously for optimal setting of process variables (figure 9).

It was found that feed rate has greater effect on metal removing rate since increase in feed rate drastically increases the metal removing rate. The optimization graph also suggests that feed rate should be moderate with the interface of depth of cut.

While increase in spindle speed increases the surface roughness. There is slight variation in feed rate, as it does not affect too much on surface roughness. This may be due to the adhesion and abrasion wear mechanisms of aluminum material. Since aluminum has the good ductility, it might have happened in this case that serrations of plastically deformed work piece were observed.

Fig. 9. Optimization graph for surface responses MRR and Surface roughness

IV. CONCLUSIONS

- This work was carried out in three stages, experimental work, modelling and multiobjective optimization. Use of taguchi method was found out to be very significant here, as 27 experiments were reduced to 9.
- It can be anticipated that spindle speed influences on surface roughness and that feed rate on metal removing rate too.
- Regression model was created through analysis and it was found that measured and predicted values of MRR and surface roughness were in agreement with each other.
- Signal to noise ratio reveals in the optimal settings of process variables in micromilling of Al 7075 material, as

spindle speed of 2600 rpm, feed rate of 600 mm/min and depth of cut 0.07 mm may help to achieve maximum MRR and minimum surface roughness.

- Predicted taguchi design was confirmed and it replicates in improvement of signal to noise ratio.
- Finally analysis of variance (ANOVA) suggests that feed rate contributes 65% of total process followed by spindle speed 18%, depth of cut 10% and rest are other parameters.

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REFERENCES

- [1] A. Marcon, S. Melkote, K. Kalaitzidou, D. Debra, "An experimental evaluation of graphite nano platelet based lubricant in micro-milling" *CIRP Annals – Manufacturing Technology*, vol.59, pp141–144, (2010).
- [2] V.S.Kathavate, P.R.Cheke, A.S.Adikine, "An Experimental Investigation of Micromilling" *Int. Jou. of Tech. Enhancements and Emerging Engineering Research*, vol.3, pp36–41, (2015).
- [3] Emel Kuram, Babur Ozcelik, "Multi-objective optimization using Taguchi based grey relational analysis for micro-milling of Al 7075 material with ball nose end mill", *Measurement*, vol.46, pp1849–1864, (2013).
- [4] Sinan Filiz, Caroline M. Conley., "An experimental investigation of micro-machinability of copper 101 using tungsten carbide micro-endmills" *International Journal of Machine Tools & Manufacture*, vol.47, pp1088–1100, (2007).
- [5] M.Y. Ali, A.S. Ong, "Fabricating micromilling tool using wire electro discharge grinding and focused ion beam sputtering", *The International Journal of Advanced Manufacturing Technology*, vol.31, pp501–508, (2006).
- [6] X. Cheng, Z. Wang, K. Nakamoto, K. Yamazaki, "A study on the micro tooling for micro/nano milling", *The International Journal of Advanced Manufacturing Technology*, vol.53, pp523–533, (2011).
- [7] H. Suzuki, T. Moriwaki, Y. Yamamoto, Y. Goto, "Precision cutting of a spherical ceramic molds with micro PCD milling tool", *CIRP Annals – Manufacturing Technology*, vol.56, pp131–134, (2007).
- [8] G. Bissacco, H.N. Hansen, L. De Chiffre, "Micromilling of hardened tool steel for mould making applications" *Journal of Materials Processing Technology*, vol.167, pp201–207, (2005).
- [9] C.R. Friedrich, "Near-cryogenic machining of polymethyl methacrylate for micromilling tool development", *Materials and Manufacturing Processes*, vol.15, pp667–678, (2000).
- [10] K. Nakamoto, K. Katahira, H. Ohmori, K. Yamazaki, T. Aoyama, "A study on the quality of micro-machined surfaces on tungsten carbide generated by PCD micro end-milling", *CIRP Annals – Manufacturing Technology*, vol.61 pp567–570, (2012).

[11] C.-J. Kim, J.R. Mayor, J. Ni, "A static model of chip formation in micro scale milling", *ASME Journal of Manufacturing Science and Engineering*, vol.126, pp710–718, (2004).

[12] M. Arif, M. Rahman, W.Y. San, "An experimental investigation into micro ball end-milling of silicon", *Journal of Manufacturing Processes*, vol.14, pp52–61, (2012).

[13] Rusnaldy, T. J. Ko, H. S. Kim, "An experimental study on micro cutting of silicon using a micromilling machine", *The International Journal of Advanced Manufacturing Technology*, vol.39, pp85–91, (2008).

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