Investigation of Micro Ball End Milling Process on SS 420 Using Vegetable Oils

A. G. Muke* and S. U. Sapkal

Mechanical Production Engineering, Department of Mechanical Engineering
Walchand College of Engineering, Sangli – 416 415, INDIA

Abstract

Micro machining on biocompatible material like Stainless Steel has created many challenges regarding its various uses in medical field. Also manufacturing using the petroleum based coolant has been the present concern considering health problems. Recently biodegradable vegetable oil are developed and applied in various micro machining processes which showed better results. In this paper, micro ball end milling is carried out on Hyper-15W micro machining center using environment friendly vegetable oils on Stainless Steel 420 grade. Four process variables such as coolant type (Jatropha and Soyabean oil), spindle speed (1400, 1800, and 2200) in rpm, feed rate (2, 4, and 6) in µm/s and depth of cut (20, 30, and 40) in µm are considered and accordingly L18 orthogonal array is used for experimentation with replications. Average top burr width and material removal rate (MRR) are measured as responses for the micro milled channels. ANOVA results showed that coolant type is the most significant one for top burr width and in case of Jatropha oil it is about 56 % less compared with Soyabean oil while for MRR, feed rate and depth of cut came out to be significant parameters and contributed about 67 % and 25 % respectively. Multi objective optimization of response variables is carried out using TOPSIS method. Jatropha oil as coolant, 1400 rpm spindle speed, 6 µm/s feed rate and 40 µm depth of cut were the optimum parameters for considered responses. These results are further analyzed and validated.

Keywords: Micro Ball End Milling, Vegetable Oil, Top Burr Width, MRR, Stainless Steel.

1. INTRODUCTION

Advanced manufacturing processes have bring out the revolution in the heterogeneity of the products. Moreover non-conventional machining has already gained its pace in producing precise components with less defects. However conventional micro machining processes (tool workpiece contact type) like turning, drilling, milling etc. are the basis of manufacturing small parts and holding their position in accordance with the changing global needs. Micro milling is one of such machining process versatile to produce complex 3D structures on different materials including metals, alloys, crystals, etc. for various industries like aerospace, medical etc. Biocompatible materials like titanium, zirconia, stainless steel etc. are being mainly focused because of its huge application [1, 2, 3]. Milling can be used for roughing as well as finishing purpose. During milling, a variety of operations such as end milling, face milling, chamfer milling etc. can be perform on the workpiece to yield the desired part shape.

Considering the productivity, material removal rate in conventional micro milling is also good when compared with non-conventional micro processes like EDM, ECM, Laser machining etc. [4, 5]. But this process also has some demerits like burr formation, tool wear, cutting forces. High cutting forces leads to faster wear of the tools which ultimately cost to the bad surface finish of machined surface. Also there are different types of burr associated with the positions in the micro milling process [3] but particular focus is on reduction of the top burr which can be seen clearly along the edges of micro channels and also spoils the surface texture.

These top burr later requires deburring process which eventually increases manufacturing cost. In micro end milling, burr dimension like width, length and thickness is observed on NiTi alloy under which the study showed that increasing feed per tooth and width of cut leads to small burr width and height. Downmilling strategy and increasing width of cut tends to reduce the burr thickness [4]. Kou at al. [6] used the support material deposition technique which prevented the plastic deformation to refrain the burr formation. Minimum depth of cut to avoid the plowing effect and burr formation mechanism is also discussed briefly. Bajpai et al. [7] performed high speed micro milling on Titanium alloy (Ti6Al4V) which showed that top burr behavior was not same as in conventional speed and also more number of flutes gave good surface finish by reducing the chip load on every flute. Researchers [8] performed micro milling experiments using 0.5 mm diameter tool on stainless steel X5CrNi18-10 and analyze that top burr height increases on increasing cutting speed, feed per tooth. Both flood and bath type lubrication are effective in reducing the burr height compared to minimum quantity lubrication method.

Coolants use are harmful to operator's health and are not disposable. Many studies shows vegetable based cutting fluid as the potential fluids with respect to this demerit. One study showed performance of vegetable oil like Kuram et al. [9] in view of comparing roughness, tool life using vegetable oils like sunflower, canola and semi-synthetic fluid showed that canola oil with 8% EP additive is good in terms of surface finish on AISI 304 stainless steel. Effect of different cutting fluids like coconut oil, emulsion and neat cutting oil is studied in turning operation [10] carried on AISI 304 SS. They observed that less surface roughness and tool wear is observed in viscous oil (coconut oil) due to effective removal of heat from cutting zone. Another work [11] is on CNC turning operation on high carbon chromium alloy steel to analyze the effect of cutting speed, feed rate and depth of cut under the coolant supply of Soyabean oil and petroleum oil. Soyabean helps in reducing tool wear and thus provides low Ra value.

2. EXPERIMENTAL WORK

Micro milling setup shown in fig.1 is used for the present investigation. Micro ball end mill carbide tool of diameter 500 µm coated with AlTiN coating is used for milling channels is held in the collet. Finished stainless steel 420 grade is used as workpiece material having thickness of 8 mm of size 60 mm by

*Author to whom correspondence should be made, Email: shun@acer.iitm.ernet.in

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40 mm and it is fix to the modular fixture using L clamps. Micro milling is carried out on Synergy Nano System HYPER 15W having stepper motor speed in the range of 300-3000 rpm. Mill length was 8mm for all experiments. Coolant type, spindle speed- s, feed rate - f and depth of cut- d are the controllable process variables used to perform L18 experiments is shown in table 1. Viscosity (in cST) of coolants was also measured at room temperature before experiments.

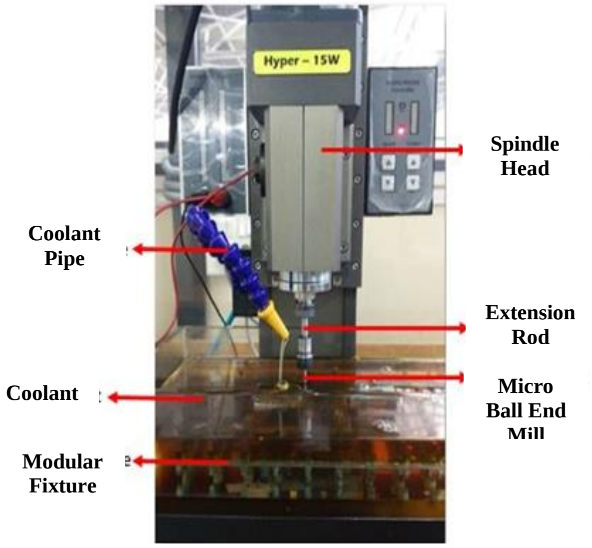

Fig. 1. Micro Milling Setup

Table 1
Process Parameters and their Levels

Parameters	Level 1	Level 2	Level 3
Coolant type	Jatropha oil	Soyabean oil	-
s (rpm)	1400	1800	2200
f (µm/s)	2	4	6
d (µm)	20	30	40

3. RESULTS AND DISCUSSION

3.1 Average Top Burr Width

Plowing effect is observed in this experimentation. Responses measured for L18 experiments are shown in table 3. Top burr width size in both upmilling and downmilling side is measured using the DINO Capture Camera and their average is taken as response variable shown in fig.2.

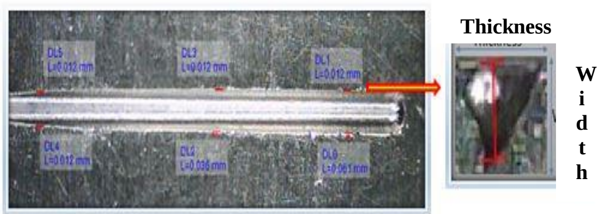

Fig. 2. Micro channel Burr Width Measurement

Feed rate and coolant type came out to be the most significant parameter using ANOVA shown in table 2. In this work, as shown in fig.3, on increasing feed rate by 100 % i.e. from 2 µm/s to 4 µm/s, burr width increases, while on increasing feed rate by 50 % from 4 µm/s to 6 µm/s and 200 % compared to 2 µm/s, burr width decreases as cutting edge able to cut the thick burrs developed during that feed rate [12]. Jatropha (45.50 cST) as a coolant shown better results i.e. 56 % average top burr width as compared to Soyabean (34.27 cST). High viscosity results into less friction which reduces plowing effect and stresses involved necessary to produce the burrs.

Table 2
ANOVA for Results

		Average Top Burr Width		Material Removal Rate	
Source	DOF	F-value	P-value	F-value	P-value
Coolant type	1	19.04	0.001	1.26	0.171
s (rpm)	2	1.05	0.385	0.23	0.868
f (µm/s)	2	6.51	0.015	50.91	0.000
d (µm)	2	3.15	0.087	19.05	0.000
Error	10				
		R-sq – 80.18 %		R-sq - 93.58 %	

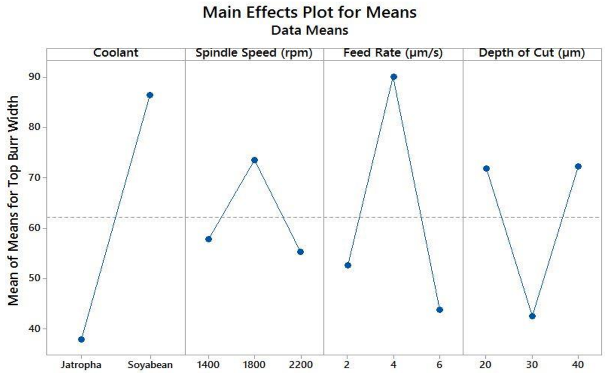

Fig. 3. Main Effect Plot for Average Top Burr Width

3.2 Material Removal Rate (MRR)

Ball milled micro slots is in the form of curvature milled along some length. Weight measurement requires clamping and de-clamping of workpiece which leads to alignment error. Hence to analyze material removal rate, volume of the slot is calculated using volume integral of partial sphere indented on the slot shown in fig.4. Here, assumption during calculation of MRR is that the actual material removal takes place along the measured length and width of the slot only.

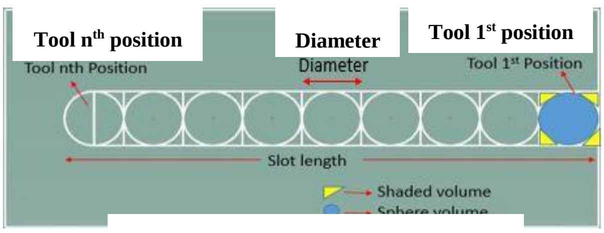

Fig. 4. Slot Volume Measurement

Volume of 1 sphere indented:

$(V_1) = \Pi*[integration\ (0\ to\ d)\ for\ (x*dx)]$ (1)

Total sphere indentation is calculated as:

$(Si) = (slot\ length\ /\ Measured\ tool\ diameter)$ (2)

Total sphere volume $(V_s) = V_1*Si$ (3)

Volume of square is calculated as:

$(V_2) = (Measured\ tool\ diameter)^2 * Depth\ of\ cut$ (4)

Four shaded portion volume (shown in yellow color)

$V_3 = V_2 - V_1$ (5)

Half of shaded portion volume $(V_4) = V_3 / 2$ (6)

Total slot volume of 1 micro milled channel:-

$V = V_s + V_3 * (Si - 1) + V4$ (7)

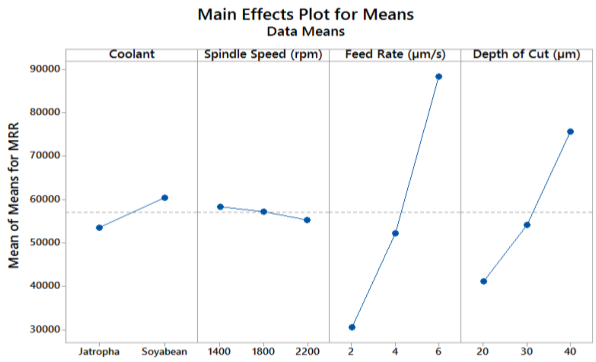

Fig. 5. Main Effect Plot for MRR

MRR is then calculated using equation (7). From ANOVA table 2, it can be analyzed that feed rate is most influencing parameter following the depth of cut for maximum material removal rate. As shown in fig. 5, on increasing feed rate, removal of workpiece increases which helps in more machined parts in less time. Also on increasing depth of cut, more material is available for cutting increasing its volume.

4. MULTI-OBJECTIVE OPTIMIZATION (TOPSIS)

4.1 TOPSIS Method

The TOPSIS of micro milling process is shown in table 3. The ranking to the experiments is given according to value of the closeness coefficient CC_i. First Rank one is given to that experiment having largest value of closeness coefficient. The experiment having smallest value of closeness coefficient is ranked as number eighteen [13, 14].

From this table it is concluded that the optimum parameter level for coolant, spindle speed, feed rate and depth of cut is level I i.e. Jatropha, level II i.e.1800 rpm, level III i.e. 6 (µm/s) and level III 40 (µm) respectively.

Table 3

Results – Average Top Burr Width, MRR and TOPSIS Rank

Exp No.	Coolant type	s	f	d	Top burr (µm)	MRR (µm^3/s)	CC_i	TOPSIS Rank
1	1	1	1	1	43.83	21886.11	0.55	13
2	1	1	2	2	20.66	38294.57	0.64	7
3	1	1	3	3	44.49	102605.67	0.85	2
4	1	2	1	1	53.66	17088.24	0.52	14
5	1	2	2	2	39.83	38357.41	0.61	9
6	1	2	3	3	20.00	105239.47	0.93	1
7	1	3	1	2	24.16	25391.66	0.60	10
8	1	3	2	3	67.33	76915.97	0.67	6
9	1	3	3	1	28.16	56553.14	0.70	5
10	2	1	1	3	61.66	43072.59	0.57	12
11	2	1	2	1	124.99	38588.22	0.31	17
12	2	1	3	2	51.66	105862.23	0.83	3
13	2	2	1	2	73.50	29740.04	0.49	15
14	2	2	2	3	180.66	80703.22	0.30	18
15	2	2	3	1	73.66	72570.48	0.63	8
16	2	3	1	3	59.66	45817.22	0.58	11
17	2	3	2	1	107.33	40269.84	0.39	16
18	2	3	3	2	45.33	87264.83	0.79	4

Table 4 is obtained by performing ANOVA of TOPSIS responses i.e. closeness coefficient. Feed rate, coolant type and depth of cut came out to be the most significant parameters with p value less than 0.05.

Table 4

ANOVA for TOPSIS Responses

Source	DOF	Adj-SS	Adj-MS	F-value	P-value
Coolant type	1	0.760	0.076	15.50	0.003
s (rpm)	2	0.008	0.004	0.90	0.439
f (µm/s)	2	0.290	0.145	29.61	0.000
d (µm)	2	0.076	0.038	7.84	0.009
Error	10	0.049	0.004		
		R-sq – 90.21 %		R-sq (adj) - 83.36 %	

4.2 Validation of Results

For validation purpose, confirmatory test is carried out on optimized experimental parameters. In this case, optimum parameter setting, i.e. coolant, spindle speed, feed rate and depth of cut is Jatropha, 1400 rpm, 6 µm/s and 40 µm respectively. These values are calculated by taking means of the different level with the corresponding process parameter.

Table 5

Confirmatory Test Results

Responses	Initial setting of parameters (coolant = Jatropha, s= 1800rpm, f=6 µm/s, d=40 µm)	Optimum parameter (coolant = Jatropha, s= 1400rpm, f=6 µm/s, d=40 µm)	
		Predicted	Experimental
Avg Top Burr Width	20		17.66
MRR	105239.47		107195.48
Closeness Coefficient	0.93291	0.9211	0.94299

Table 5.4 shows the confirmatory test results. Experiment number 6 which is having highest rank is selected as initial

setting parameter with coolant as Jatropha oil, spindle speed as 1800, feed rate as 6 µm/s and depth of cut as 40 µm. Closeness coefficient for optimum parameter setting is also calculated. Improvement in the closeness coefficient obtained by taking difference between closeness coefficient of initial and optimal setting parameters. Results shows that the improvement in the closeness coefficient for the micro ball end milling process on stainless steel 420 grade is 0.01008.

5. CONCLUSIONS

The analysis of experimental results indicate that feed rate has the most significant influence on burr width, material removal rate and surface roughness during micro ball end milling on stainless steel 420. Stainless steel has top burr which are hard to remove and reduce friction suppresses the deformation involved for its formation. Upmilling has least burr width size than downmilling hence can be used for making finished micro channels. Jatropha has 56 % less top burr width size compared with Soyabean because of reduced friction due to viscous nature. As depth of cut and feed rate increases more material is removed increasing productivity. Validation from optimum condition of TOPSIS showed 0.01008 as improvement in the closeness coefficient.

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