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Experimental Evaluation of Machinability of Monel 400 Alloy During High Speed Micro Milling Using Various Tool Coatings

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ABSTRACT

Quality of finished miniature products is characterized by surface roughness as well as burr formation after manufacturing processes. It gains more significance when it is gauged in terms of high precision and dimensional accuracy of final micro parts. The requirement of complex features in 3D micro parts also figures out its significance. Similarly, tool wear is an important indicator of production efficiency and quality related to finished parts. In the current research, the impact of key input parameters like depth of cut, feed rate, cutting speed and various tool coatings (TiAlN, TiSiN, nACo, including an uncoated tool) were statistically analyzed while carrying out micro-milling of Monel 400 super alloy. Surface roughness along with burr formation and tool wear were considered as response parameters due to their significant nature. Machining experiments were performed up to 80,000 rpm (high-speed range). Feed rate values were selected in comparison with cutting tool edge radius. The selected values of feed rate were taken into consideration at moderate and high-speed ranges while selecting the values equal to below and above the values of cutting-edge radius. Digital microscopy and scanning electron microscope (SEM) were utilized for analysis in addition to statistical techniques for response parameters. Methodology utilizes Taguchi's Experimental design. L16 orthogonal array was formulated to carry out micro milling experiments on Monel 400 specimen, having dimensions 20×30×40 mm. Contribution ratio (CR) of individual input parameter was calculated through Analysis of Variance (ANOVA). The outcome of experimental work indicated that feed rate was the most significant factor for surface roughness with CR 27.86%. It also became most significant factor for top burr width in both categories (Up-milling & down-milling) with CR 56.56% and 56.60% respectively. Moreover, it was also most significant factor for top burr height in both categories (Up-milling and down-milling) with CR 23.84% and CR 28.47% respectively. Whereas in case of tool wear, the depth of cut and tool coatings were significant factors with CR 19.46% and 28.47% respectively. The findings in this work highlighted the importance of selection of suitable cutting conditions with appropriate tool coatings in micro-machining in enhancing productivity, quality and cost effect. In addition, the significance of burr height parameter, mainly unexplored till now, has also been underlined.

Keywords: micro millin, Monel 400 alloy, manufacturing processes, Taguchi design of experiments, process design, sustainability, green manufacturing, precision machining.

INTRODUCTION

Demand for high dimensional accuracy of miniaturized finished parts has been on the rise during the last decade [1, 2]. The Demand for high dimensional accuracy of miniaturized finished parts has been on the rise during the last decade [1]. The industries like aerospace chemical, automotive, biomedical, communication, and microelectronics require a variety of micro parts such as connectors, switches, medical implants, micro pumps, printing heads, diagnostic devices etc [2]. Manufacturing these micro parts with correct micro tooling requires more reliable and precise methods. Thus micro machining provides the opportunity of producing these parts in mass production with the required accuracy [3]. Multiple micro fabrication processes like ION beam, photolithography, and micro electro-discharge machining methods are also used for production of micro components. However, such processes have limitations like low productivity and high-cost effect [4]. These fabrication processes provide precise geometrical features within allowable tolerances but at the cost of time consumption and expensive set-up [5].

Mechanical micro-machining presents different processes including milling, turning and drilling which can directly produce micro components/ 3D functional parts [6]. Among these processes, micro-milling processes give the cost-efficient production of micro components with 3D geometry. It can also achieve improved surface roughness, required accuracy and high Material Removal Rate (MMR) [7]. There are certain key issues related to micro milling which include the cutting tool size (diameter 25 µm), [8] tool vibrations, its runout and tool breakage [9]. The sizes of the micro cutting tool edge radius and un-cut chip thickness are almost comparable [10]. Therefore, the ploughing effect dominates the material deformation mechanism surface quality is inadequate [11]. De-burring in micro-sized features is extremely difficult and adds to the final cost of the finished products [12]. Multiple industries focus micro-milling of super alloys due to their increased demand in market as investigated by many researchers in open literature. This shows the contribution of advancements in the micro-milling domain which can achieve the required dimensional accuracy while producing the micro-components of nickel-based super alloys as per-required design [13]. Figure 1 shows the family of Nickel based alloys including Monel 400 which is being used in many industries. It becomes focus for industry because of possession of properties like lightweight, ability to retain properties at high-temperature and high corrosion resistance [14]. Monel 400 being super alloy is hard to cut material with low thermal conductivity, high hardness and low elastic modulus [15]. It has the tendency to strain hardening formation which results in a large amount of heat generation at the process zone (cutting zone). It also results in the increase of thermal stresses at the micro tool thus causing rapid tool wear [16]. Nikel based alloy (Inconel 625) is a hard to cut alloy which causes rapid tool wear [17]. Inconel 718 is also among alloys being widely used in aerospace and aviation industry, poses serious machining challenges due to its property of hard to machine material, causing rapid cutting tool wear [18]. Titanium super alloys are also widely used in aerospace sector and causes challenges to machining due to low thermal conductivity. As it has been reported in earlier research, dealing with milling technology of titanium alloys, the cutting conditions play an important role on tool wear and cutting forces [19].

Many researchers focused machinability of Monel 400 in both domains (macro and micro) due to its hard to cut status. Recent past has

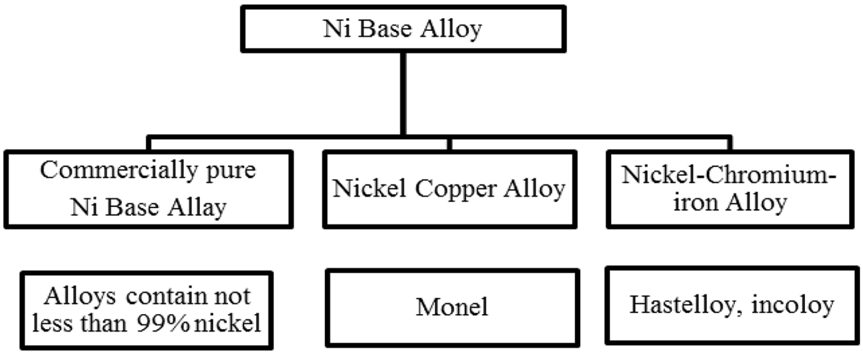


Figure 1. Nickel-based alloy classification

observed an elevated interest in research related to eco-friendly manufacture, energy conservation and the application of renewable energy technologies. It has been realized in various industries that technologies need to be in line with workers and environment safety protocols. These are necessary to avoid health issues including skin cancer and respiratory disorders which have been a point of great concern for many years. Moreover, the adverse effect on atmosphere results in collateral damage including imbalance of weather patterns, extinction of certain life forms and worldwide food insecurity. Many assistive processes have been used in past for improving machinability of difficult to machine super alloys using flame heating, different types of cooling agents, preheating of workpieces to soften these super alloys using laser-assisted machining for easy material removing from these metals [20]. Irfan et al. investigated the micro-machining of superalloy at moderate speed (48m/min). The work also analyzed surface roughness and effects of various tool coatings on tool wear. It was concluded that Diamond like coating (DLC)and TiAlN + WC/C coating gave good results against tool wear and Build up Edge formation. DLC coated tools produced minimum surface roughness in comparison to TiAlN + WC/C coated tools [21]. Aslantas et al. carried out study on quality of micro milling of Ti6Al4V (super alloy) while using multiple tool coating for micro machining processes and he also investigated their effects on tool wear. His results showed that main cause for reduction in machining quality was tool wear, which increases the cutting forces [22]. Ozel et al. carried out the comparison of coated (cBN) and uncoated tool performance during the micro-milling of Ti 6Al4V. He showed that cBN coated tool produced a good quality surface finish after micro-milling on Ti alloy [23]. Aramcharoen et al. carried out the analysis of different tool coatings during the micro-milling of hardened steel. He concluded that TiN coated tool showed higher wear resistance for edge chipping and flank wear [24]. Abd Rahman et al. studied the dry machining and economical machining technique MQL (Minimum Quantity Lubrication) of Super alloys. His investigation concluded that this technique produced good results compared to dry machining. The investigation by Muhammad et al. shows that tool life improves due to heat removal processes for super alloys. So, wet machining was preferred over dry machining processes [25].

Jaffery et al. investigated superalloys for micro milling and commented on delicacy of micro tools which are prone to nosie factors as well. Tool wear in the micro-milling domain remains unpredictable due to more residual effects. Burr formation is a significant problem in micro machining domain whereas its bigger size in macro domain does not cause serious problem. As deburring in micro domain is difficult task so its removal in the micro-domain may damage the micro features of miniaturized parts during the de-burring process [26]. It is preferred to have fewer burr formations during the micro-milling process by effectively / properly employment of different cutting condition [27]. Dornfeld et al. investigated the micro and conventional machining processes and found that size of burr size is larger in conventional machining as compared to micro milling. It is because of more material deformation at low cutting speed [28]. Atif et.al. investigated the micro machinability of super alloys for tool wear and burr formation. Maximum burr width size was achieved after use of TiSiN coated tool. Literature also highlights the significance of cutting conditions on output responses including tool wear and cutting forces [29].

Tool wear in micro domain is an important aspect which remained part of many past studies. As the cutting tool edge radius increases the tool wear rate also increases, which in turn lowers quality of final product [30]. Frictional forces at lager depth of cut results in more wear and greater tool edge radius. Tansel et al. estimated tool wear rate with help of cutting forces data and tool wear data during the micro-machining of Aluminum and steel 65. He showed that tool wear was more in case of steel machining compared to Al machining [31]. Wenle et al. concluded from their study that machined material greatly affects the tool wear [32]. So different researchers reported that multiple tool coating increase tool life during the micro-machining of Super alloys. Zhang et al. reported that with increase in milling speed the temperature of work pieces also increases [33]. Surface finish can be improved by using tool coatings having low coefficient of frictions [34]. Another important factor is the surface quality of finished products during the micro-milling processes. Aldo Attanasio studied the machining quality, formation of burr, cutting forces and tool, while focusing on the material microstructure [35]. Z Sun et al. focused on surface quality with input matching parameters like spindle speed, feed rate, depth of cut, tool wear. Aurich et al. studied the burr formation and surface roughness during micro-machining with a conclusion that tilt angle of spindle speed improved the surface quality of the finished product [36]. Jinxuan Bai et al. studied the behavior of input parameters during ductile micro-machining and concluded that brittle fracture is due to vibration thrust force. Moreover, smooth thrust force helps in achieving a smooth ductile cutting [37].

From the literature review, many researchers focused on the surface quality of finished Super alloys in macro domain but only a handful of studies are available in micro domain at high speed and transition speed ranges. In the current work, Monel 400 has been selected due to its industrial importance worldwide. It has proved to be an attractive choice of various modern industries including aerospace, oil and gas sector in addition to certain other applications under corrosive, acidic and alkaline environments. It has also widely used in marine applications owing to its superior properties. Nevertheless, limited work has been reported on Monel 400 alloy and that too under a narrow band of machining inputs and response parameters. Specifically, no work has been reported on burr height in micro machining of Monel 400 alloys, on up and down side of micro milling operations. Monel 400 being a super alloy present a good choice for researchers because of its ability to retain its properties in extreme conditions. Therefore, there was a requirement to carry out research in micro domain with variety of key input parameters by selecting the values of feed rate in range above and below the values of cutting-edge radius. Past researchers focused on tool life, their compatibility with different materials and effects of cutting parameters on surface quality at low-speed machining. To cover this research gap, multiple tool coatings at moderate and high-speed micro-milling have also been incorporated in addition to the feed rate value in below and above the cutting tool edge radius. Surface integrity has been analyzed with response parameters like burr formation (up and down milling side), surface roughness and tool wear. This unique combination of key process parameters gives opportunity for identification of better combination to achieve the best quality of finished miniature product.

MATERIALS AND METHODS

Monel 400 workpiece material having dimensions (20×30×40 mm) was used in this study. This material, being nickel-copper based super alloy, was selected due to its peculiar properties like greater strength, high hardness, excellent resistance to corrosion and ability to retain its characteristics at extreme temperatures. Light weight Monel 400 is hard to machine material which has low thermal conductivity. Table 1 shows the comparison of mechanical properties of some common super alloys. Chemical composition of work piece material has been displayed in Table 2.

Experimental set-up

Figure 2 shows the experimental arrangement for micro milling operation on CNC machine (Yida MV-1060). Motion controller FANUC-Oi-Mc

Table 1. Super-alloys with comparison of mechanical properties [39, 40]

Super alloys	Monel 400	Inconel 600	Inconel 718
Hardness (HB)	110–150	330	390
Tensile strength (MPa)	512–620	1050	1600
Elastic modulus (GPa)	179	205	205
Density (gcm^{-3})	8.8	8.4	8.2
% Elongation	48	25–30	15
Thermal conductivity (W m^{-1} K^{-1})	21.8	10	11.4
Specific heat (J kg^{-1} K^{-1})	427	410	432
Poisson’s ratio	0.32	0.31	0.28

Table 2. Chemical composition – Monel 400

Ni	Cu	Mn	Fe	Si	C	S
67%	27.67	2	2.5	0.5	0.3	0.024

Figure 2. The experimental setup – workpiece, micro end mill and spindle whereas the magnified view shows interaction between the workpiece and micro tool

was used to control relative motion between micro-tool and workpiece. Table 3 summarizes the experimental conditions of the tests.

The reference between micro tools and workpiece surface was catered for by utilizing Tool pre-setter (BMD Messwell 410 V). Digital microscope Olympus DSX1000 and Scanning Electron Microscope (SEM – JEOL JSM-6490A-3 nm resolution at 30 kV) were used to analyse the finished surface of Monel 400 alloy. Olympus DSX1000 has accuracy up to 0.5 micron and magnification up to 9637X whereas Micro hardness tester of Wolpert Group 401MVD has total magnification of 100× and 400×. It has eight dial-selectable test forces ranging from 10g to 1000 g, equipped with a 100×100 mm precision XY stage with 25 mm movement in each direction. With the help of Micro hardness tester of WOLPERT GROUP (401MVD-) Vickers hardness of Monel 400 alloy was calculated. Multiple tests were performed on five different locations of the workpiece in order to ensure accuracy. 9800 mN force along with 10 s Dwell time was used during these tests. 225.16 HV came out as average value of micro-hardness.

Table 3. Summary of experimental conditions

Material-workpiece	Monel 400
Machining process conditions	Dry without coolant
Milling type	Full immersion
Diameter of micro-tool (mm)	0.5
Micro-tool with number of flutes	2
Length of cut (mm)	20

Specifications – micro cutting tools

The use of Carbide milling tool, with diameter of 12 mm, was ensured for levelling the work piece surface for subsequent reference in experiments. Micro-cutting tools, with diameter of 500 μm, were used for micro milling processes. These tools, made of tungsten carbide specifically S10–S25 grade (ISO standard carbide grade – S tools), are recommended by the tool manufacturer for super alloys. These ultra-fine micro tools had two flutes with helix angle 35 degree were used for cutting slots. Tool edge radius of coated and uncoated tools were also calculated. The cutting tool edge radii for uncoated micro tool, TiAlN, TiSiN and nACo micro coated tools were measured to be

Figure 3. Multiple coated micro tools

Table 4. Specifications of micro-cutting tools

Characteristics	Specification
Tool type	End mill
Micro-tool material	Tungsten carbide (S10-S25 grade)
Tool brand	North carbide tools
Diameter (mm) of micro-tool	0.5
Number of flutes	2
Rockwell hardness (HRC)	60
Overall length (mm)	50
Cobalt content (%)	12
Micro-tool blade length (mm)	1
Helix angle (“)	35

2.11 µm, 2.51 µm, 2.85 µm and 2.90 µm respectively. Fresh micro tool for each experiment was used during the experimentation phase. Pictures of these tools have been shown in Figure 3. Table 4 gives specifications of micro-tools whereas Table 5 shows the specifications of coating of micro-tools.

Experimental design

In current study, Taguchi’s Design of the experiment [41] was used as it provides the opportunity to have a lesser number of experiments over full factorial without compromising on overall efficiency. Various past researchers have employed this methodology because of its robustness and precise results [42, 43]. Four process parameters were investigated in this study. These include Feed rate, depth of cut, cutting speed and multiple mcro tool coatings (including one uncoated and 3 x coated tools). Table 6 present detail of process parameters including their levels. L16 orthogonal array was formulated which has been tabulated in Table 7. Value of Feed rate (F) was selected in comparison with micro tools cutting edge radii. Therefore, its range varies from 0.5 to 4 µm/tooth which is below and above the cutting-edge radii of uncoated and coated micro-tools. The range of cutting speed values (50 to 125 m/min) is based on data from literature as various researchers utilized speed variation between 16 m/min to 141 m/min [44, 45] so cutting speed (Vc) was picked up with in this range from 50 m/min (32 k RPM) to 125 m/min (80 k RPM). Four levels of tool coatings, un-coated, TiAlN, TiSiN and nACo were used for carrying out experiments on micro-milling of Monel 400. Depth of cut (ap) was selected between 35–125 µm, basing on values already mentioned in literature in past. The diameter of the micro tool used was 0.5 mm. Keeping in view, Niagara Cutter (Cutter 2018): for a cutting tool having a diameter 3.18 mm and below, the minimum and maximum values of depth of cut can be calculated by following formula:

- cutting depth (ap) = Diameter of tool × (0.25 to 0.05),
- minimum ap = 0.5 × 0.05 = 0.025 mm = 25 µm,
- maximum ap = 0.5 × 0.25 = 0.125 mm = 125 µm.

Responses

Keeping in view the direction of feed and tool rotation, two categories of milling cases have been considered during the experimental phase. i.e., up milling and down milling category. Response parameters include tool wear, surface roughness, and burr width and height in both categories of micro milling operations. To ensure

Table 5. Coating specifications of micro tools as provided by supplier

Detail	TiSiN	nACo	TiAlN	Uncoated tool
Thickness of coating (microns)	3	3	2.5-3	-
Hardness (HV)	3600	4500	3200	1500
Frictional coefficient	0.45	0.4	0.38	0.37
Oxidation temp (°C)	1000°	1200°	900°	700
Coating color	Golden	Blue	Black	Grey

Table 6. Detail of key process parameters including their levels

Parameters	Units	Level 1	Level 2	Level 3	Level 4
Tool coatings (Tc)	-	Uncoated	TiAlN	TiSiN	nACo
Depth of cut (ap)	µm	35	65	95	125
Feed rate (F)	µm/tooth	0.5	1	2	4
Cutting speed (Vc)	m/min	50	75	100	125

Table 7. Input and response parameters based on L16 orthogonal array

Process parameters						Response parameters				
Test	Cutting speed (Vc) µm	Feed (F) µm/ tooth	DoC (ap) µm	Tool coatings (Tc)	Surface roughness (Ra) µm	Burr width up milling-µm	Burr height up milling-µm	Burr width down milling-µm	Burr height down milling- µm	Tool wear-µm
1	50	0.5	35	Uncoated	0.0015	102.575	9.8525	317.8235	31.988	8.793
2	50	1	65	TiAlN	0.001	55.017	7.5655	103.858	5.98	6.135
3	50	2	95	TiSiN	0.002	53.3665	6.5725	85.938	15.975	10.4465
4	50	4	125	nACo	0.002	27.636	2.944	27.8	11.7035	7.1095
5	75	0.5	65	TiSiN	0.002	66.3035	37.943	261.413	97.081	7.5095
6	75	1	35	nACo	0.0015	60.896	7.712	113.083	19.9415	14.4225
7	75	2	125	uncoated	0.003	24.2695	9.2485	25.517	12.254	6.464
8	75	4	95	TiAlN	0.002	52.618	18.014	115.9895	29.526	26.9685
9	100	0.5	95	nACo	0.0025	74.3815	25.887	255.0205	30.1975	9.4685
10	100	1	125	TiSiN	0.002	125.2415	94.108	247.31	136.921	27.0115
11	100	2	35	TiAlN	0.002	36.5625	7.168	50.539	15.0535	6.753
12	100	4	65	uncoated	0.001	15.6785	3.4965	20.643	6.255	11.4795
13	125	0.5	125	TiAlN	0.0015	47.4405	8.573	79.8595	14.079	22.623
14	125	1	95	uncoated	0.0015	117.2225	27.6155	157.317	81.387	8.3295
15	125	2	65	nACo	0.002	44.655	11.602	123.665	22.256	6.2345
16	125	4	35	TiSiN	0.00035	21.014	5.3295	66.1645	6.5725	11.686

accuracy average results have been recorded in Table 7 after calculating multiple readings.

Measurement of burr formation

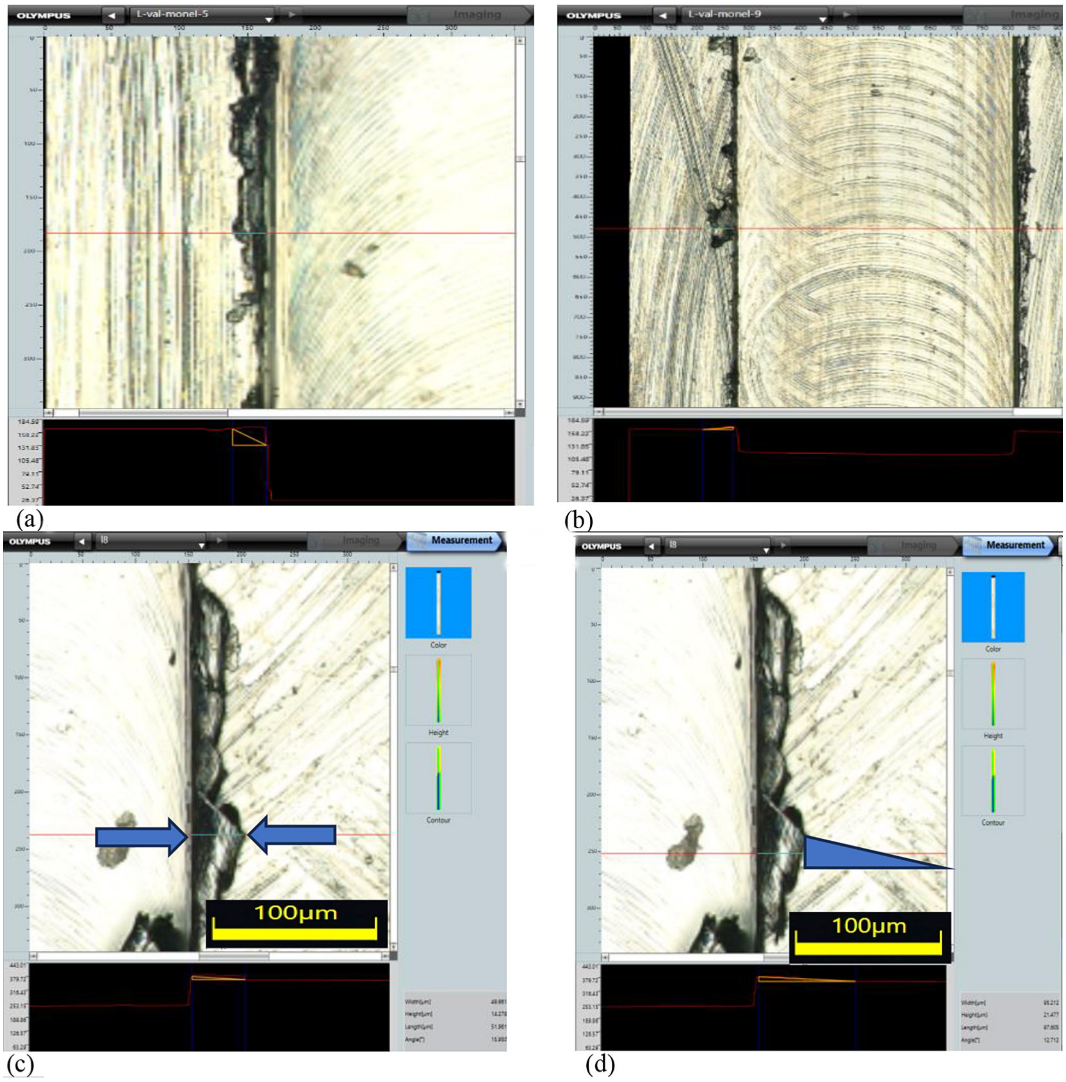
Burrs are formed at various locations which include entrance burr, exit burr and top burr. During this study, top burr width and height in both milling categories were calculated with the help of Olympus DSX 1000 digital microscope and Scanning Electron Microscope at various magnification levels as shown in Figure 4a and 4b. During the analysis phase the maximum burr width and maximum burr height for each micro milling slot were recorded. Maximum top burr width on up milling side and down milling side were measured as depicted in Figure 4c and 4d. Figure 5 shows both sides of micro milling cases. One side of anti-clockwise rotating tool (in relatio to feed direction) is up milling side whereas the other side is down milling side. Figure 5b shows the machining marks and burr formation along the finished surface. Magnified uneven grey protrusions are the burr formation which have been produced during micro milling process, whereas the machining marks (on finished surface between burr protrusions) are present on finished surface, hence these machining marks can be neglected.

Surface roughness

Surface roughness is a key contributing factor towards quality of finished product therefore it was given due consideration. Its values were calculated using scanning electron microscope (SEM - JEOL JSM-6490A) and digital microscope (Olympus DSX 1000) at various locations of micro milled slots as shown in Figure 6. Readings taken at multiple locations of milled surface was then averaged for measuring average surface roughness to ensure accuracy.

Tool wear

Quality and dimensional accuracy is significantly influenced by progressive tool wear especially in the case of finished miniature products [47]. Optical microscopy using Olympus DSX 1000, and SEM were used in measuring tool flank wear as shown in Figure 7. Tool wear was measured twice and the average was used to eliminate variation and ensure accuracy. Analysis of tool wear also incorporated ANOVA (Analysis of Variance) technique. Magnified imagery of tool wear before and after experimentation phase helped in analyzing the wear progression and wear measurement.



(a) (b) (c) (d)

Figure 4. Burr measurement: (a) top burr width measurement; (b) top burr height measurement; (c) top burr widmeasurement; (d) top burr height measurement

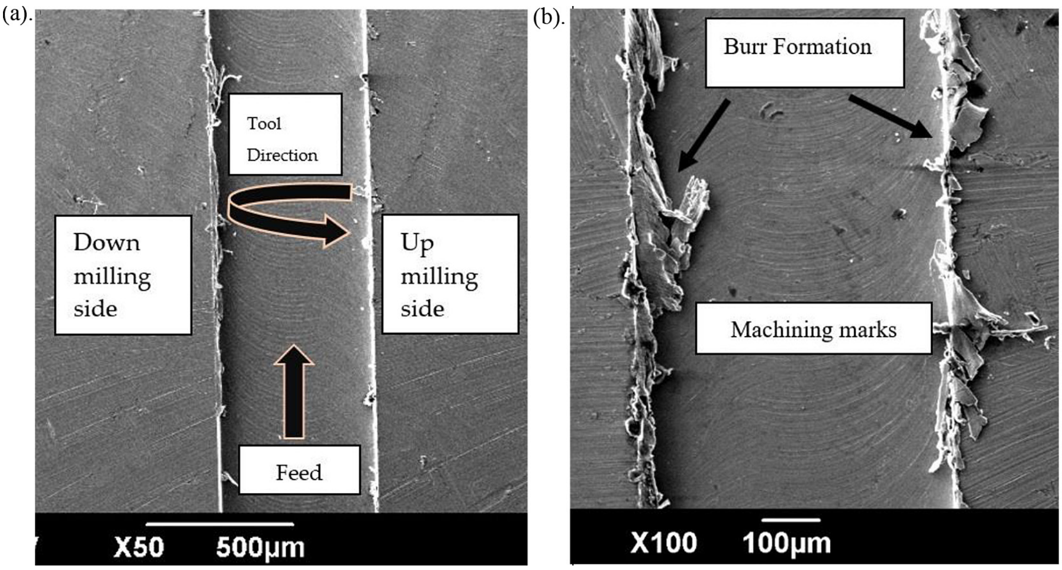
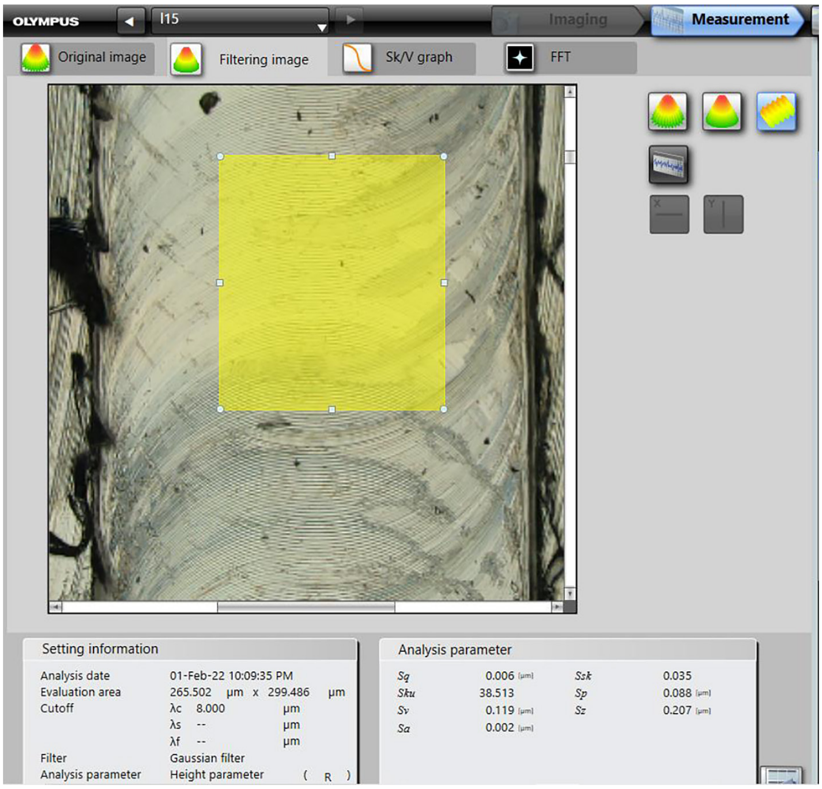


Figure 5. (a) Categories - down milling and up milling; (b) magnified burr formation and machining marks on finished surface



Setting information

Analysis date	01-Feb-22 10:09:35 PM
Evaluation area	265.502 µm x 299.486 µm
Cutoff	λc 8.000 µm
	λs -- µm
	λf -- µm
Filter	Gaussian filter
Analysis parameter	Height parameter (R)

Analysis parameter

Sq	0.006 (µm)	*Ssk*	0.035
Sku	38.513	*Sp*	0.088 (µm)
Sv	0.119 (µm)	*Sz*	0.207 (µm)
Sa	0.002 (µm)		

Figure 6. Surface roughness measurement

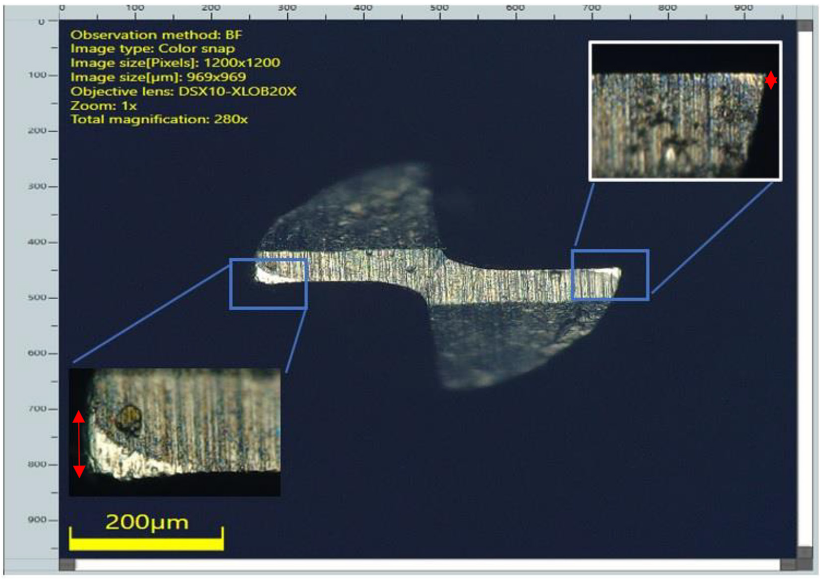

Observation method: BF
Image type: Color snap
Image size[Pixels]: 1200x1200
Image size[µm]: 969x969
Objective lens: DSX10-XLOB20X
Zoom: 1x
Total magnification: 280x

Figure 7. Tool flank wear as marked by red arrow

RESULTS AND DISCUSSIONS

The experimental results of response parameters and values of key process parameters have been presented in Table 7. Each experiment was repeated twice in order to cater for various factors at micro milling level as at micro level there are certain issues which need to be catered for better results. Normally the variation in different runs of experiments are due to variations in tool quality, human error and machine noises etc. Jaffery et. al also highlighted in his research that at micro level the residual effects are much significant. Therefore, even small errors including noises contributes much towards the values of output parameters.

To cater for accuracy, average values of responses were considered after repetition of all experiments. After plotting of results Analysis of Variance (ANOVA) was also carried out and mentioned in subsequent paras.

Application of ANOVA

After getting the results of measured responses using Olympus DSX1000 digital microscope, ANOVA was performed for determining of the significance of each factor on various response parameters. Therefore, various tables in subsequent paras show the significance of each response parameter. Analysis of variance (ANOVA) utilizes various equations for computing significance of each parameter [42]. Equation 1 computes SSA (Sequence of sum of squares) for individual parameter, where A is a process parameter involved, n is total number of runs at a specific level whereas *i* shows *ith* level. Moreover, N is total number of runs and T is the response value at each run. Total sum of squares is calculated by equation 2. Equation 3 computes SSe (Sequential sum of square of error) whereas Equation 4 calculates the %CR (percentage contribution ratio of each parameter).

$$SS_A = \sum_{i=1}^{3} \frac{A_i^2}{n} - \frac{(\sum_{j=1}^{N} T_j)^2}{N} \qquad (1)$$

$$SS_T = \sum_{j=1}^{N} T_j^2 - \frac{(\sum_{j=1}^{N} T_j)^2}{N} \qquad (2)$$

$$SS_e = SS_T - \sum_{i=A}^{Z} SS_i \qquad (3)$$

$$\%CR = \frac{SS - (df \; X \; MSS_{Res})}{SS_T} \times 100 \qquad (4)$$

Parameter with lower F-ratio value shows its low impact on the response parameter and vice versa. P –value is the probability value which indicate about failure of a test. If its value is less than 0.05 it means that there are only 5% chances that a test would fail. Or it can be interpreted like test would succeed with 95% confidence level. Table 8 to 13 records the analysis of variance of all six response parameters which include surface roughness micro tool wear and burr width and height in both micro milling (up and downside) categories.

Surface roughness

The critical quality characteristic of miniature finished product is its surface finish, as in literature, large area of research focuses on the effect of key process parameters on surface roughness. Parameters like depth of cut, cutting speed, feed rate and various tool coatings have been considered in this research to analyse their effects on surface roughness. In the present work surface roughness has been measured as explained in Section 2.6 and tabulated in Table 7. The effects of these set of process parameters have been shown in Figure 8, which presents the result of plotted values.

From Figure 8, multiple coated micro tools have nonlinear effects on surface roughness. Moreover, TiSiN coated tool achieved the minimum value of surface roughness during micro milling operation on Monel 400 alloy. It is because of the fact that TiSiN coated tool has the highest value of frictional coefficient compared to the other coated micro tools used. It resulted in an increase in temperature in the cutting zone which helped the material for easy removal from the workpiece. The increase in temperature coupled with high speed and feed rate TiSiN coated micro tool produced the best outcome for surface roughness. The next micro tool with a comparable value of the coefficient of friction was TiAlN which produced the next best value for surface roughness. The highest value for surface roughness was produced by nACo-coated tools which has the highest value of hardness compared to the rest of the tools. Comparable results for micro tool coatings have also been reported in previous literature. Figure 8 indicates the direct relation between surface roughness and depth of cut. As value of depth of cut increases from 35 to 125

Table 8. Surface roughness – analysis of variance

Source	Seq SS	Adj SS	DF	Adj MS	F-Value	P-Value	Significance	Contribution
Vc (m/min)	0.000003	0.000003	3	0.000001	5.30	0.008	Significant	19.12%
Feed (μm/tooth)	0.000004	0.000004	3	0.000001	7.73	0.001	Significant	27.86%
DOC (μm)	0.000003	0.000003	3	0.000001	6.76	0.003	Significant	24.36%
Tool coatings	0.000001	0.000001	3	0.000000	1.62	0.219	Non-Significant	5.83%
Res	0.000003	0.000003	19	0.000000				22.83%
Total	0.000014		31					100.00%

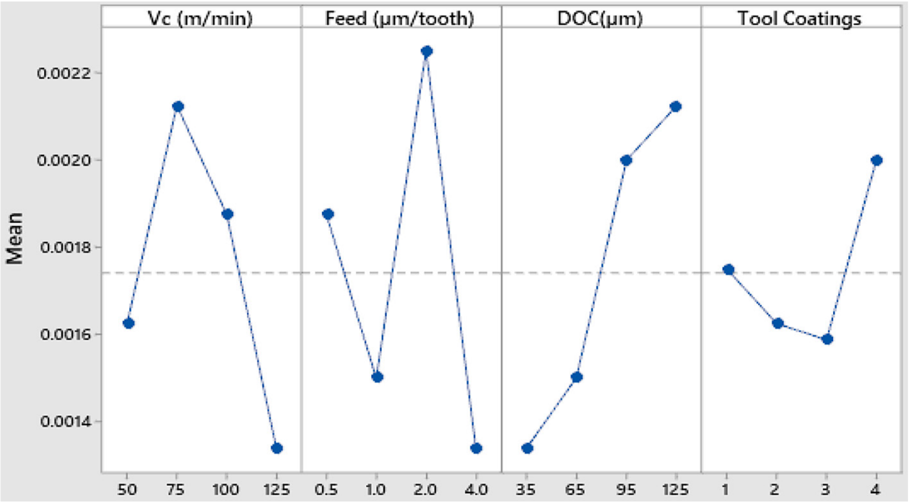


Figure 8. Surface roughness – main effects plot for Monel 400 alloy

µm, the value of surface roughness also rises affecting the quality of finished surface. There might be certain reasons for this phenomenon. For example, cutting forces at micro level in addition to the tool vibration play their role towards increasing values of surface roughness.

Another conclusion that can be drawn from this research work is feed rate has a unique impact on surface roughness value. The value of feed rate was selected in relation to the cutting tool edge radius to analyses its effect on the finish surface. When value of feed rate is selected just above the value of cutting tool edge radius it results in achieving the best value of surface finish. It also clarifies the sensitivity of the relationship between micro cutting tool edge radius and the feed rate in achieving a better quality of the finished surface. The undeformed chip thickness contributes towards the variations in surface roughness values. This is because undeformed chip thickness directly affects the micro cutting tool edge radius which is a consideration in selecting the feed rate values. The analysis shows that operating at feed rate value below the cutting tool edge radius do not provide significant advantage over the operations performed at feed rate value above the cutting tool edge radius. Main effects plot from Figure 8 indicate that lowest value of surface roughness is achieved when we operated at feed rate value above the values cutting tool edge radius. Moderate and high cutting speeds were remained focus during the experimentation phase to avoid Build Up Edges (BUP) which are normally occurs during low-speed micro milling. When welded chips are removed from finished surfaces these contribute towards the higher values of surface roughness. The welded chips are out come of BUP during low-speed operations. Deterioration to the finished surface can be minimized by operating at moderate and high-speed ranges in micro milling.

ANOVA for surface roughness has been carried out and displayed at Table 8. It figured out feed rate as the most significant factor having contribution ratio 27.36%. The values of cutting-edge radii vary between 2.11 µm to 2.9 µm. Operating at feed rate value below cutting tool edge radius gives the nonlinear effect with less advantage as compared to feed rate value equal to 4.0 µm/tooth (which is above the cutting tool edge radius). Surface roughness vales initially decreases till feed rate value equal to 1 µm/tooth with pronounced effect at 2 µm/tooth and it has best value at feed rate value equal to 4 µm/ tooth. Comparable results have been reported in literature by Mian et. al. who worked on couple of steel sheets (AiSI 1005 and AISI 1045). His research shows that when feed rate values crosses the cutting edge radius values, the surface roughness decreases till 10 µm/tooth [47].

ANOVA of surface roughness in Table 8 presents depth of cut and cutting speed as subsequent significant factors with contribution ratios 24.36% and 19.12% respectively. Depth of cut has direct relation with surface roughness whereas cutting speed Vc m/min shows a nonlinear effect in transition and high-speed range (Figure 7). During transition phase, when the value of cutting speed increases from 50 m/min to 75 m/min, the value of surface roughness also increases while during high-speed range (75 m/min to 125 m/min) the value of surface roughness decreases which results in improving the quality of final surface finished.

Burr formation

Burr is a geometrical defect which occurs on the edges of machined surfaces because of micro milling. Its size is usually smaller than the burr size, which is observed in conventional macro milling domain, but it greatly affects the quality of finished product. At the micro level, burr removal from the finished product is an extremely difficult and challenging task. There are certain processes for deburring are available at micro component level but at times deburring of micro level finished products is not possible in various cases. Because these processes may distort the workpiece, change dimensional accuracy in the micro-machining domain and influence mechanical properties like elastic limit, residual stresses, surface finish and fatigue strength etc. In the micro-domain, no common approach is available for measuring 3D burr shapes. The previous studies show that burr, as per their shapes, can either be compared qualitatively [48, 49] or their width/ height are measured for comparison [50, 51]. Burr width and height as a combination contributes towards the analysis of overall burr formation. Thus, in current study, top burr width including burr height have been measured for overall assessment and statistical techniques have also been used for obtaining the results (Table 7). Up and down milling sides showed the formation of burr. So, in both categories top burr height and width over the entire range of parameters were investigated. As a result, it is highlighted that down milling side has greater intensity of burr formation when compared to up milling side. Digital images were taken using Olympus digital microscope and scanning electron microscope. Maximum top burr width on up milling side and down milling side were calculated using Olympus DSX 1000 digital microscope. Likewise, maximum height of the burr on up milling side and down milling side were also calculated as shown in Figure 4c and d. The results have been tabulated in Table 7 where higher values of burr height and width on down milling side are observed. Cutting velocity explain this phenomenon in a more logical way. As the cutting velocity on the down milling side in the localized region will always be on the lower side as compared to the value of cutting velocity on the up-milling side which causes a bigger burr size on down-milling side. Comparable results showing same behavior has also been reported by a previous research that investigated the burr formation behavior in the field of micro milling on Ti-alloy (Ti-6Al-4V) [27]. The higher frictional forces which result from rubbing between finished surface and burr that may be caught in flute of micro end tools also contributes towards the higher intensity of burr formation on down milling side.

Figures 9 to 12 shows the plotted results of Table 7. It includes both the categories of up milling and down milling incorporating burr heights

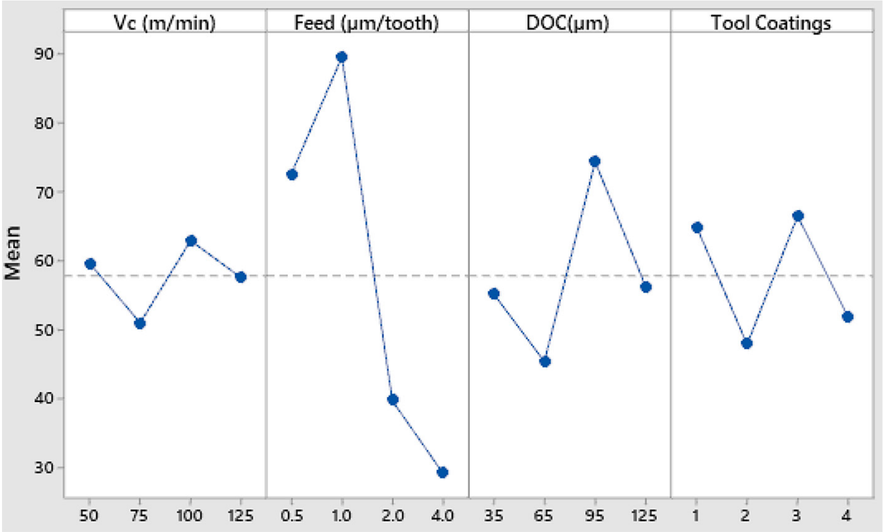


Figure 9. Burr width up milling case – main effects plot for Monel 400 alloy

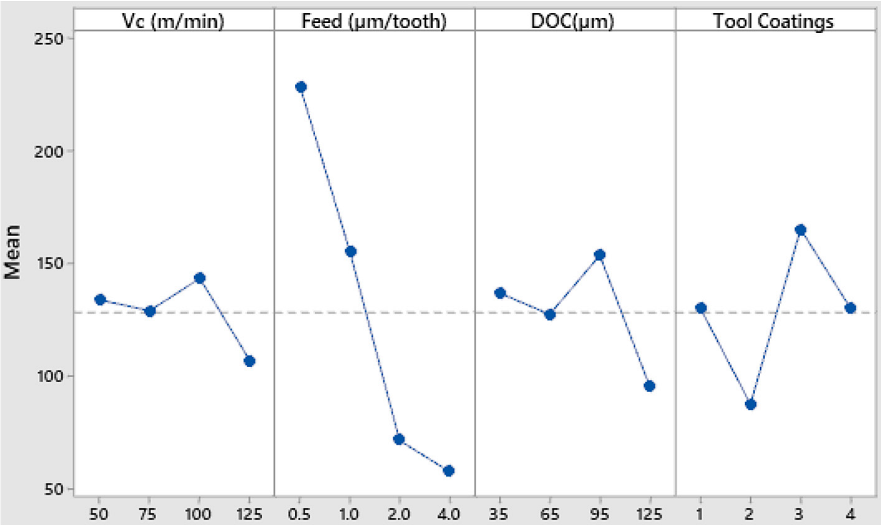


Figure 10. Burr width down milling case – main effects plot for Monel 400 alloy

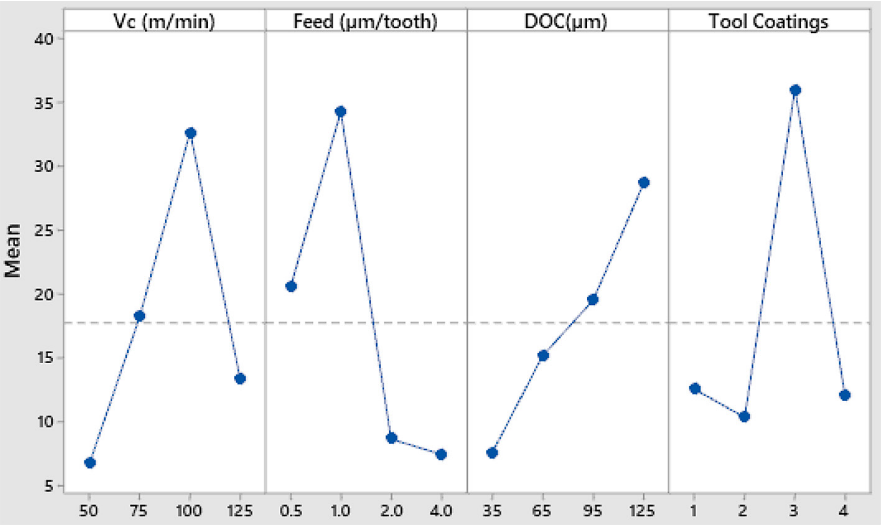


Figure 11. Burr height up milling case – main effects plot for Monel 400 alloy

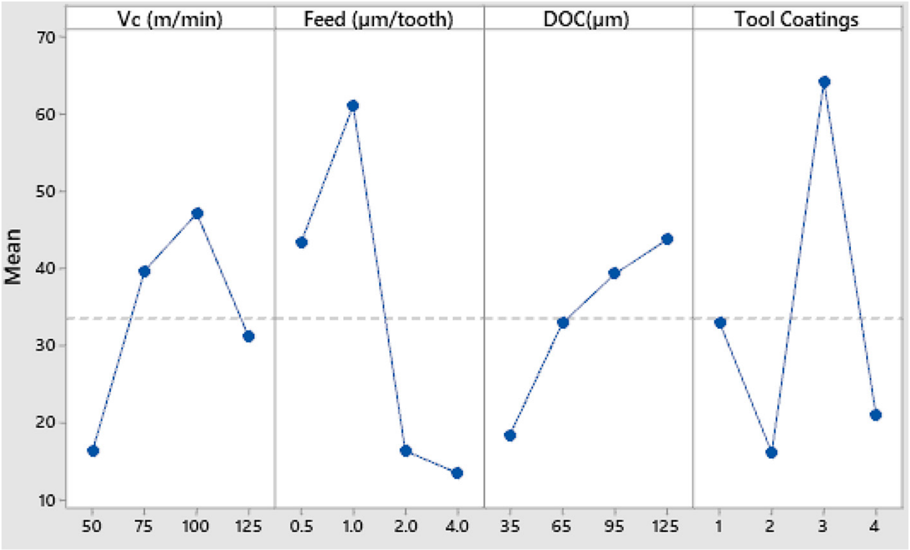


Figure 12. Burr height down milling case – main effects plot for Monel 400 alloy

and widths. These main effect plots show the relation between individual process parameters and burr formation in both categories. After analyzing these graphs, we see that operating with feed rate value below cutting tool edge radius do not give significant advantage as compared to operating at feed rate value above the cutting tool edge radius. Such similarity in behavior has also been reported in another research on Ti Alloy [27]. It is evident that TiAlN coated tool produced the best results for burr formation in terms of burr height and width whereas TiSiN showed the highest values for burr height and width. This might be due to the higher value of friction of TiSiN coated tool which resulted in deformation during the machining process and higher burr size in terms of height and width.

Figures 9 and 10 indicate the similar trends in both categories (up and down milling) for achieving minimum top burr width. As the value of feed rate approaches to 4 µm/ tooth (which is just above the cutting-edge radius of micro tools) we achieve the best value of top burr width in both categories. ANOVA (Analysis of Variance) Tables 9 to 12 show the significance of individual process parameter on response parameter (Both categories – top height and width). Tables 9 and 10 show that feed rate is the most significant factor for top burr width in up and down milling categories having contribution ratios 56.57% and 56.60% respectively. These results are also comparable with the previous study which was carried out on Inconel 718 [52].

Figures 11 and 12 show almost similar trends in both categories (up and down milling) for achieving minimum top burr height. As the value of feed rate approaches to feed rate value equal to 4 µm/tooth (which is just above the cutting tool edge radii) we achieve the best value for top burr height. We see another important trend which is between depth of cut and top burr height. There is a direct relation between

Table 9. Burr width up milling case – analysis of variance

Source	Seq SS	Adj SS	DF	Adj MS	F-Value	P-Value	Significance	Contribution
Vc (m/min)	608.8	608.8	3	202.92	0.46	0.714	Non-Significant	1.81%
Feed (µm/tooth)	19001.1	19001.1	3	6333.70	14.33	0.000	Significant	56.57%
DOC(µm)	3504.5	3504.5	3	1168.17	2.64	0.079	Non-Significant	10.43%
Tool coatings	2072.2	2072.2	3	690.72	1.56	0.231	Non-Significant	6.17%
Res	8400.7	8400.7	19	442.14				25.01%
Total	33587.2		31					100.00%

Table 10. Burr width down milling case – analysis of variance

Source	Seq SS	Adj SS	DF	Adj MS	F-Value	P-Value	Significance	Contribution
Vc (m/min)	5784	5784	3	1928.1	0.51	0.681	Non-Significant	2.15%
Feed (µm/tooth)	152058	152058	3	50686.1	13.36	0.000	Significant	56.60%
DOC(µm)	14512	14512	3	4837.3	1.28	0.311	Non-Significant	5.40%
Tool coatings	24227	24227	3	8075.5	2.13	0.130	Non-Significant	9.02%
Res	72064	72064	19	3792.8				26.82%
Total	268645		31					100.00%

Table 11. Burr height up milling case – analysis of variance

Source	Seq SS	Adj SS	DF	Adj MS	F-Value	P-Value	Significance	Contribution
Vc (m/min)	2912.2	2912.2	3	970.73	5.10	0.009	Significant	18.50%
Feed (µm/tooth)	3753.6	3753.6	3	1251.19	6.57	0.003	Significant	23.84%
DOC(µm)	1879.5	1879.5	3	626.51	3.29	0.043	Significant	11.94%
Tool coatings	3578.7	3578.7	3	1192.90	6.26	0.004	Significant	22.73%
Res	3619.2	3619.2	19	190.49				22.99%
Total	15743.2		31					100.00%

Table 12. Burr height down milling case – analysis of variance

Source	Seq SS	Adj SS	DF	Adj MS	F-Value	P-Value	Significance	Contribution
Vc (m/min)	4171.8	4171.8	3	1390.59	2.05	0.140	Non-Significant	9.59%
Feed (μm/tooth)	12388.1	12388.1	3	4129.35	6.10	0.004	Significant	28.47%
DOC(μm)	2934.8	2934.8	3	978.26	1.45	0.261	Non-Significant	6.74%
Tool coatings	11161.8	11161.8	3	3720.62	5.50	0.007	Significant	25.65%
Res	12859.6	12859.6	19	676.82				29.55%
Total	43516.0		31					100.00%

them. When the values of depth of cut increases the top burr height values also increases in both categories (up and down milling). ANOVA (Analysis of Variance) Tables 11 to 12 present the significance of individual process parameter on response parameter (top burr height both categories). Tables 11 and 12 indicate that the feed rate figured out as most significant factor for burr-height in both categories up and down milling, having contribution ratios 23.84% and 28.47 % respectively.

Tool wear analysis

Tool flank wear has been focus of many researchers in the past, as in micro milling processes it is highly unpredictable and greatly affects the dimensions of products, their surface quality and tool life. Its importance becomes more significant in the micro-machining domain due to desired high surface finish quality in micro 3D components. In current study, impact of key input machining parameters was analyzed for evaluating the tool flank wear. Table 7 presents results of the experiments under multiple factors. Main effects plot for tool flank wear of micro end mills have been shown in Figure 13. It is worth mentioning that a micro tool showing greater tool life may not be the best-performing tool as the material removed by that micro tool may be lesser than another tool having lesser life but have higher material removal rate. So, from Figure 13 we see that tool having longest tool life operate with depth of cut (ap = 65μm), feed rate (F = 2 μm /tooth) and cutting speed, (Vc = 50 m/min). Whereas tool having shorter life but higher rate of material removal operates with depth of cut (ap = 125 μm), feed rate (F = 4.0 μm/tooth) and cutting speed (Vc = 75 m/min). Feed rate and cutting edge of micro tools have a certain relationship, as operation at feed rate nearly equal to cutting edge radius gives minimum tool wear. As we see in Figure 12, tool wear has a nonlinear behavior with respect to feed rate (when its value changes from 0.5 to 4.0 μm /tooth), with

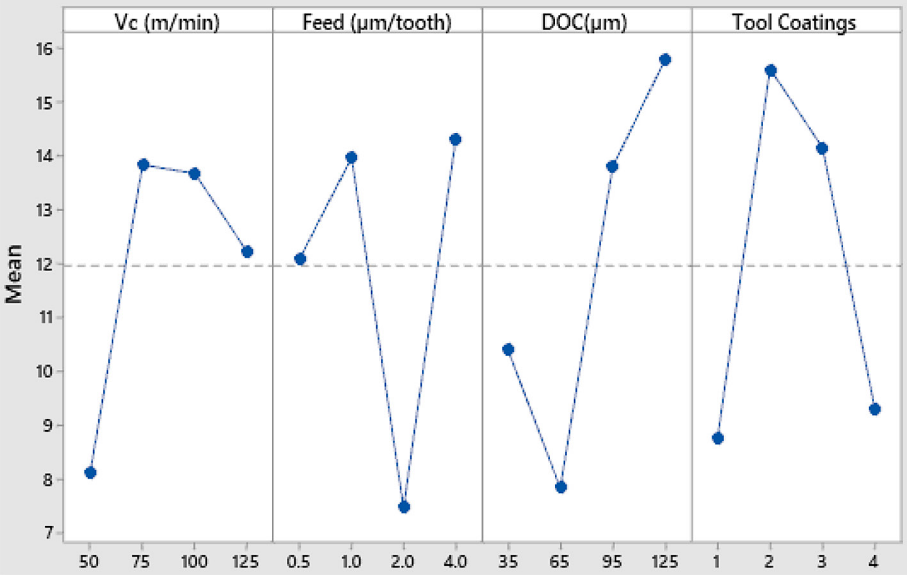


Figure 13. Main effects plot for tool wear

Table 13. Tool wear – analysis of variance

Source	Seq SS	Adj SS	DF	Adj MS	F-Value	P-Value	Significance	Contribution
Vc (m/min)	170.36	170.361	3	56.787	1.96	0.154	Non-Significant	11.04%
Feed (μm/tooth)	237.79	237.793	3	79.264	2.73	0.072	Non-Significant	15.41%
DOC(μm)	300.22	300.218	3	100.073	3.45	0.037	Significant	19.46%
Tool Coatings	283.82	283.816	3	94.605	3.26	0.044	Significant	18.39%
Res	550.72	550.718	19	28.985				35.69%
Total	1542.91		31					100.00%

pounced effect at F = 2.0 µm/tooth. This value is almost in close vicinity of average cutting tool edge radii of four categories of micro end mills (2.11 µm, 2.51 µm, 2.85 µm and 2.9 µm). The phenomena can be explained in terms of elastic recovery which is more intense when micro tool cuts the work piece material to minimum chip thickness and feed rate value becomes nearly equal to minimum chip thickness value. During experimentation value of cutting speed has been selected from 50 to 125 m/min. Initially when cutting speed varies from 50 to 75 m/min the tool life decreases sharply. The same phenomena has also been reported in an earlier research during turning operations on Ti Alloy [53]. The micro-cutting tool TiAlN has less friction as compared to other cutting tools so there is less temperature in the cutting zone and material deformation is difficult which results in more tool wear.

Table 13 shows the Analysis of Variance for Tool wear. The significance of process parameters which includes depth of cut and tool coatings on tool wear are shown in Table 13 with contribution ratios of 19.46% and 18.39% respectively. It is also observed that there is greater residual effect in micro milling domain when operations are carried with feed rate selected in a range below and above the cutting-edge radius. In micro-domain elastic recovery effects, relation between cutting tool edge radius and minimum chip thickness are more prominent. Moreover, high noise factors at the micro level in addition to the delicacy of micro tools add towards the high residual effects. Thus, residual effects are more significant. Tool wear in the micro-milling domain remains highly unpredictable when operating under these conditions.

VALIDATION EXPERIMENTS

This research focuses on investigation of machining response parameters while taking into consideration the input process parameters like surface roughness, burr formation and tool wear. Methodology used is based on Taguchi design of

Table 14. Validation experimental results

Experiments	Cutting speed (Vc) (m/min)	Feed (F) (μm/tooth)	DoC (ap) μm	Tool coatings (Tc)	Conditions	Output parameters	Run 1	Run 2	Average
1	125	4	35	TiSiN	Best	Ra	0.0004	0.0003	0.00035
2	75	2	125	nACo	Worst	- do -	0.004	0.006	0.005
3	75	4	65	TiAlN	Best	BW-U	15.166	14.166	14.666
4	100	1	95	TiSiN	Worst	- do -	130.216	151.919	141.0675
5	125	4	125	TiAlN	Best	BW-D	20.245	27.113	23.679
6	100	0.5	95	TiSiN	Worst	- do -	323.690	317.910	320.8
7	50	4	35	TiAlN	Best	BH-U	2.211	4.554	3.3825
8	100	1	125	TiSiN	Worst	- do -	97.576	74.372	85.974
9	50	4	35	TiAlN	Best	BH-D	5.177	3.225	4.201
10	100	1	125	TiSiN	Worst	- do -	139.081	131.085	135.083
11	50	2	65	uncoated	Best	Vb	5.859	6.386	6.1225
12	75	4	125	TiAlN	Worst	- do -	28.464	35.946	32.205

Note: Ra – surface roughness, BW-U – burr width-up milling, BW-D – burr width-down milling, BH-U – burr height-up milling, BH-D – burr height-down milling, Vb – tool wear.

experiments, statistical technique, digital microscopy, scanning electron microscope (SEM) and Analysis of Variance (ANOVA) has been utilized for identification of contribution by various key process parameters. The model is based on strategy ‘this smaller the better model’. The outcome of this methodology, as predicted by Taguchi design of experiments in terms of desired values of input and response parameters has been displayed in Table 7. Later on confirmatory/vadidation tests were performed by utilizing best and worst combination of input process parameters to validate achieved results. Table 14 gives validation results which are comparable with the results produced by Taguchi methodology.

CONCLUSIONS

This research aimed at analysis of various key process parameters and to see effects on response parameters like surface roughness, micro tool wear and overall burr formation in high-speed micro milling of Monel 400 alloy. Experimentation phase was carried out with micro end mills having various tool coatings including TiAlN, TiSiN and nACo. Monel 400 being a super alloy and having ability to retain its properties under extreme conditions made it a best choice for researchers for current industry. But due to absence of investigation on super alloy over wide range of cutting parameters specially with multiple micro tool coatings presented research gap. The past studies did not have much material on both ranges of cutting speed (transition and high speed) with feed rate values above and below the radii of cutting-edge of micro tools. So, this study focuses the research gap and covered maximum parameters in both speed ranges with multiple tool coatings. Taguchi design of experiments (L16 orthogonal array) followed by experimental and validation results and statistical analysis using ANOVA conclude the following:

- Feed rate being the key factor for the micro-milling domain, came out to be the most significant factor having its effects on burr formation (in both categories – up milling and down milling) and also on surface roughness with contribution ratios as following:
  - burr width-up milling – 56.57%,
  - burr width-down milling – 56.60%,
  - burr height-up milling – 23.84%,
  - burr height-down milling – 28.47%,
  - surface roughness – 27.86%;
- TiSiN coated tool, with a higher coefficient of friction than other coated micro tools, resulted in the best surface finish because of elevated temperature and increased cutting velocity at the cutting zone, which aids in material removal from the workpiece;
- Mmicro milling with feed rate below cutting tool edge radius did not give significant advantage. Moreover, feed rate selected just above the cutting tool edge radius in micro-milling produced best surface finish;
- At the micro level, burr removal from the finished product is an extremely difficult and challenging task. Although there are certain deburring processes available at micro component level but at times effective deburring of micro level finished products is not possible, since these processes distort the workpiece, change dimensional accuracy in the micro-machining domain and influence mechanical properties;
- Higher burr formation intensity was found on the down milling side when compared to the up-milling side which is the outcome of the higher localized velocity on the down milling side;
- TiSiN coated tool, with a higher coefficient of friction than other coated micro tools, resulted in the highest values of burr height and width during micro milling of Monel 400 alloy;
- Minimum burr height and minimum burr width were achieved at feed rate of 4 μm/ tooth. The reason for this occurrence is that feed rate value of 4 μm/ tooth is above the cutting edge radius of end mills;
- Increase in depth of cut from 35 μm to 125 μm resulted in 55% higher surface roughness. Vibrational forces and tool chatter were the causes for the poorer surface finish at higher depth of cut values;
- Depth of cut is identified as the most significant factor for tool wear having contribution ratio of 19.46%. Moreover, micro end mills are delicate and prone to noise factors which results in greater residual effects. Thus, tool wear in micro domain remains highly unpredictable under a such combination of machining parameters.

Best surface finish and minimum overall burr formation in micro milling of super alloys can be achieved by use of coated micro tools instead of uncoated micro tools. This is a clear advantage for other hard to machine materials in current manufacturing industry. In addition to significant conclusions, the current work has paved the way of further research endeavors as follows:

- Subsurface characterization in micro-machining of Nickel based Super alloy Monel 400 alloy;
- Analysis of correlation/ interaction of machining parameters;
- Hybrid laser mechanical micro-machining of super alloys to investigate improved machinability in terms of enhanced tool life, better surface roughness, and burr formation;
- Develop advanced modeling and simulations to predict tool life, surface roughness, and burr formation in addition to selection of optimal machining parameters.

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