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Surface topographical analysis on lead free brass in high speed micro step-turning

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Abstract

Micromachining technologies are widely used to produce miniaturized components with high accuracy. Micro turning is capable to generate smooth surface finish on micro cylindrical components. However, these micro components consist of very small surface area resulting in high cutting heat generation which leads to rapid surface roughness. Therefore, micro turning operations have been performed at very slow cutting speed which affects the productivity of the components. This paper deals with high speed micro turning on lead free brass to compensate the productivity. Lead free brass is a difficult-to-machine material which causes unfavorable chip formation, rapid tool wear, high cutting temperature and cutting force. In this study, the surface topography on lead free brass has been analyzed. Each experiment has been performed at constant cutting speed (100 m/min). Three different levels of feed rate and depth of cut were selected and their effects on surface roughness have been evaluated. A mixture of air and cryogenic gas has been injected at the machining zone as lubricant to reduce the cutting temperature. Additionally, a regression equation was proposed to predict the average surface roughness (Ra). Eventually, the optimum feed rate and depth of cut have been determined to minimize the surface roughness. This experiment has provided a minimum of 0.3 µm average surface roughness on lead free brass component at a combination of 7.5 µm/rev feed rate and 50 µm depth of cut.

Keywords: *High speed micro turning, Lead free brass, Surface roughness, ANOVA*

1. Introduction

The growing demand of high-accuracy miniaturized components has opened a new trend in modern manufacturing facilitating the requirement of micromachining. The miniaturized components have several applications in aerospace, automobile, electronics, and biomedical industries. Mechanical micromachining is one of the most versatile micromachining technologies which can be applicable for difficult-to-machine materials as well [1, 2]. However, low tool or workpiece stiffness and low material removal rate have limited the application of mechanical micromachining. These influenced the requirement of high speed micromachining technologies [3]. The chip is reduced in this process leading to less requirement cutting force. Additionally, the material removal rate is increased by high speed machining. Micro turning is one of the most commonly used mechanical micromachining technologies where miniaturized cylindrical components are turned to fabricate high accuracy products with a smooth surface finish.

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Initial researches revealed the dimensional inaccuracy and workpiece deformation were the major challenging issues [4]. However, low speed operation has been observed in this case. Saoubi and Chandrasekaran [5] investigated that sharp cutting edge was favorable to reduce the cutting temperature at the machining zone. Additionally, tool coating, low cutting speed, and low feed rate reduced the tool temperature as well at the rake surface. Basically, micro turning was considered as negative rake angle process due small uncut chip thickness [6]. However, very low uncut chip thickness was responsible for higher consumption of specific cutting energy in micro turning. Liu et al. [7] determined an optimum negative rake angle causing favorable plastic deformation and chip formation. However, larger negative rake angle led to increase the cutting force, tool wear and surface roughness. The plastic side flow of the workpiece material is significant for micro turning due to indentation of the cutting tool [8]. Singh et al. [9] achieved good quality surface on brass alloy by micro turning at very low cutting speeds. However, the material removal rate was very low. Additionally, tool wear and cutting force are significant for micro turning. Tool flank wear has been increased with the cutting speed, feed rate, and depth of cut [10]. Additionally, high feed rate and cutting edge radius were further responsible for increased cutting force [11]. Eventually, significant tool wear has been observed during micro turning operation of difficult-to-machine titanium alloy [12]. These predominant issues restricted the application of mechanical micro turning for commercial and research purposes. Meanwhile, nonconventional micro turning such as laser assisted micro turning and electrochemical micro turning have been performed as well to considering these issues [13, 14]. However, desired surface quality and material removal rate have not been achieved.

High speed machining can be introduced to improve the material removal rate. It further reduces the cutting force as well. Additionally, the surface roughness has been increased as well at higher cutting velocities in some cases. However, high amount of cutting heat generated in the cutting zone during high speed turning which further caused significant tool wear [15]. Cryogenic cooling might be a solution to reduce the tool wear; however, the cryogenic liquid was unable to reach the tool-work interface at high cutting speed [16]. Application of minimum quantity lubrication (MQL) and high pressure coolant supply were able to suppress the tool wear in high speed turning [17, 18]. Additionally, cryogenic treatment of coated carbide inserts was able to reduce the tool wear in high speed turning as well [19].

In this study, the surface topography of lead free brass has been analyzed in high speed micro turning. The objective was to improve the productivity of micro components. Step turning method has been applied during the machining operation. Constant cutting speed of 100 m/min was utilized in each experiment. Three different levels of feed rate and depth of cut have been utilized in the experiment and their effects on surface roughness have been evaluated. A mixture of air and cryogenic gas has been incorporated for lubrication. Additionally, a regression equation has been proposed to predict the average surface roughness on lead free brass in high speed micro turning.

2. Materials and methods

2.1 Experimental setup

The high speed micro turning experiments have been performed in the semi-high speed micromachining center (model V60) developed in the microfabrication laboratory of IIT (ISM) Dhanbad. Fig. 1 represents the experimental setup. The workpiece has been mounted on the vertical spindle as shown in the Fig. 1. The range of operating rotational speed of the spindle is 10000 to 60000 rpm. The tool post has been mounted on the X-Y linear stage. The feed rate has been provided to the workpiece by controlling the movement of the Z stage. However, the depth of cut has been provided by controlling the movement of the X-Y stage. An acrylic container has been used as the reservoir of the lubricant.

The workpiece was round bar of lead free brass having length and diameter of 50 mm and 3 mm respectively. The brass alloy consists of 58% copper, 39% zinc contents and slight amount of lead contents (0.3%). EDS spectrum of the brass alloy is depicted in Fig. 2. Sandvik made TiAlN (PVD) coated cemented carbide inserts have been used for micro turning. The details of tool geometry have been represented in Table 1. The experiments have been performed at semi-cryogenic environment where a mixture of air and cryogenic gas has been injected to the machining interface at high pressure (0.8 bar). It has been a cost effective as well as an eco-friendly solution for the machining process. Additionally, it was capable to dissipate the cutting heat generated at the chip tool interface during high-speed micro turning.

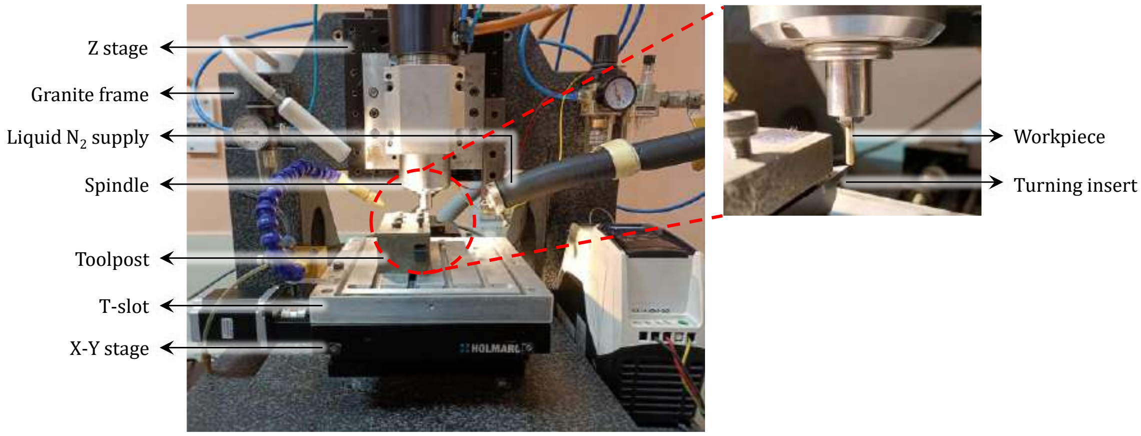


Fig. 1 The experimental setup (Micromachining center model "V60")

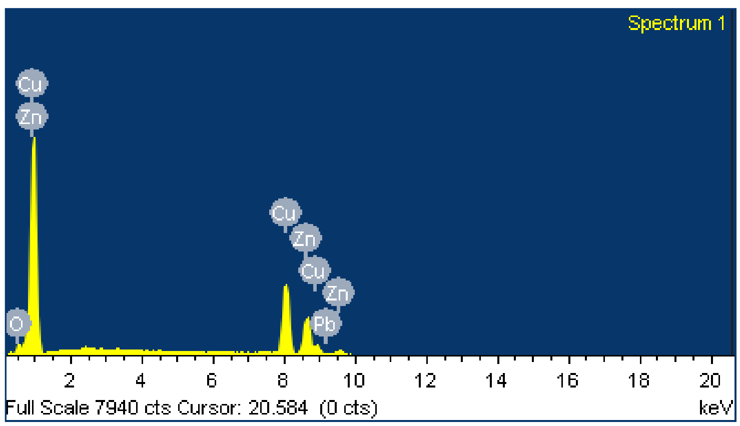


Fig. 2 EDS analysis of the brass alloy

Table 1. Tool geometry

Rake angle	0º
Side releif angle	6º
End releif angle	35º
Princpal cutting edge angle	90º
End cutting edge angle	9º
Nose radius	30 µm

The major objective was to investigate the surface roughness of micro samples of lead free brass at high speed micro turning. Therefore, the experiments were performed at constant cutting speed of 100 m/min. Three different levels of feed rate and depth of cut length was selected for the experiments. Taguchi L9 orthogonal array design was utilized to prepare the design of experiment. The brass samples were machined for 3 mm length in each experiments and the surface roughness has been measured. Step tool path has been utilized for the machining operation. Therefore, each sample has been utilized for a particular feed rate. Three different machining experiments have been performed on eaxh sample at three different depth of cut. The details of the machining parameters have been enlisted in Table 2.

Table 2. Machining parameters

Cutting speed (m/min)	100
Feed rate (µm/rev)	7.5, 10, 15
Depth of cut (µm)	30, 40, 50
Machining length (mm)	3

2.2 Surface topographical measurement and analysis

The surface roughness of the machined components have been measured by Mitutoyo make portable surface roughness tester (model "SJ-210"). It is comprised of a stylus probe having diameter 5 µm. The measurement parameters, considered during the surface roughness measurement, have been depicted in Table 3. Additionally, the surface topography of the machined samples have been captured and analyzed by optical microscope (Model BX51M, Olympus).

Table 3. Measurement parameters for surface roughness

Cut off length λ_c	0.25 mm
Cut off length λ_s	2.5 µm
Measuring length	1 mm
Measuring speed	0.25 mm/s

3. Results and discussions

3.1 Analysis of surface roughness

The cutting edge of the turning insert involves into the workpiece material resulting removal of material. In general, the cutting edges leave some feed marks on the workpiece surface due to feed motion resulting surface roughness. However, the machined surface roughness is strongly dependent on machining parameters, extent of cutting heat generation, plasticity of the workpiece material. The design of experiment along with the surface roughness values have been depicted in Table 4. It has been shown that the surface roughness values have not changed with length due to small machining length. From Table 4, it can be seen that best surface profile has been achieved at feed rate and depth of cut of 7.5 µm/rev and 50 µm respectively. Average surface roughness (Ra) of 0.3 µm has been obtained in this combination. Additionally, combination of feed rate and depth of cut of 10 µm/rev and 30 µm respectively precipitated maximum average surface roughness (Ra) of 4.53 µm. A wide range of surface roughness has been achieved in the full experiment.

Table 4. Design of experiment with measured surface roughness.

Experiment No.	Feed rate (μm/rev)	Depth of cut (μm)	R_a (μm)	R_q (μm)	R_z (μm)
1	7.5	30	1.69	2.12	8.52
2	7.5	40	2.11	2.7	10.67
3	7.5	50	0.3	0.37	1.72
4	10	30	4.53	6	24.06
5	10	40	3.75	5.04	25.9
6	10	50	0.74	1.1	6.09
7	15	30	2.53	3.24	12.09
8	15	40	2.92	3.91	16.04
9	15	50	1.55	2.05	9.1

3.1.1 Effect of process parameters and step tool path

The micro turning operation at high cutting speed was able to generate submicron surface finish. The surface roughness data has been analyzed by Taguchi method to determine the individual effect of feed rate and depth of cut on surface roughness. Fig. 3 represents their influences on surface roughness. It was observed that on increasing the feed rate, the average surface roughness has been increased initially and then decreased. The surface roughness has been increased drastically when the feed rate has been changed from 7.5 μm/rev to 10 μm/rev. In general, the surface roughness monotonically increases with feed rate. However, in this study, the surface roughness has not followed the traditional trend. This was observed mainly for two reasons. Primarily, the overhang length of the workpiece has attributed to some extent of tool-work relative vibration. This resulted in some additional surface integrity induced on the machined surface. Additionally, the step tool path (as shown in Fig. 4) led to some mount of chip accumulation on the principal cutting edge of the turning inserts at point B and C as shown in the Fig. 4. Due to higher ductility, the tendency of longer chip formation has been observed for lead free brass even in high speed micro turning as well. The accumulated chips on the cutting edge has interacted with the work surface and created some scratch marks on the machined surface (BC and CD as shown in Fig. 4). Therefore, the surface roughness has been increased rapidly in the section BC and CD, as compared to the section AB. Fig. 5 depicts the surface topographies for experiment 1 and 3. The sections for experiment 1 and 3 can be considered as section CD and AB. It can be seen that the surface topography was quite smooth for experiment 3 with straight tool marks on the machined surface. However, some cross scratch marks has been observed on the machined surface for experiment 1. It can be noticed that the amount of plastic deformation on the machined surface was higher for experiment 1 due to excessive rubbing of the chips accumulated on the cutting edge of the turning insert. This resulted in submicron peaks on the machined surface increasing the surface integrity. The surface roughness was seen to be decreased with increasing the depth of cut. The uncut chip thickness increases with increasing the depth of cut as well. This phenomenon reduces the tendency of rubbing of the cutting edge on the work surface. As a result, the specific cutting energy required for micro turning has been reduced. Consequently, the surface quality improves. Additionally, at higher depth of cut, the higher asperities present on the work surface removed easily resulting in good quality surface on the machined zone.

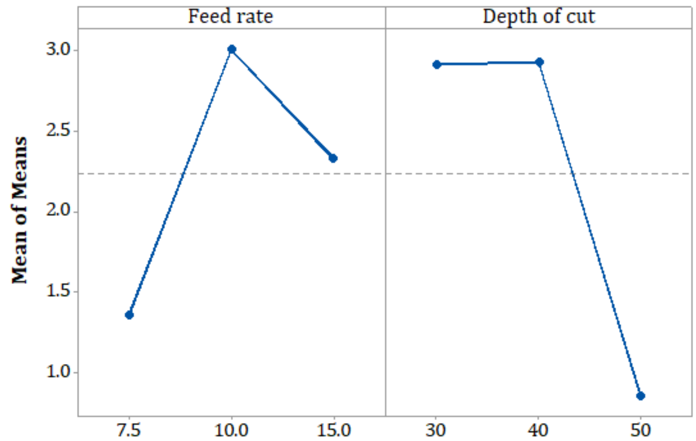


Fig. 3 Effect of feed rate and depth of cut on surface roughness analyzed by Taguchi method

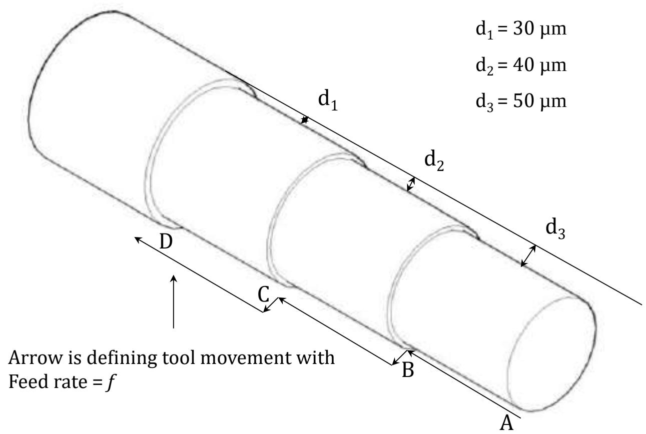
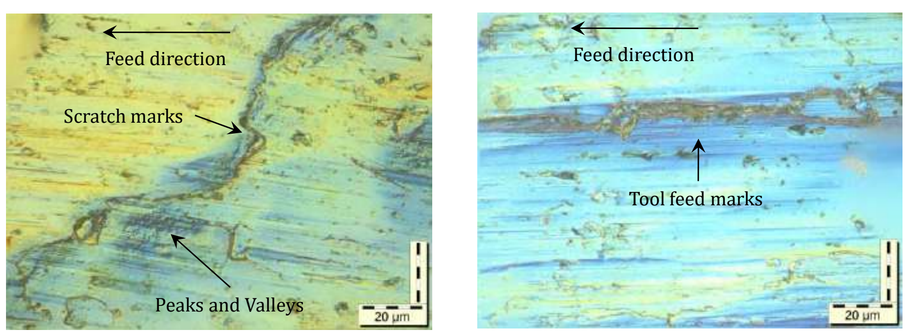


Fig. 4 Step tool path for the micro turning operation



(a) f = 7.5 μm/rev, d = 30 μm (Experiment 1) (b) f = 7.5 μm/rev, d = 50 μm (Experiment 3)

Fig. 5 Surface topography for Experiment 1 and 3

3.1.2 Effect of lubricant

Brass alloys has shown higher thermal conductivity. However, low surface area has resulted in huge amount cutting heat generated during high speed micro turning. The cutting temperature has increased rapidly with cutting speed during dry machining. This phenomenon led to burning and degradation of the work surface. Therefore, the utilization of lubricant has been emphasized for high speed micro turning. In this study, a semi-cryogenic environment has been generated where a mixture of air and cryogenic gas has been injected on the chip tool interface at 0.8 bar. This reduced the cutting temperature upto a great extent in high speed micro turning. Consequently, the plastic deformation of the work surface has been reduced. This precipitated a good quality machined surface.

Eventually, high cutting speed during the micro turning operation led to huge amount of plastic deformation on the machined surface. Therefore, desirable super-finished surface was unable to be achieved. Direct application of cryogenic fluid may reduce the amount of plastic deformation and the amount of surface roughness as well. Additionally, a proper tool path strategy for step turning may reduce the accumulation of chips on the cutting edge. As a result, a super-finished surface can be produced in high speed micro turning. This can be investigated in future research.

3.2 Statistical analysis and prediction of surface roughness

The surface roughness data has been plotted in Design Expert software to analyze and predict the surface roughness statistically. The suitable polynomial has been selected based on the sequential ANOVA model of curve fitting in this software. The level of significance was 0.05. The model should be insignificant with minimum p value ($p > 0.05$). Table 5 represents the sequential model of fit summary which suggested quadratic model (bold one) for surface roughness prediction. The acceptability of the quadratic model has been determined by ANOVA. Table 6 depicts the ANOVA table for quadratic model with 95% confidence interval. The table incorporated all the relevant terms for surface roughness. The result of the ANOVA analysis has shown that the model was insignificant for surface roughness.

Table 5. Sequential ANOVA model for fit summary

Source	Sum of Squares	df	Mean Square	F-value	p-value
Mean vs Total	44.98	1	44.98		
Linear vs Mean	7.05	2	3.53	2.7	0.1455
2FI vs Linear	0.2357	1	0.2357	0.1553	0.7098
Quadratic vs 2FI	**5.5**	**2**	**2.75**	**3.94**	**0.1448**
Cubic vs Quadratic	2.09	2	1.05	397.41	0.0354
Residual	0.0026	1	0.0026		
Total	59.86	9	6.65		

Table 6. ANOVA table for Average Surface roughness (Ra) (Quadratic model)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	12.78678849	5	2.557357698	3.66587798	0.1570078
A-Feed rate	1.401666667	1	1.401666667	2.00923749	0.2513538
B-Depth of cut	5.896842293	1	5.896842293	8.45290604	0.0621282
AB	0.235744048	1	0.235744048	0.3379304	0.6018221
A^2	3.349038095	1	3.349038095	4.80072265	0.1161396
B^2	2.149355556	1	2.149355556	3.08102195	0.1774772
Residual	2.09283373	3	0.697611243		
Total	14.87962222	8			

Based on the quadratic model, the regression equation to predict the surface roughness has been defined as Equation 1, where f and d are feed rate and depth of cut respectively.

$$R_a = -20.49413 + 2.24660f + 0.657798d + 0.006357fd - 0.105422\,f^2 - 0.010367\,d^2 \quad (1)$$

The contour plot for average surface roughness has been generated based on the analysis. Fig. 6 represents the contour plot for surface roughness where red and blue colors represent the maximum and minimum surface roughness respectively minimum surface roughness. The contour map shows that lower surface roughness can be obtained by operating at lower feed rate and higher depth of cut i.e. feed rate of 7.5 μm/rev and depth of cut of 50 μm according to the contour plot. Eventually, the optimum process parameters have been investigated to minimize the average surface roughness by Design Expert software. This determined the optimum feed rate and depth of cut are 7.56 μm/rev and 49.34 μm respectively.

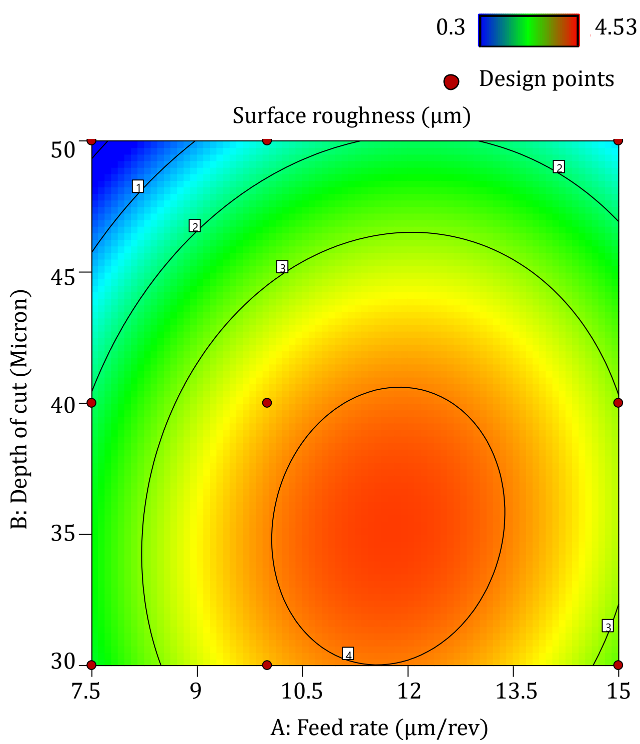


Fig. 6 Contour plot for average surface roughness (Ra)

4. Conclusions

This study has investigated the surface roughness on lead free brass in high speed micro turning. This phenomenon improved the productivity of manufacturing micro cylindrical components. The experiments were performed at constant cutting speed of 100 m/min and three different levels of feed rate and depth of cut. The surface roughness of the machined components has been determined and analyzed. The variation of surface roughness with feed rate and depth of cut were investigated. Additionally, a quadratic regression equation has been proposed for surface roughness prediction. Eventually, the optimum process parameters have been evaluated to minimize surface roughness. The conclusions of the study are listed below:

- High cutting induced higher plastic deformation on the machined surface resulting in high surface roughness on micro components.

- The surface roughness initially increased and then decreased with increasing the feed rate.
- Higher depth of cut led to lower surface roughness during high speed micro turning.
- Utilizing lubricant has reduced the cutting temperature upto a great extent reducing the plastic deformation of the micro components in high speed micro turning. This improved the surface quality as well.
- The step tool path strategy for micro turning has increased the tendency of chip accumulation on the principal cutting edge of the turning insert. This phenomenon induced scratch marks on the machined surface increasing surface roughness. A novel tool path strategy needs to be developed in future research to compensate the problem in high speed micro turning.

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