Analysis and prediction of surface roughness on lead free brass in high speed micro 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 roughness 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 (R_a). 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, Micro cutting, Lead free brass, Surface roughness, ANOVA

1. Introduction

The increasing demand of miniaturized components is promoting the development of micromachining technologies. Micromachining technologies are capable to generate high dimensional precision and smooth surface finish on difficult-to-machine materials as well. Tool based mechanical micromachining process has been characterized by direct contact of tool and workpiece, which attributed to mechanical stress induced by the cutting tool for material removal [1]. Micro turning is a tool based micromachining technology, extensively used to fabricate several micro components such as micro valves, micro nozzles, micro moulds in aerospace, automotive, electronics and biomedical industries. However, cutting heat generation is very prominent in micro turning which consequences rapid tool wear and degradation of surface quality. Therefore, most of the researchers have gone for nonconventional micro turning to compensate the tool wear [2]. Regardless of the problem, mechanical micro turning can be applicable for all materials irrespective of their mechanical properties [3]. The effect of tool rake angle in micro turning has been investigated by Wu et al. [4], where the process has been established as a negative rake angle process as the uncut chip thickness is much smaller compared to cutting edge radius. Additionally, higher uncut chip thickness and smaller cutting edge radius have been preferred to reduce specific cutting energy and this phenomenon is responsible to reduce the surface roughness due to plastic side flow of material. Singh et al. [5] investigated the variations of cutting force and surface roughness with process parameters during micro turning. The experiments have been performed at very low cutting speed because the heat generation may be rapid at higher cutting speed due to low surface area leading to deteriorating the accuracy of the miniaturized product. However, it directly affects the productivity of the components. Additionally, high cutting speed may improve the machined surface quality as a consequence of low cutting force [6].

Lead content in brass alloys improves the machinability in terms of low tool wear and favorable chip formation. However, due to hazardous effect on the environment, the lead content has been reduced in the brass alloys. Consequently, the machinability of brass alloys has been reduced due to formation of longer chips, rapid tool wear and increased cutting temperature [7]. The zinc content in the lead free brass increases the α-phases in the microstructure and improves ductility. As a result, the α-brass alloys are prone to longer chip formation. However, lesser amount of tool wear has been reported for diamond CVD coated and diamond-like carbon PVD coated cutting tools during machining lead free brass [7]. Imai et al. [8] improved the machinability of lead free brass alloys substantially by dispersing 1% (mass) graphite particles. Additionally, Schultheiss et al. [9] determined that the higher strength and lower thermal conductivity precipitated larger cutting force for lead free brass as compared to leaded brass. However, higher plasticity of lead free brass alloys led to better surface finish at low feed rate. Similar results have been obtained by Amaral et al. [10]. The surface roughness and cutting force have been increased at higher uncut chip thickness during turning of lead free brass [11]. In addition, presence of Mg and Sb in low amount has improved the machinability of lead free brass [12].

However, very limited number of researches has been reported on micromachining of lead free brass alloys. In this study, the surface roughness of lead free brass has been analyzed in high speed micro turning. The objective was to improve the productivity of micro components. 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 schematic diagram of 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.

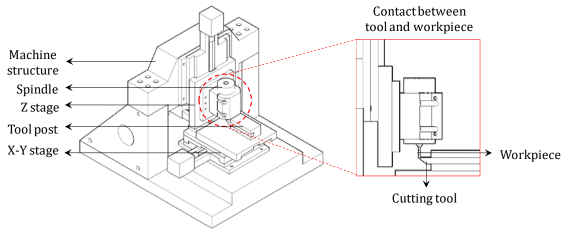


Fig. 1 Schematic diagram of the experimental setup (Micromachining center model "V60")

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. In micro turning, rake angle and cutting edge radius are the major tool geometrical parameter influencing micro cutting. The tool has sharp cutting edge. Due to increasing the strength of the cutting edge, zero rake angle has been preferred in this case [13]. 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.

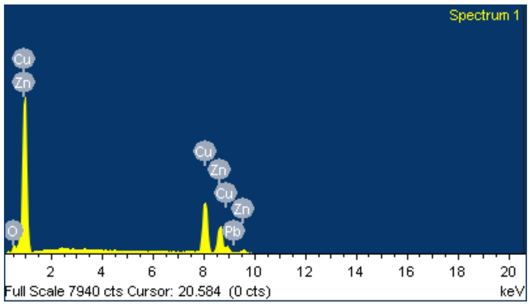


Fig. 2 EDS analysis of the brass alloy

Table 1 Tool geometry

Rake angle	0º
Side releif angle	6º
End releif angle	35º
Princpal cutting edge	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. The process parameters and their levels have been selected based on the recommended parameters of the cutting tool, movement of the linear stages and capability of the material to sustain. 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 roughness measurement

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 (R_a) 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 (R_a) 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

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 has been decreased with increasing the depth of cut as shown in Fig. 3. 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.

During micro cutting, micro cutting force is a significant parameter. Due to chip accumulation at the chip tool interface, BUE has been formed resulting in variation of the micro tool geometry. This phenomenon led to fluctuation of the micro cutting forces. This fluctuation directly reflects into the machined surface resulting in rapid surface roughness formation [14].

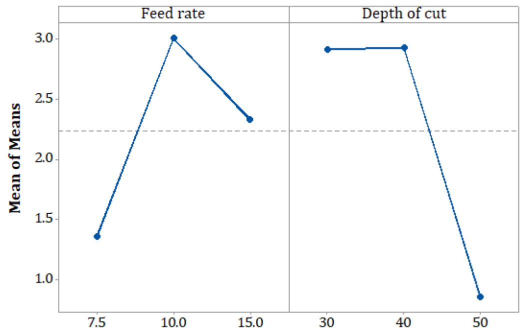


Fig. 3 Effect of feed rate and depth of cut on surface roughness analyzed by Taguchi method

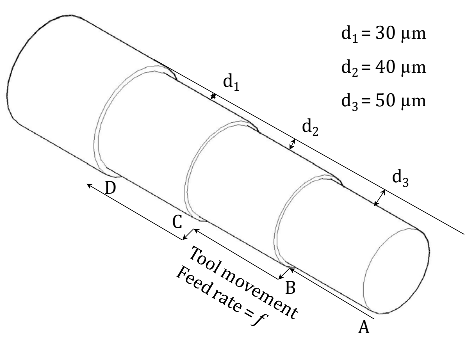
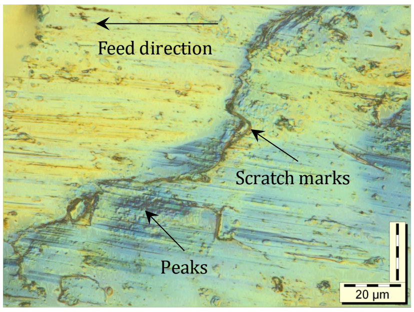
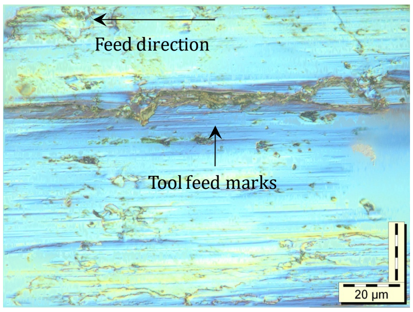


Fig. 4 Tool path for the micro turning operation



(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.

In some cases, the lubricant is unable to reach at the chip tool interface at high speed turning due to high speed rotation of the workpiece [15]. Additionally, the tool wear rate is quite higher at high cutting speed due to rapid heat generation and improper lubrication. This results in degradation of the surface finish. Therefore, super-finished surface has not been able to achieve. Additionally, the effect of various cutting speeds was not studied in this case. The effect of various lubricants and lubricating parameters was not studied as well. These can be included in future study.

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	0.146
2FI vs Linear	0.2357	1	0.2357	0.1553	0.71
Quadratic vs 2FI	**5.5**	**2**	**2.75**	**3.94**	**0.145**
Cubic vs Quadratic	2.09	2	1.05	397.41	0.035
Residual	0.0026	1	0.0026		
Total	59.86	9	6.65		

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

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	12.78678849	5	2.557357698	3.66588	0.157
A-Feed rate	1.401666667	1	1.401666667	2.00924	0.2514
B-Depth of cut	5.896842293	1	5.896842293	8.45291	0.0621
AB	0.235744048	1	0.235744048	0.33793	0.6018
A^2	3.349038095	1	3.349038095	4.80072	0.1161
B^2	2.149355556	1	2.149355556	3.08102	0.1775
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.

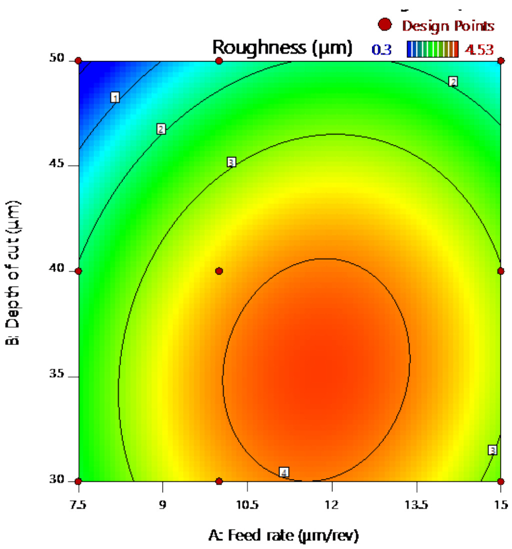


Fig. 6 Contour plot for average surface roughness (R_a)

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:

1. High cutting induced higher plastic deformation on the machined surface resulting in high surface roughness on micro components.
2. The surface roughness initially increased and then decreased with increasing the feed rate.
3. Higher depth of cut led to lower surface roughness during high speed micro turning.
4. Utilizing lubricant seemed to be a great mean of reducing cutting temperature and the plastic deformation of the micro components in high speed micro turning. This improved the surface quality as well.
5. 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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