Effect of Femtosecond Laser Texturing on Roughness Characteristics of Tin Bronze Alloy

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Abstract

Femtosecond laser surface texturing of soft bearing materials such as tin bronze has gained greater attention in manufacturing community for various contact applications. This paper examines the effect of scanning speed and texture pitch on roughness characteristics of femtosecond textured high tin bronze alloy under lubricated conditions. These mainly include average roughness (R_a), root mean square roughness (R_q), skewness (R_{sk}) and Kurtosis (R_{ku}). Reciprocating wear test was conducted to assess the tribological performance of high tin bronze alloy at load conditions of 17, 27 and 38 N and constant frequency of 5 Hz. The correlations between the roughness characteristics and friction coefficient of high tin bronze alloy were assessed through regression analysis. Both scanning speed and pitch were found to be inversely related to Ra and Rq. The textures produced at higher pitch of 60 µm and scanning speed of 10 mm/s caused ~40 times higher kurtosis as against ~6 times achieved at 60 µm and 5 mm/s. The condition of higher kurtosis and negative skewness achieved at higher scanning speed and pitch could cause the improvement of lubrication conditions through reduced friction.

Keywords: *Femtosecond laser, tin bronze alloy, surface roughness, kurtosis*

1. Introduction

In recent years, ultra short pulsed lasers are adopted for tailoring the surface properties of various metals, alloys and ceramics. Laser texturing is one of the surface modification processes adopted to reduce friction by producing different patterns in the form of micro-dimples or grooves Femtosecond laser surface texturing of soft bearing materials such as tin bronze has gained greater attention in manufacturing community for various contact applications. These include boundary lubricated bearings such as aircraft landing gear assemblies, control surface hinges and linkages [1]. Generally, bronze parts act as sacrificial components to protect the valuable steel components and becomes the major sources of friction and wear [2]. Since the surface roughness and topography strongly influence the tribological behavior of such soft contact interfaces especially under lubricated conditions, it is most vital to understand the influence of laser and groove geometrical parameters on the surface roughness characteristics to achieve better performance of mechanical components.

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Some of the commonly adopted surface roughness parameters are R_a, R_q, R_{sk} and R_{ku}. The most widely used roughness parameter for general quality control is the arithmetic average height parameter (R_a). Ra is meaningful for random surface roughness (stochastic) machined with tools that do not leave marks on the surface, such as sand blasting, milling and polishing. Rq corresponds to root mean square deviation of the assessed profile and is more sensitive to deviations from mean line than Ra. Eventhough, Ra and Rq provide a good general description of height variations, they do not provide the distinction between the peaks and valleys and hence surface with sharp peaks and deep valleys could not be characterized precisely [3]. Furthermore, other standard roughness parameters such as R_{sk} and R_{ku} provides realistic description of the surfaces. The skewness of the surface (R_{sk}) describes the asymmetry of the height distribution on the sampling length. Positive values of the skewness signify the high peaks spread on a regular surface while negative values are found on surfaces with pores and scratches as shown in Fig. 1. Rsk becomes vital in specifying honed surfaces and monitoring for different types of wear conditions. Rku is the measure of the sharpness of the profile peaks. If $R_{ku} < 3$, surface has few high peaks and low valleys (Platykurtic). If $R_{ku} > 3$, the surface has relatively many high peaks and low valleys (Leptokurtic) [4]

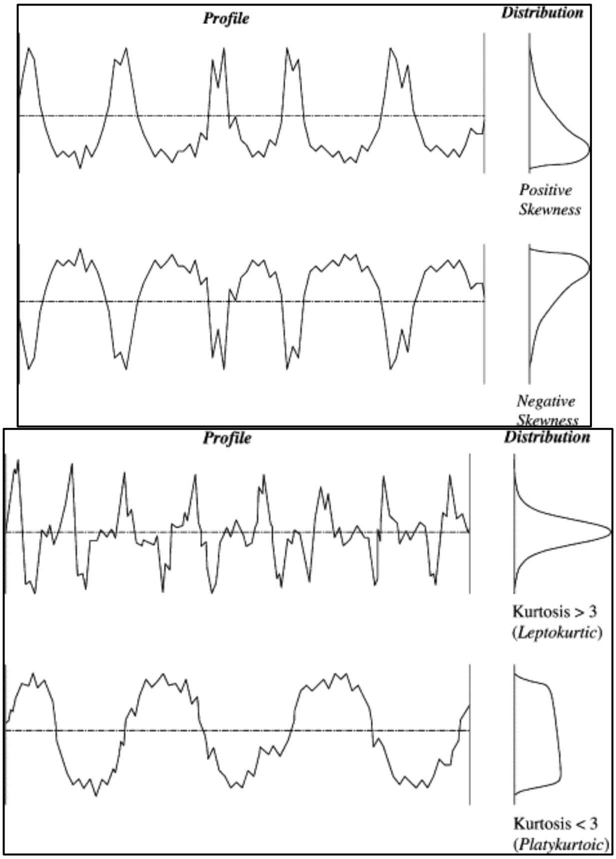

Fig. 1. a). Definition of Skewness and **b).** Kurtosis [4]

Some of the researchers have focused on influence of surface preparation on the friction and wear behavior of various metallic and ceramic surfaces. M. Sedlacek et al [5] reported the effect of surface preparation on roughness parameters and established a correlation between roughness parameters and friction coefficient. Disc type steel samples were examined in terms of different average surface roughness, using different grades of grinding, polishing, turning and milling. Lower roughness resulted in lower coefficient of friction under lubricated conditions. The same authors M. Sedlacek et al [6] investigated the effect of skewness and kurtosis parameters on the wear behavior of contact surfaces made of steel under dry and lubricated conditions. The authors reported that a higher value of Sku and a more negative Ssk results in lower friction under boundary lubrication conditions. G Lazzini et al [7] developed a correlation between areal roughness parameters and laser parameters (laser energy dose, repetition rate and scanning velocity) during surface texturing of 316L stainless steel adopted in food industry. The authors reported that increase in the laser energy dose results in average rise of height of the highest peaks and depth of the deepest dales. F Svahn et al [8] investigated the effect of surface roughness on the friction and wear behavior of carbon coatings containing tungsten and chromium. The friction was higher for rougher surfaces because of shearing of oxidized coating material deposited in the scratches. S Zhu et al [9] derived the correlations between dry or lubricated friction coefficient and bearing area ratio during turning, milling and grinding of steel samples. Positive correlation for dry friction coefficient and negative correlation for mixed lubrication coefficient and bearing area ratio was observed. V Podgursky et al [10] developed a correlation between the coefficient of friction and surface geometrical parameters such as average roughness, skewness and kurtosis during polishing of TiN, TiAlN and AlTiN coatings deposited on top of WC-Co substrates. The authors reported that that the coefficient of friction was inversely proportional to kurtosis, assuming positive skewness of the surface. B Podogornik et al [11] investigated the influence of laser texture parameters on kurtosis and skewness of the AISI 52100 steel surface and consequently coefficient of friction under lubricated conditions. The surface texturing was performed using Nd: YAG laser operated at an average power of 12.8 W, wavelength of 1064 nm, and frequency of 15 kHz. The authors reported that a higher kurtosis and a more negative skewness are obtained for semicircular grooves or dimples having larger depth, decreased density and size. X Jia et al. [12] fabricated nano patterns on ZnO crystal by adjusting the laser polarization combinations of multi-beam interference. J Chen et al. [13] investigated the influence of laser parameters such as beam diameter, pulse fluence, wavelength and number of pulses on the texture of aluminium surface by forming laser interferometry patterns. M M Calderon et al. [14] reported the formation of longitudinal and transversal LIPSSs on stainless steel surface at 2.71 J/cm2 fluence and 1 mm/s scanning speed resulting in 30 pulses per spot

Eventhough some of the authors have focused on analyzing the effect of surface texturing on friction and wear behavior of metals and ceramic coatings, the surfaces were prepared mostly with conventional techniques such as turning, polishing, milling and grinding, except [15]. The authors had also made an attempt to explore the possible correlation between surface geometrical parameters and frictional performance of various steel surfaces. With the rapid development of ultra short pulsed lasers, the surface texturing is more effective since high peak power intensities could produce minute structures in different materials ranging from polymers to semiconductors and metals [16]. The process is mainly controlled by various laser parameters such as laser fluence, scanning speed, pulse duration and number of pulses. Among these parameters, scanning speed effectively controls the material depth, material removal rate and plays an important role in producing textures with irregularities in the form of roughness, waviness and form errors. Also, texture geometrical parameters such as texture density can improve the wetting of the surface and support the formation of a lubrication film [11, 13]. The effect of femtosecond pulsed laser parameters on the surface roughness and friction performance of soft bearing materials such as tin bronze is not yet addressed so far. Hence, the present research focuses on investigating the effect of scanning speed and texture pitch on roughness parameters such as R_{sk} (skewness) and R_{ku} (kurtosis) and coefficient of friction of tin bronze under lubricated conditions.

2. Materials and methods

2.1 Specimen preparation

Sand-casted tin bronze alloy containing 12 wt. % tin was procured from M/s Meltech Alloys, Coimbatore. The casted rods of dimensions Φ 50 mm × 500 mm were grit blasted (20/40 mesh size) and then cut into square pieces of dimension of 25 mm × 25 mm × 5 mm in order to meet the experimental wear test rig requirements. The chemical composition of the casting was analyzed using Meta Vision tungsten arc spectrometer. The composition of the alloy was found to be within the range of ± 0.1 % wt from the nominal composition. The chemical composition of the sample is as shown in Table 1. The surface hardness of the samples containing 12 wt % tin was found to be 139.16 HV, which is averaged from six measurements. The testing conditions of 500 gf load and 10 s dwell time were adopted. The samples were polished to obtain the surface roughness of about 0.3 µm. Samples were cleaned with acetone prior to laser processing.

Table 1. Chemical composition of the sample

Element (%)	Cu	Sn	Pb	Zn	Fe	Si	Mn	Sb	P	S	Cr	Be	As
Sample	85.35	12.66	0.185	0.153	0.0054	0.014	0.01	0.013	0.142	0.012	0.01	0.002	0.002

2.2 Laser surface texturing with fs pulses

A commercial Ti: sapphire fs laser- Spitfire Ace power amplifier (12 W output power, 50ps - 100 fs pulse width, 10 kHz repetition rate) was employed to create micro-grooves on the samples. A near Gaussian laser beam at normal incidence was focused onto the tin bronze samples that were placed in processing chamber. The laser scanning speed could be controlled by the mirrors of galvanometer. An area of 20 mm × 8 mm was considered to generate linear micro groove textures, comprising of regularly spaced features. The experimental conditions are presented in Table 2.

Table 2. Experimental plan for fs laser surface texturing

Sl No	Texture (L)	Laser Power (mW)	Scanning Speed (mm/s)	Pitch (µm)
1	L1	100	10	40
2	L2	100	10	60
3	L3	100	5	40
4	L4	100	5	60
6	UL	0	0	0

Four types of textures with varying scanning speeds (5 and 10 mm/s) and pitch between the grooves (40 and 60 µm) were created on tin bronze sample having 12 wt % tin. The textured samples were designated as L1, L2, L3, and L4. The untextured sample was designated as UL5. Throughout the experiments, the laser power was maintained at 100 mW. The depth, width and roughness parameters of the grooves were measured using Bruker 3D Non-contact Profiler and presented in Table 3. The surface topography of the all the four textures and their associated cross-sectional profile (Y profile) are as shown in the Fig. 2 - 5.

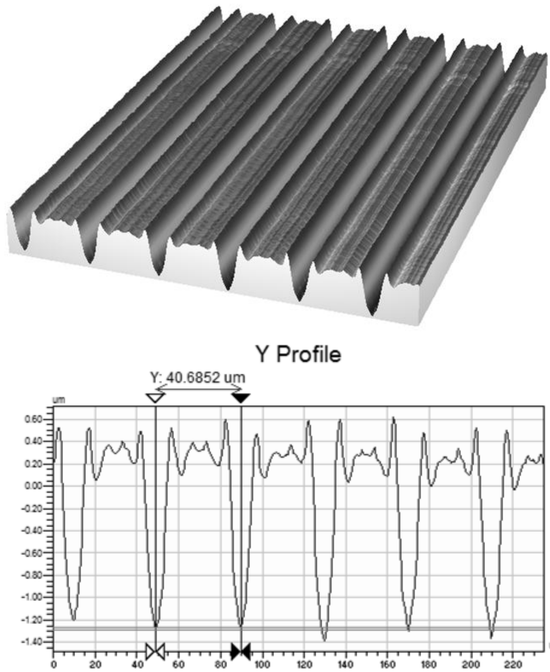

Fig. 2. **a).** Surface topography and **b).** Cross sectional profile of texture L1

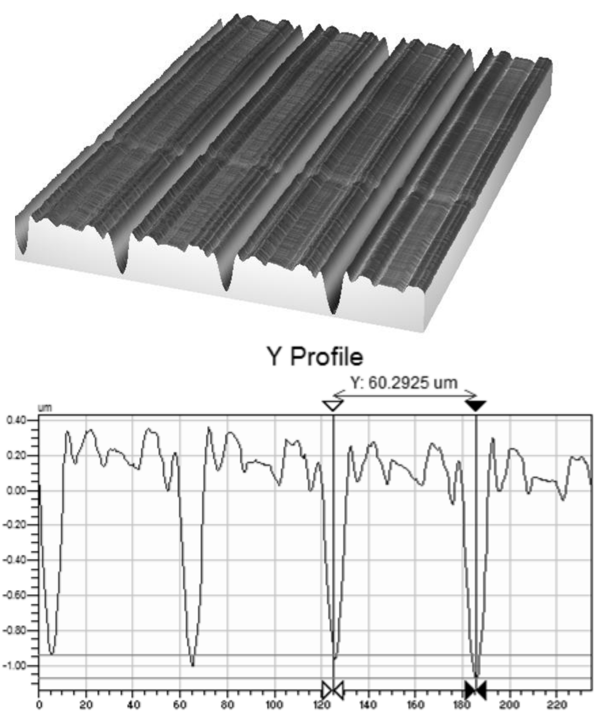

Fig. 3. **a).** Surface topography and **b).** Cross sectional profile of texture L2

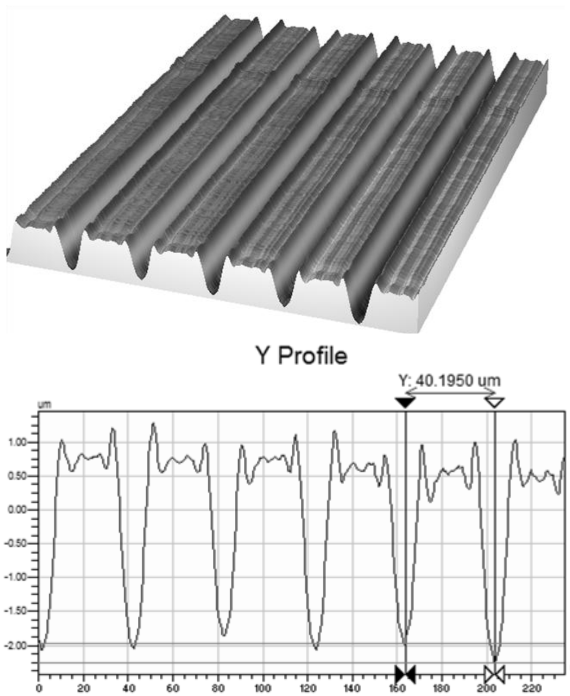

Fig. 4. a). Surface topography and **b).** Cross sectional profile of texture L3

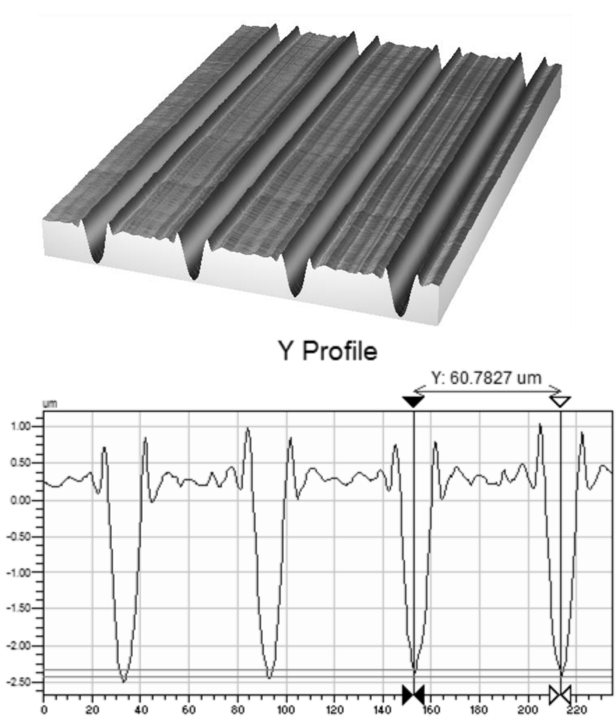

Fig. 5. a). Surface topography and **b)**. Cross sectional profile of texture L4

Table 3. Measured roughness characteristics of laser textures

Sl No	Texture (L)	Depth (μm)	Width (μm)	Measured Roughness Characteristics			
				Ra (μm)	Rq (μm)	Rsk	Rku
1	L1	1.66	12.21	0.44	0.545	-1.236	0.056
2	L2	1.29	12.41	0.237	0.342	-1.849	2.34
3	L3	2.77	14.21	0.826	0.993	-1.122	-0.277
4	L4	2.90	14.70	0.665	0.889	-1.632	1.242

2.3. Tribological Testing

The reciprocating ball-on-flat tests according to ASTM G133 standard were carried out using a customized wear test rig in order to assess the friction behavior of textured and untextured tin bronze surfaces slid against EN - 31 steel balls (60 HRC, Ra = 0.06 μm). The reciprocating wear test rig was adopted for performing tribological tests. The oscillating motion was provided by a controlled variable speed AC motor. An eccentrical scotch yoke mechanism was adopted for the adjustment of the stroke. The normal load was measured by a cantilever type load cell. The frictional force was acquired in the form of voltage output from piezoelectric transducer which was connected to flexure mechanism. The coefficient of friction was considered as ratio of frictional load to normal load and the sliding direction was chosen to be perpendicular to surface textures (grooves). The tribological test conditions were chosen based on review of literature and initial experiments, and are presented in Table 4.

The effect of load (17, 27 and 38 N) at reciprocating frequency of 5 Hz on coefficient of friction of all textured and untextured samples was reported. Hence, three conditions of wear parameters were tested on each of the textured (L1, L2, L23 and L4) and on untextured sample (UL5) constituting of total 15 experiments. These tests were carried out at oil lubricated conditions, 25ºC room temperature and 30 % relative humidity. For the lubricated tests, SAE 15W-40 oil was smeared on the surface only once well before the start of the experiment. Each experiment was performed with the combination of new track contacting with a new ball surface.

After each test, the ball and specimen were cleaned with acetone for 10 min and blown with dry air at 40ºC in order to remove any debris and oil droplets on the generated tracks.

3. Results and Discussion

3.1 Influence of scanning speed and texture density on Roughness parameters

Average surface roughness (Ra), root mean square (Rq), skewness (Rsk) and kurtosis (Rku) obtained for textured tin bronze samples are summarized in Table 3. The effect of scanning speed and texture pitch on Ra and Rq is as shown in Fig. 3. Increasing the pitch from 40 to 60 µm at constant higher scanning speed of 10 mm/s results in the decrease of Ra from 0.44 to 0.237 µm. When the scanning speed was reduced from 10 mm/s to 5 mm/s, Ra drastically increased from 0.237 to 0.826 µm. Increase in pitch from 40 to 60 µm at constant lower scanning speed of 5 mm/s resulted in the decrease of Ra from 0.826 to 0.665 µm. Thus, both scanning speed and pitch were found to be inversely related to Ra. Rq also exhibited the same trend as Ra at higher scanning speed of 10 mm/s. At lower scanning speed of 5 mm/s, Rq decreased slightly from 0.933 to 0.889 µm. Hence, increasing the pitch and producing textures at lower scanning speed had little effect on Rq.

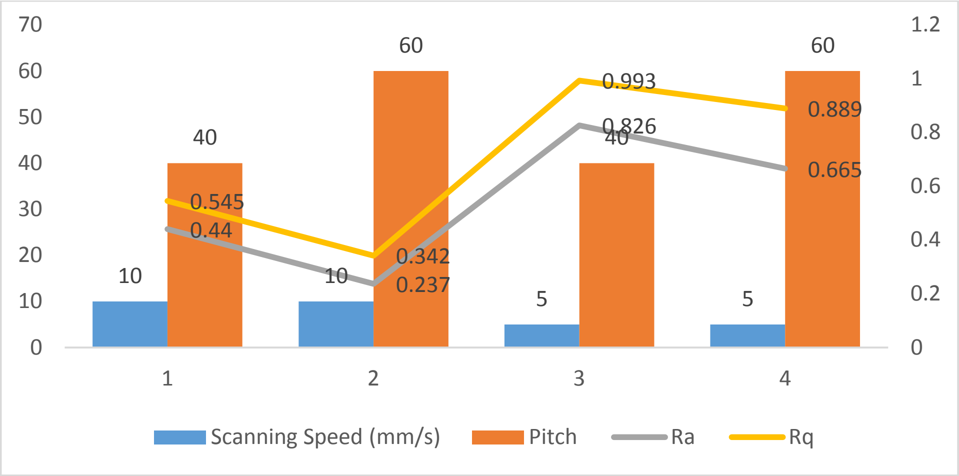

Fig. 3. Effect of scanning speed and pitch on Ra and Rq

The effect of scanning speed and pitch on R_{sk} and R_{ku} are as shown in the Fig. 4. At higher scanning speed of 10 mm/s, increasing the pitch from 40 to 60 µm leads to more negative value of Rsk i.e. decrease in Rsk from -1.236 to -1.849. But, Rku increased from 0.056 to 2.34 by increasing the pitch from 40 to 60 µm. Decreasing the scanning speed from 10 to 5 mm/s resulted in an increase of Rsk from -1.849 to -1.122. However, R_{ku} decreased from 2.34 to -0.27, thus attained a negative value. Increasing the pitch at lower scanning speed of 5 mm/s leads to more negative value of R_{sk}. R_{ku} also changed back from negative (-0.2769) to positive (1.242). The effect of increasing the pitch is more evident at higher scanning speed of 10 mm/s, where an increase in pitch from 40 to 60 µm resulted in ~40 times higher kurtosis as against ~6 times achieved at lower scanning speed of 5 mm/s. Increase in pitch provides higher surface area and higher scanning speed leads to lower degree of interaction of laser with material due to the which the kurtosis increases. Thus, higher kurtosis and negative skewness could be obtained at higher scanning speed and higher pitch.

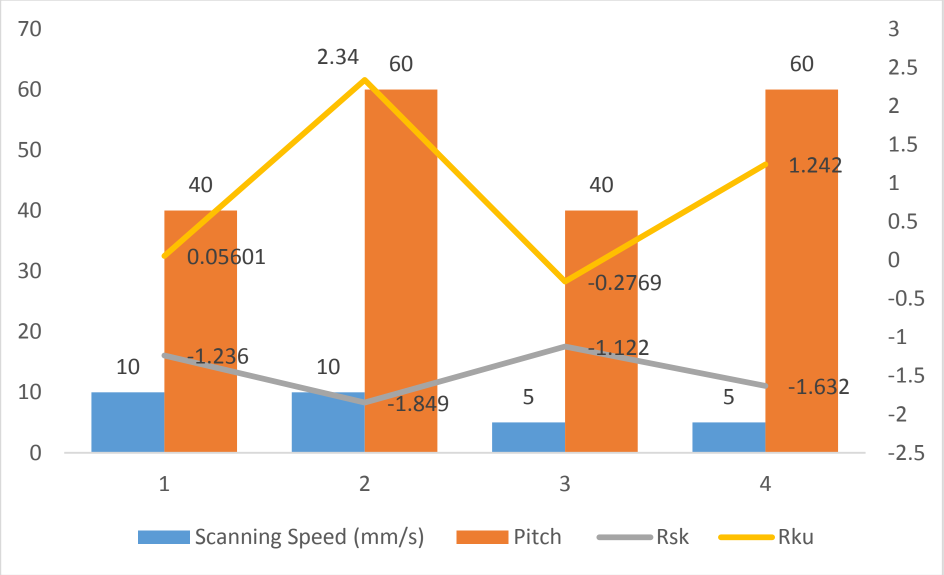

Fig. 4. Effect of scanning speed and Pitch on R_{sk} and R_{ku}

3.2 Influence of scanning speed and texture density on Coefficient of Friction

The effect of scanning speed and texture density on coefficient of friction (COF) is as shown in Fig. 5. The coefficient of friction was evaluated at frequency of 5 Hz and load conditions of 17, 27 and 38N. At higher scanning speed of 10 mm/s, increase in pitch from 40 to 60 µm leads to decrease in COF from 0.098 to 0.091 at a load of 17N. With decrease in scanning speed from 10 to 5 mm/s, the COF increased from 0.091 to 0.17. Again increasing the pitch leads to decrease in COF. When the load is increased from 17 to 27 N, the COF remains stable irrespective of change in pitch from 40 to 60 µm at higher scanning speed of 10 mm/s. With decrease in the scanning speed from 10 to 5 mm/s, COF increases from 0.091 to 0.105. Increasing the load from 27 to 38 N leads to decrease in COF from 0.0921 to 0.083 at higher scanning speed of 10 mm/s. Now, increasing the pitch from 40 to 60 µm further causes a decrease in COF from 0.083 to 0.0725. The COF decreases by ~15% with increase in load from 17 N to 38 N for the textures produced at higher scanning speed (10 mm/s) and higher pitch of 60 µm. For the textures produced at lower scanning speed (5 mm/s), the same conditions leads to a decrease in COF by ~20%. However, the textures produced at lower scanning speed of 5 mm/s and pitch of 40 µm exhibited ~48% decrease in COF when the load was increased from 17 to 38N. The friction performance of textured and untextured specimen at 5 Hz and 38 N is as shown in Fig. 6. All the textures (L1 to L4) exhibited COF less than that of untexured ones. After completion of 2500 cycles, L2 and L4 textures attained a more stable state when compared to that of L1 and L3. Thus, textures formed at a pitch of 60 µm and a scanning speed of 5 mm/s reduced the friction coefficient from untextured one (0.091) by ~25%.

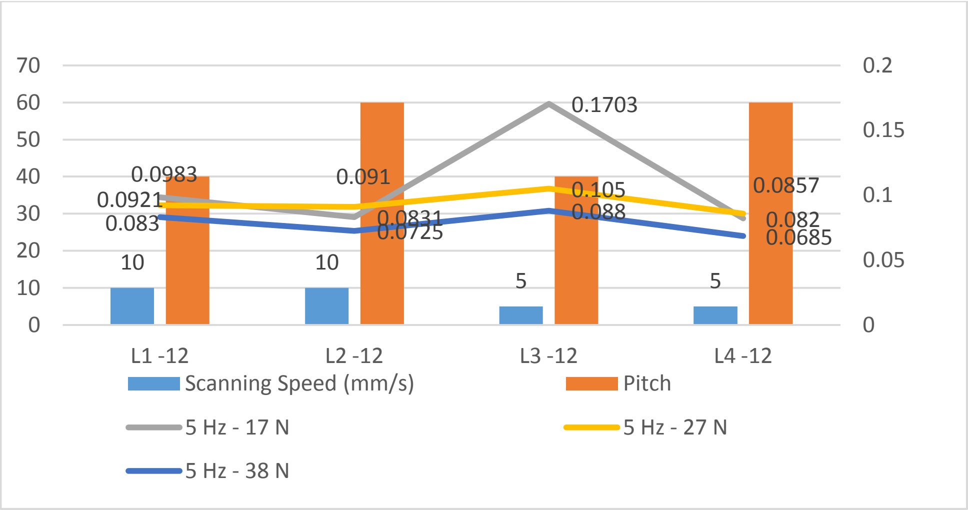

Fig. 5. Effect of scanning speed and texture density on coefficient of friction (COF)

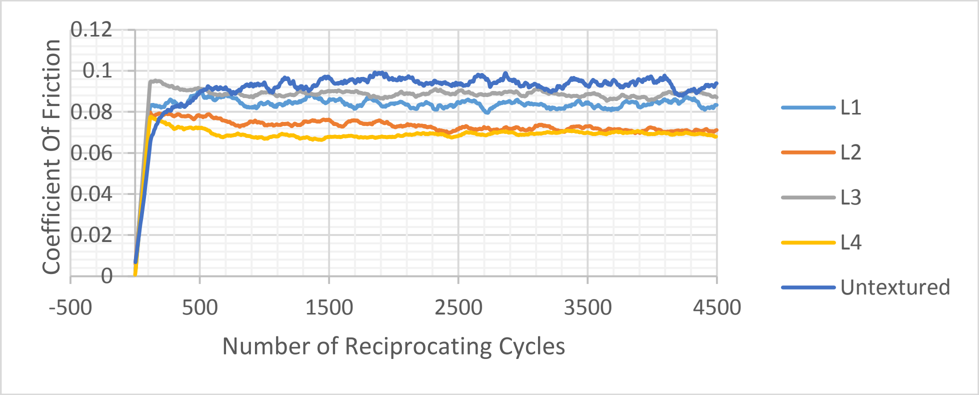

Fig. 6. Friction performance of textured and untextured specimen

3.3 Correlation between the Roughness parameters and Coefficient of Friction

Under lubricated conditions, the correlation between the roughness parameters and coefficient of friction of tin bronze is established. Fig. 7 predicts the relation of average surface roughness Ra with coefficient of friction evaluated at frequency of 5 Hz and three load conditions mainly 17, 27 and 38N. A polynomial curve fit with R-squared value mainly indicates the degree of correlation between the two factors. It can be observed that increase in load from 17 N to 38 N gradually decreases the correlation between Ra and COF. Increase in R_a leads to increase in COF at lower load of 17 N. Lowest COF of 0.0831 corresponds to lowest Ra of 0.237 for L2 sample i.e. texture produced at higher pitch and higher scanning speed. Thus, at higher loads of 27 N and 38 N, increase in R_a do not show much effect on COF. The same trend is even observed between R_q and COF as shown in the Fig. 8. The correlation gets completely deteriorated at higher load of 38 N which is indicated through lowest R-squared value. Thus, Ra and Rq are not sufficient enough to predict the friction performance at higher loads.

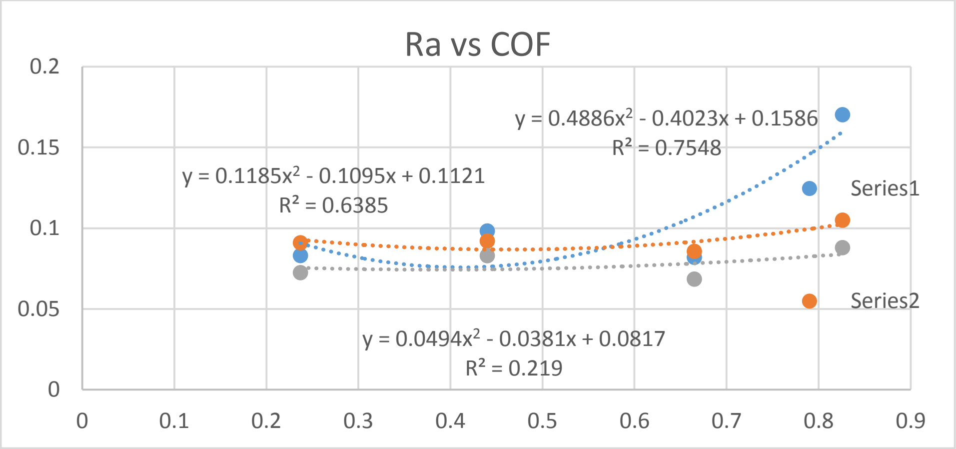

Fig. 7. Correlation of Ra with COF predicted at 17, 27 and 38 N

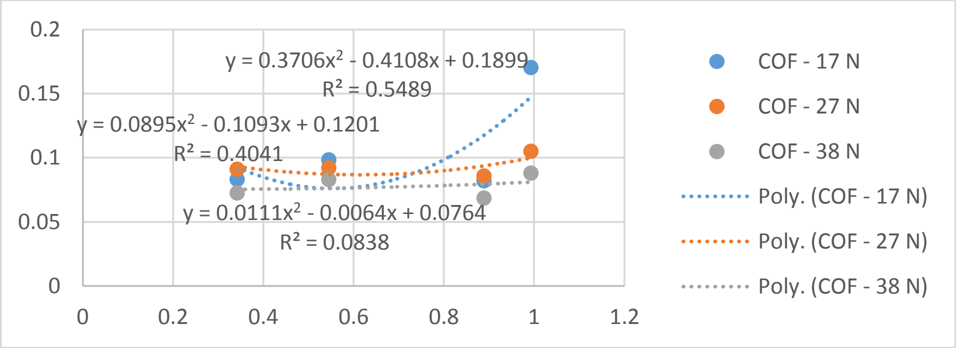

Fig. 8. Correlation of Rq with COF predicted at 17, 27 and 38 N

The correlation between the skewness (R_{sk}) and COF is as shown in Fig. 9. At all load conditions, skewness was found to be inversely related to COF. More negative the skewness lesser is the coefficient of friction under lubricated conditions. At higher load of 38 N, higher negative skewness (Rsk) of -1.849 was obtained for L2 sample having minimum COF of 0.0725. However, COF attained maximum value of 0.1703 when skewness became less negative (-1.122) for L3 texture produced at lower scanning speed and lower pitch. The correlation between Rsk and COF was found to increase with increase in load from 17 N to 38 N which is indicated by high R-squared values i.e. 83% at 17N, 94% at 27N and 98.23% at 38 N. This clearly indicates that the deep valleys and grooves that are characterized by negative skewness act as lubricant reservoirs [20] and causes the decrease in friction coefficient at higher loads. The effect of

R_{ku} on COF is as shown in the Fig. 9. The highest skewness of 2.34 was obtained for L2 sample having COF of 0.0725 at a load of 38N. Thus texture produced at higher scanning speed and higher pitch leads to higher kurtosis and negative skewness. The surface morphology of L2 texture is as shown in the Fig. 10. The uniformity of texture, waviness and roughness patterns obtained at certain area indicated the high quality of textures. However, kurtosis value remained less than 3 which also confirms that higher scanning speed (10 mm/s) will cause lower groove depth. Negative kurtosis of -0.2769 was found for L3 sample i.e texture produced at 5 mm/s and 40 µm. Thus, texture produced at lower scanning speed and lower pitch corresponds to negative kurtosis and less negative skewness. The corresponding surface morphology of L3 texture is as shown in the Fig. 12. The non-uniform patterns of texture, waviness and roughness obtained at certain area indicated the decreased quality of textures. Similar to R_{sk}, the correlation between R_{ku} with COF increased with increase in load i.e. 89% at 17N, 78.3% at 27N and 99.25% at 38 N.

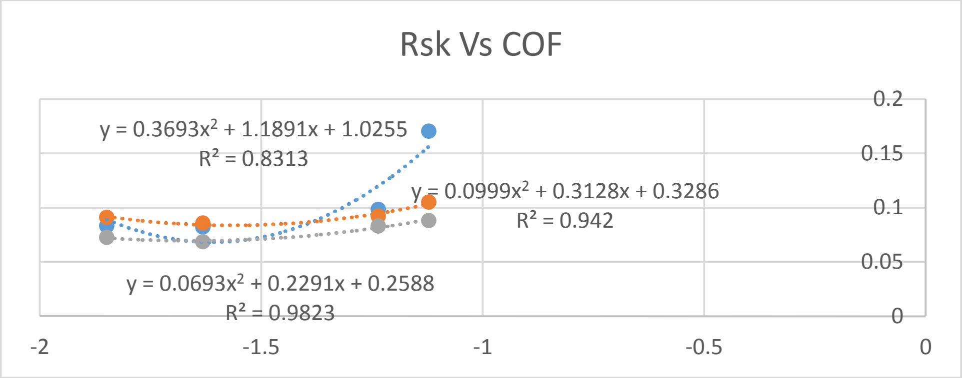

Fig. 9. Correlation of Rsk with COF predicted at 17, 27 and 38 N

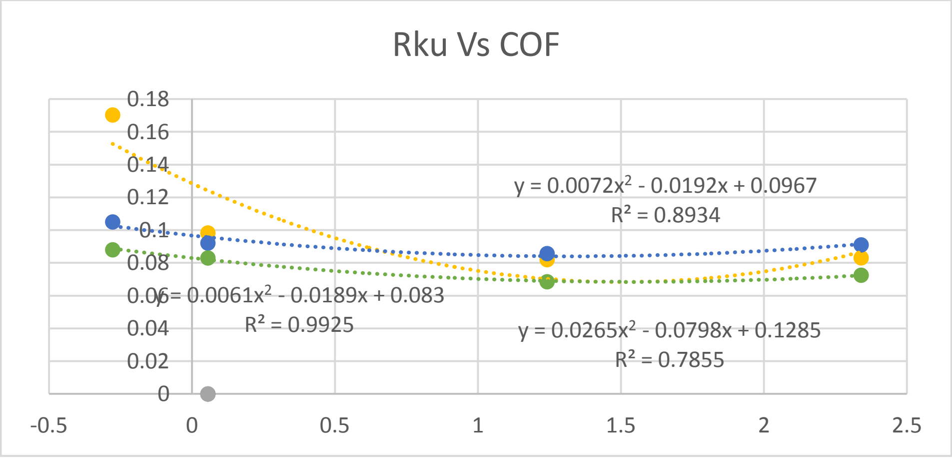

Fig. 10. Correlation of Rsk with COF predicted at 17, 27 and 38 N

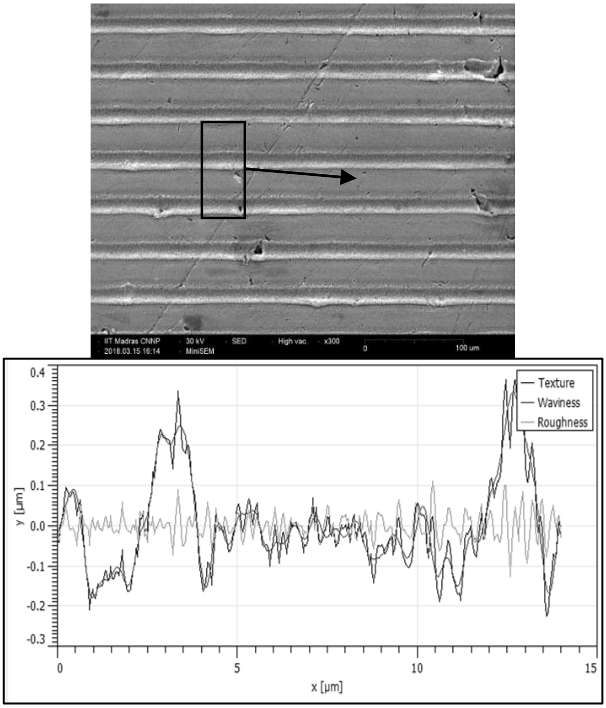

Fig. 11. Surface morphology of L2 texture (Higher scanning speed and higher pitch)

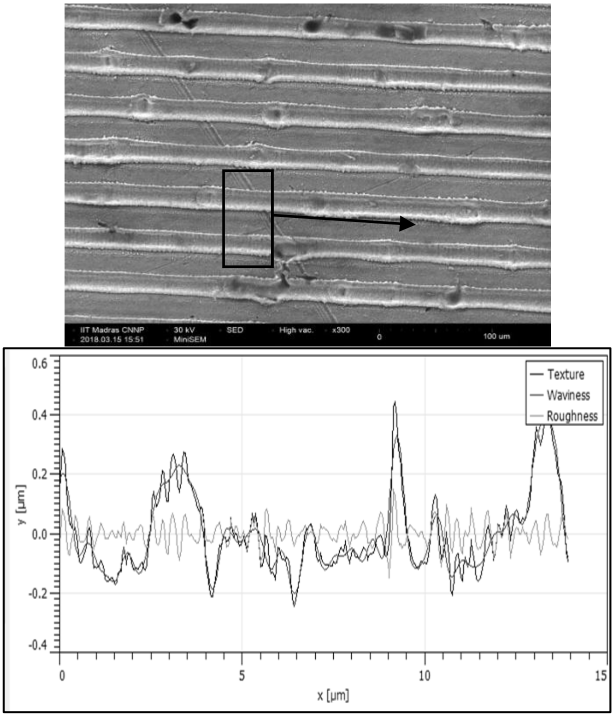

Fig. 12. Surface morphology of L3 texture (Lower scanning speed and lower pitch)

4.0 Conclusions

Femtosecond laser surface texturing of high tin bronze alloy was carried out in order to assess the effect of scanning speed and texture pitch on surface roughness parameters such as Ra, Rq, Rsk and Rku. While the scanning speed and pitch were found to be inversely correlated with Ra, increasing the pitch and producing textures at lower scanning speed had little effect on Rq. Textures produced at higher pitch and higher scanning speed showed ~40 times higher kurtosis as against ~6 times produced at lower scanning speed. The correlations between Ra and COF, and Rq with COF did not agree well at higher loads whereas the same achieved between Rsk and COF, and R_{ku} and COF were completely agreeable indicated by high R-squared values. Maximum COF was attained for the texture produced at lower scanning speed and lower pitch that corresponded to negative kurtosis and less negative skewness. Also, the textures produced at higher scanning speed and higher pitch leads to higher kurtosis and negative skewness which indicates the improved lubrication conditions. Thus, the analysis of roughness parameters before and after the tribological assessment could lead to better understanding of contact applications.

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