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Effect of scanning speed and tin content on the tribological behavior of femtosecond laser textured tin-bronze alloy

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ABSTRACT

Femtosecond laser surface texturing of soft bearing materials such as tin bronze is of great interest to manufacturing community since it aims at protecting valuable steel components by reducing wear and friction. This paper examines the effect of scanning speed on femtosecond laser texture characteristics of tin bronze alloy containing 8% and 12% tin. The friction and wear behavior of microgrooves produced on tin bronze alloy were reported under lubricated conditions. Higher tin content and lower scanning speed led to higher depth and width of the grooves. The friction performance was improved by increasing the number of reciprocating cycles on tin bronze alloy containing 12% tin at higher normal load. Grooves formed at lower scanning speed exhibited lower wear rate at higher load and higher frequency because of improved lubrication conditions. However, wear performance of tin bronze alloy containing 8% tin was less than that of untextured samples. The morphology of worn surfaces indicated the trapping of wear debris and possibility of formation of oil film due to which the lower coefficient of friction was observed.

1. Introduction

High tin bronze alloys are those which contain at least 6% tin. They are typically found in gear and high-strength bushing and bearing applications – especially where high strengths, low speeds, and heavy loads are present. For instance, they find applications in 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]. Hence, the effect of friction and wear on the durability of tin bronze components becomes a primary concern. In most of the cases, the failure of the components due to friction, wear, erosion and fatigue always take place on the surface. Hence, surface texturing of copper alloys has been effectively adopted from many decades in order to improve their tribological performance against hard mechanical components.

Femtosecond laser is a powerful tool for microprocessing of different materials ranging from polymers to semiconductors and metals [3]. During the process, cooling of electrons takes place rapidly due to energy transfer to the lattice and heat conduction to the target. Ablation is considered as direct solid – vapour transition. Lattice gets heated in picoseconds which results in direct vapour and plasma followed by rapid expansion in vacuum [4]. Hence, minimum energy is transferred to the material and results in controlled HAZ, heat rate and interfacial velocity [5]. Interaction of fs pulses with target material is highly non-linear which results in high pulse intensities allowing the fabrication of minute structures [6]. These include creation of dimples, grooves and micro channels. Femtosecond laser textured surfaces find wide variety of applications that include thrust bearings [7], journal bearings [8], cylinder liners [9], piston rings [10,11], concentrated contacts [12,13], mechanical seals [14], magnetic storage devices [15] and piston pins [16].

Some of the researchers have focused on surface texturing of copper alloys. Quanbo Shang et al [17] investigated the effect of surface texturing on wear performance of tin bronze (CuSn6) alloy using Nd:YAG laser under millisecond pulse regime. The authors found that the higher wear rate of laser surface textured (LST) specimen was mainly due to the softening of Heat affected Zone (HAZ) of laser dimples. Also longer wear period was observed for LST specimen than that of non-textured specimen. Auezhan et al. [18] investigated the effect of groove geometry on the height of bulges formed during the surface texturing of tin bronze alloy using Nd:YAG laser operated under nanosecond regime. The effect of load and reciprocating speed on the sliding friction and wear was also reported under lubricated conditions. The dimpled

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specimen with lowest density and smallest diameter showed the lowest friction coefficient and resistance to wear. Also bulges with the height of 3.5 μm caused the reduction of friction coefficient. Xia he et al. [19] investigated the effect of laser power and number of pulses on the geometrical characteristics of surface textures created on rock bit sliding bearings made of beryllium bronze. The tribological tests were performed using rock bit grease, a non-Newtonian fluid. The friction coefficient of textures with depth-to-diameter ratio of 0.165 and 0.483 decreased with increase in shear rate from $500\,s^{-1}$ to $1300\,s^{-1}$. The lubrication regime of textured mating pairs was improved from boundary to mixed level when compared to that of untextured specimen. Waldemer et al. [20] investigated the effect of surface textures on anti-seizure properties of steel – tin bronze assembly. The authors showed that texturing could increase the lifetime of the assembly up to five times than that of untextured block samples. Waldemer et al. [21] investigated the effect of dimple size and distribution on the wear performance of slider bearings made of tin bronze (CuSn10P). The dimples were created using impulse burnishing technique and wear experiments were performed using mineral oil as a lubricant. Lowest wear rate was observed at highest dimple depth. Same authors also extended their study to investigate the effect of wear behavior of tin bronze under mineral oil filled with abrasives (alumina and silica). The abrasive particles present in the oil caused 50% higher wear rate when compared to the test without abrasives. Cherian et al. [22] investigated the effect of tin content (4, 6, 8 and 12 wt%) on the microstructure, hardness and tribological characteristics of surface refined Cu-Sn alloys. The surface refinement was carried out using gas tungsten arc as a heat source. They reported that wear rate and hardness decreased with increase in tin content whereas coefficient of friction remained stable irrespective of variation in hardness.

Among the various surface modification processes, femtosecond laser surface texturing (FLST) is a clean and efficient process that produces minute structures in order to improve the functionality of the surface. 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. Such modification also lead to altering of tribological behavior of material surface. Even though, some of the authors have focused on laser surface modification of tin-bronze alloys by producing microtexures [17,18], their studies are limited to long pulse regime (ms, ns) under which the laser parameters were optimized. This necessitates a comprehensive research to predict the surface characteristics of tin bronze alloys subjected to ultra short pulsed laser irradiation. The influence of scanning speed and tin content on the surface texture characteristics of tin bronze alloy using fs laser is not yet reported so far. Hence, the aim of the present research was to investigate the influence of scanning speed and tin content on the friction and wear behavior of femtosecond laser textured tin bronze alloys under sliding lubricated conditions. Rectangular microgrooves were produced with varying scanning speed on each of the sand-casted tin bronze specimen containing 8% and 12 wt% tin. Reciprocating wear test rig was adopted to produce tracks on each of the textures to assess the effect of load and reciprocating frequency on friction and specific wear rate. Morphology of worn surfaces were analyzed using Scanning Electron Microscope (SEM).

2. Materials and methods

2.1. Specimen preparation

Sand-casted tin bronze alloys containing 8 and 12 wt% tin were 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 castings were analyzed using Meta Vision tungsten arc spectrometer. The composition of the alloys were found to be within the range of ±0.1% wt from the nominal composition. The chemical composition of the samples are as shown in Table 1. The surface hardness of the samples with 8 and 12 wt% tin were found to be 136.4 HV and 139.16 HV respectively, which were 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.

2.2. Laser surface texturing with fs pulses

A commercial Ti: sapphire fs laser- Spitfire Ace power amplifier (12 W output power, 50 ps–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. Two types of textures with varying scanning speeds (5 and 10 mm/s) were created on each of tin bronze samples containing 8 and 12 wt% tin. The textured samples were designated as T1-8, T2-8, T3-12, and T4-12. The untextured samples were designated as UT-8 and UT-12 for 8 and 12 wt% of tin, respectively. Throughout the experiments, the pitch between the grooves and laser power were maintained at 40 μm and 100 mW respectively. The depth and width of the grooves were measured using Bruker 3D Non-contact Profiler. The surface topography of the T1 - 8 texture and its cross-sectional profile are as shown in the Fig. 1(a) and (b).

Table 2
Experimental plan for fs laser surface texturing.

Sl no	T	Tin content (wt. %)	Laser power (mW)	Scanning speed (mm/s)	Pitch (μm)
1	T1 -8	8	100	10	40
2	T2 - 8	8	100	5	40
3	UT-8	8	0	0	0
4	T3-12	12	100	10	40
5	T4-12	12	100	5	40
6	UT - 12	12	0	0	0

Table 1
Elemental composition of tin bronze alloys.

Element (wt. %)	Cu	Sn	Pb	Zn	Fe	Si	Mn	Sb	P	S	Cr	Be	As
Sample 1	90.83	8.428	0.416	0.061	0.006	0.023	0.01	0.015	0.163	0.036	0.009	0.002	0.002
Sample 2	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