INFLUENCE OF INITIAL SURFACE STATE ON LASER SURFACE TEXTURING RESULT

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Abstract

Laser surface texturing (LST) is one of the methods for obtaining surfaces with specific properties. In this paper the influence of initial surface state of sliding bearing steel on laser texturing of this material was studied. Initial surface with roughness R_a = 0.13 µm was used for providing shifted laser surface texturing (sLST) by ultrashort laser pulses. On initial "rough" surface laser formation of above-surface-growth (ASG) structures was found. Morphology and chemical composition of the ASG structures were analysed by SEM with EDX spectrometer in comparison with initial surface. Two ways of regression of ASG structures were investigated - fine mechanical repolishing of surface for R_a = 0.01 µm and optimisation of laser processing parameters. It was found that the most suitable method of ASG structures regression is optimisation of laser processing parameters in comparison with mechanical repolishing. Regression of ASG structures formation by optimisation of laser processing parameters was provided by application higher laser fluence. Temperature field distribution for different laser processing parameters is determined from semi-planar thermal model. Heat accumulation effect is evaluated for both - sLST by simple pulses and burst mode. Advantages and disadvantages of presented methods for regression of ASG structures formation were discussed with theoretical background. Presented results improve understanding of physical principles of ASG structures formation and the ways for their regression.

Keywords: Shifted laser surface texturing, optimisation, above-surface-growth, semi-planar model, heat accumulation

1. INTRODUCTION

Laser processing of material has several limitations, such as heat accumulation, shockwaves, remelting with structure changes of material and other [1 - 3]. There are several types of structure changes of the surface. The most known are laser induced periodical structures which are formed by interaction of laser light with surface scattered electromagnetic waves or by self-organised periodical structural changes by thermo-mechanical fields [4 - 7]. Formation of non-periodical structures under series of the laser pulses is connected with hydrodynamical processes of material reposition [8]. One of the type of surface changes mentioned by Zuhlke et al. (2013) is formation of above-surface-growth (ASG) structures [8]. It was mentioned, that ASG structures is defined by precursor sites on the surface [8, 9]. One of the way for suppression of the ASG structures is elimination of precursor sites surface by surface cleaning [10]. The next possibility for increasing of quality of laser processing is correction of laser beam parameters - fluence, scanning speed, spot overlapping, pulse duration or by connecting of the laser pulses in one burst [1, 11, 12]. Laser surface texturing (LST) is used for forming of array of microobjects on material surface. In the experiments with LST processing of material for tribology applications the depth of microobjects should be in the region 4-5 µm [13, 14]. The correct form of the microobject has influence on the lubricant movement and decreasing of the friction coefficient [15, 16]. The shifted laser surface texturing (sLST) gives possibility to provide high precision micromachining of material with avoiding of heat accumulation effect [7]. The goal of this paper is sLST of bearing steel in connection with several methods of suppression of the ASG structures. Suppression of the ASG structures is provided by mechanical repolishing of initial surface as preprocessing, and increasing of laser pulse fluence and laser spot diameter in sLST of material.

2. EXPERIMENTAL SETUP

Two different slab lasers (Edgewave) were used, both on second harmonic (wavelength λ = 536 nm) with 10 ps laser pulse. The maximum pulse energies were 50 µJ and 160 µJ. Effective spot diameters were 12 and 20 µm respectively. For all tests the galvanic laser scan heads (SCANLAB) were used with maximal applied scanning speed 4 m/s. The sLST was realized on the surface of bearing steel DIN 100CrMnSi6 in as-obtained surface state and on metallographically polished surface. Roughness of initial surface was Ra = 0.13 µm with main width of surface ridges equal to 2.49 µm. After polishing, the roughness did not exceed Ra = 0.01 µm.

All processing of material was provided by sLST method with equidistributed laser spots between whole objects in the scanning field. The objects are simple dimples collected by sLST method from several laser spots ordered in one, two or three circles, in depending of the laser spot size. The diameter of the sLST objects varied between the 55 - 60 µm. Resulted morphology of textured objects was analysed by 3D digital microscope HIROX KH-7700 and SEM FEI Quanta 200. Chemical analyses was provided by EDX detecting unit XL-30.

3. RESULTS OF EXPERIMENTS AND DISCUSSION

The first series of experiments was done on the rough initial surface (Ra = 0.13 µm) by 10 ps laser and 50 µJ. Laser processing was done by sLST method and on the rough surface initiated formation of ASG structures (**Figure 1a**). The same sLST method was applied on polished surface to suppress the formation of ASG structures by more homogeneous absorption of the laser energy. The result is presented in **Figure 1b**. It can be seen that the ASG structures were not formed under laser processing and matched micro-dimples have smooth bottom as a result of removing the surface roughness. This fact underlies the influence of the homogenous distribution of the laser energy along surface.

Although fine repolishing of the bearing surface helps for obtaining high quality tribological sLST, it does not work correctly for micromachining of dimples with depth bigger than 30 µm. Further processing of material again activates formation of the ASG structures. Moreover, fine repolishing of surface makes it not practical for serial manufacturing.

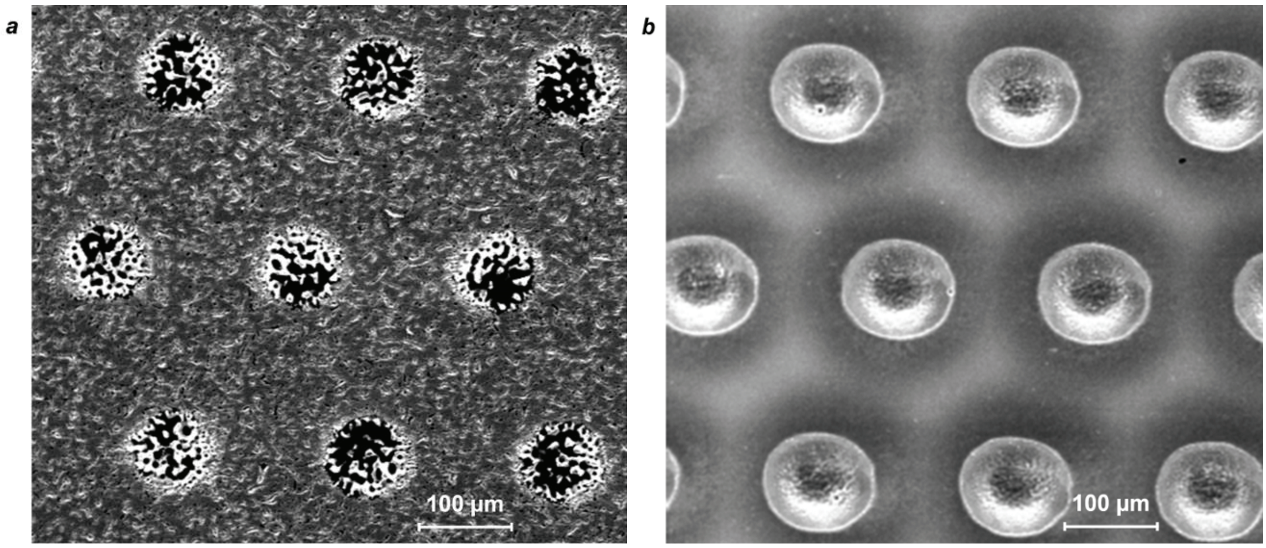

Figure 1a) SEM image of AVG structures appeared after sLST processing of initial rough surface of bearing steel, **1b)** SEM image of dimples formed by sLST processing of repolished surface of bearing steel

The next method of suppression of the ASG structures was applying of higher energy of the laser pulses. On **Figure 2** is presented sLST provided by 10 ps laser and with pulse energy of 160 µJ. This higher energy of laser shots makes bigger effective diameter of the laser spot and it was equal to 20 µm. The sLST for this value of energy was provided. Higher energy of the laser pulses involves deeper penetration of the light and wider distribution of heat [17]. As a result, influence of imperfection of the initial surface morphology has no effect on internal structure of sLST objects (see **Figure 2a** in comparison with **Figure 2b**). Processing of material by sLST has not involved heat accumulation. As a result, no oxidation increase was detected inside of the textured objects. In the next paragraph the comparison of temperature changes for both regimes of sLST processing is calculated by application of 3D-model of heat flow from discrete sources ordered by Gaussian distribution [18].

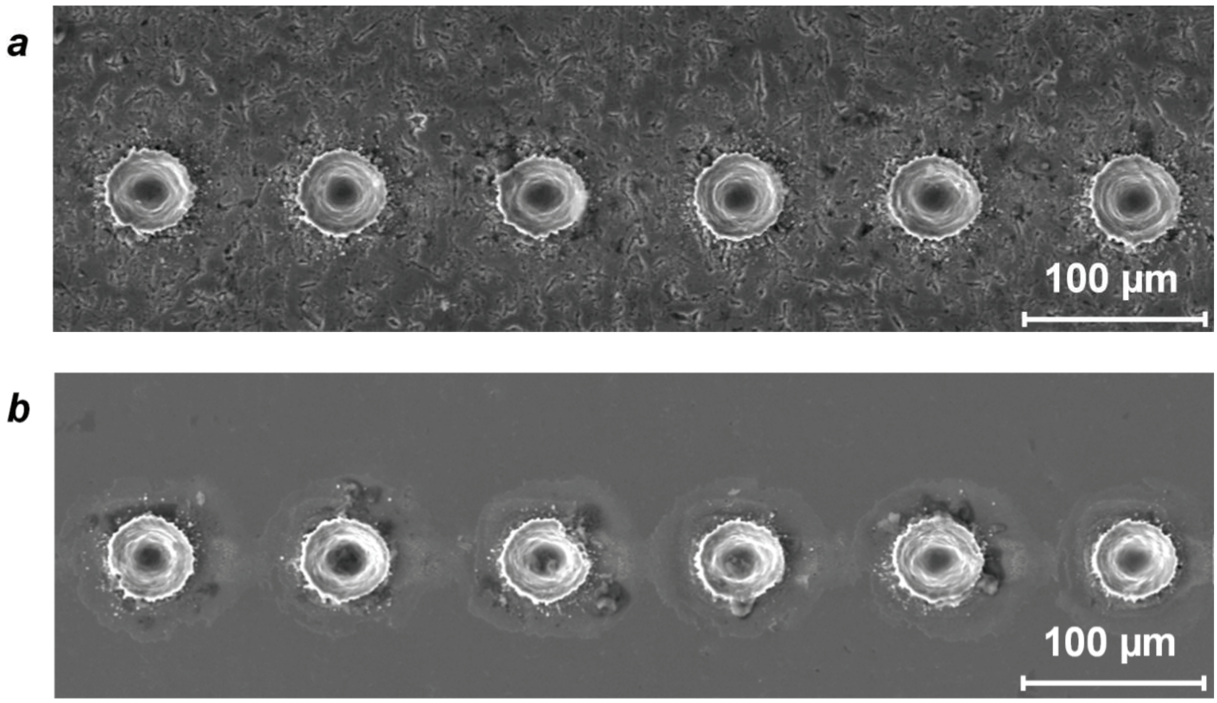

Figure 2 SEM image of dimples formed by sLST processing of **a)** initial rough surface of bearing steel; **b)** repolished surface of bearing steel

4. CALCULATION OF TEMPERATURE FIELD

Time interval between overlapped laser shots for processing material by sLST is about 0.1÷0.5 sec. Long delay between laser pulses gives possibility to describe temperature distribution under laser spots without overlapping or heat accumulation effect. Heat distribution under surface initial defect was evaluated from classical integral solution of heat distribution from point heat sources [19, pp. 256 - 260]. Heat distribution in the material body from one surface instantaneous heat source has exponential form:

$$T(t,z) = \frac{Q}{\rho \cdot c\sqrt{\pi \cdot \alpha \cdot t}} \cdot e^{-z^2/4 \cdot \alpha \cdot t} \quad (1)$$

where t - time from laser pulse application, ρ - material density, c - specific heat capacity, α - thermal diffusivity, Q - energy of one surface heat source, z - depth from surface.

Evaluation of heat distribution under rough initial surface is provided as summation of array of instantaneous heat sources which are contained in the laser spot. Every instantaneous heat source has individual strength F_i - surface density of absorbed energy (J/cm²). For laser processing of a polished initial surface the strength of all heat sources is described by Gaussian distribution. Suitable approximation in this case it is square of cos function, because it gives possibility to involve in calculations effective laser spot radius, which corresponds to the radius of the laser affected surface area, as R_{max}:

$$F_i = F_0 \cdot cos^2\left(\frac{\pi \cdot r_i}{2 \cdot R_{max}}\right) \tag{2}$$

where F_0 - density of heat energy in the center of the laser spot, equal to $3.363 \cdot E/\pi \cdot R_{max}$(here E - absorbed energy from the laser pulse, which was taken 12.5% from full laser pulse energy [17]); r_i - distance between center of the laser spot and one instantaneous heat source. The value of Q is calculated from F_i by $Q = S \cdot F_i$, where S is the area of one instantaneous heat source in array.

In the case, when initial surface has a defect, then heat strength of the individual heat sources from the defect area have bigger strength $F_{i(defect)}$:

$$F_{i(defect)} = d \cdot F_0 \cdot cos^2\left(\frac{\pi \cdot r_i}{2 \cdot R_{max}}\right) \tag{3}$$

here d - is coefficient indicating how many times the absorption coefficient is higher in the defect area than in the clear area. In this paper calculations were done for three time bigger heat strength of the heat sources ($d = 3$). According to experimental conditions the calculations were made for parameters with two pulse energies 50 µJ and 160 µJ with diameters 12 µm and 20 µm respectively. Temperature changes were evaluated for subsurface layer of metal in depth of 3 µm under laser spot at 0.1 µs after the laser pulse. In calculation for the case of surface with defects, influence of only one surface defect with size of 2 µm x 2 µm was involved in Equation 3. The distance between initial defect and laser spot center was 3 µm (**Figure 3a** and **3b**). The same calculations were provided for a case when distance was 7 µm, pulse energy 160 µJ and spot diameter 20 µm (**Figure 3c**).

When the distance between surface defect and center of the laser spot is the same, then temperature increase is similar for both laser energies. The temperature increase under defected area is about 21% and 29% higher compared to the maximal temperature changes under clear surface (**Figure 3a** and **3b**). Width of the temperature affected zone under defect is bigger in the first case with smaller spot diameter. It can be explained by bigger relative part of area under defected zone in comparison with the laser spot area. When the defect area is positioned more close to the edge of the laser spot (7 µm from center, bigger spot), then influence on temperature distribution is dramatically smaller (**Figure 3a** and **3c**). It can be explained by smaller part of energy absorbed by defect zone in comparison with whole energy absorbed under laser spot.

The next calculations were provided for burst mode of sLST. The time interval between two coupled pulses was 3.3 µs and it corresponds to the frequency of the laser generation 303 kHz. Heat accumulation in this case should be taken in the account in the short time interval Δt. The resulting temperature is described as superposition of the residual and actual temperature values:

$$T_{t+\Delta t} = T_t + T_{\Delta t} \tag{4}$$

where t - is the time after last laser pulse; Δt is the time after previous laser pulse.

For the mentioned laser frequency 303 kHz the residual temperature change $T_{\Delta t}$ corresponds to the blue solid line ("Defected surface I" on **Figure 3d**). The influence from the defected area has vanished at time 3.3 + 0.1 µs. The heat is not accumulated under the defect after previous laser pulse. This fact has shown that the burst mode is suitable method for processing of defected initial surfaces.

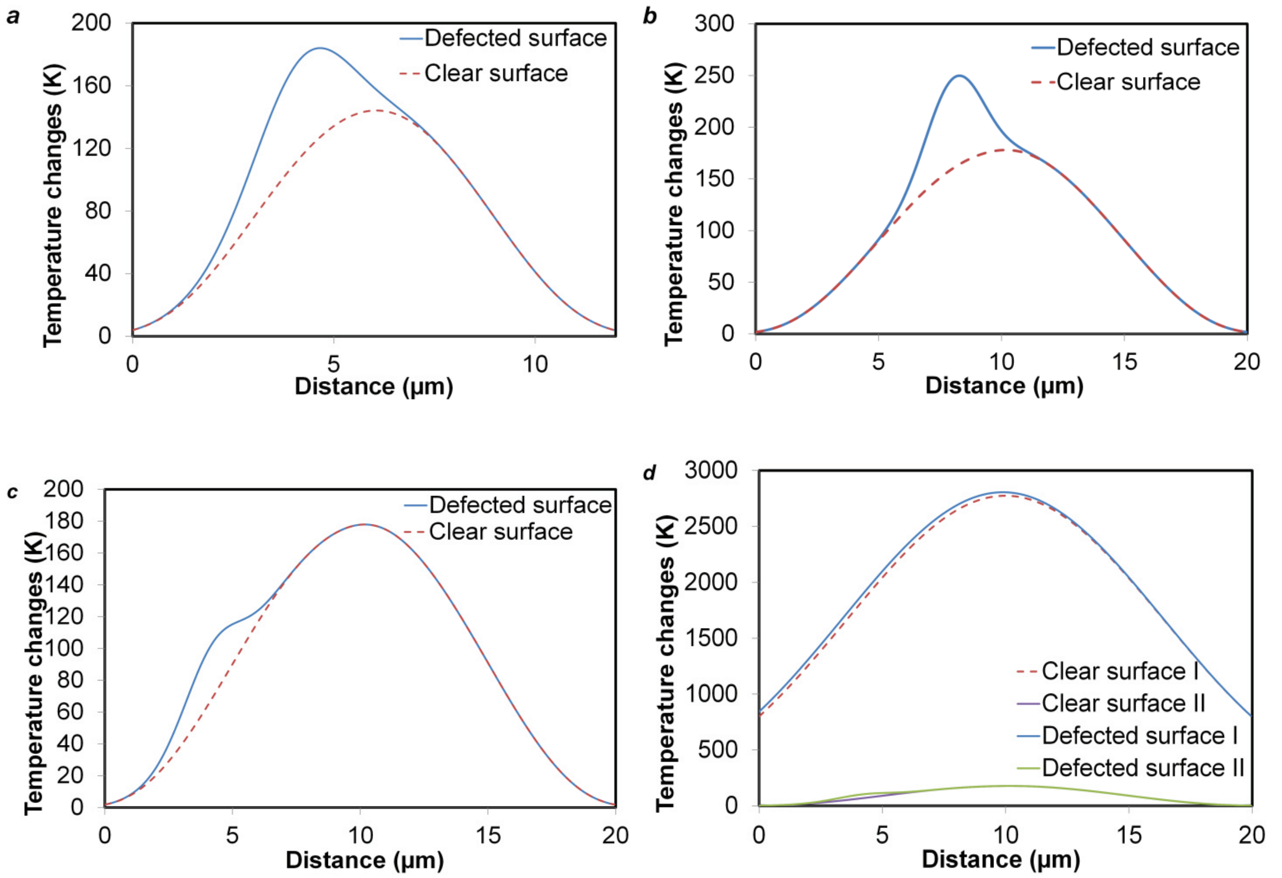

Figure 3 Temperature increase along laser spot diameter in depth 3 µm under surface. Red dotted line - temperature distribution under clear initial surface; blue solid line - temperature distribution under initial surface with one defect of 2 µm x 2 µm size. **a)** pulse energy 50 µJ and spot size 12 µm. Distance between center of laser spot and initial defect is 3 µm; **b)** pulse energy 160 µJ and spot size 20 µm. Distance between center of laser spot and initial defect is 3 µm; **c)** pulse energy 160 µJ and spot size 20 µm. Distance between center of laser spot and initial defect is 7 µm; **d)** burst double pulses with energy 160 µJ and spot size 20 µm. Distance between center of laser spot and initial defect is 7 µm. Indexes **I** and **II** indicates first and second pulse in the burst mode

5. CONCLUSION

In this paper the experimental study of influence of initial surface roughness on the laser surface texturing was studied. It was shown that smaller energy of the laser pulse and smaller diameter of the laser spot initiate the ASG structures forming. Two methods of the ASG structures suppression is described - repolishing of the material surface and increasing of the laser pulse energy with bigger laser spot diameter. The second method was defined as more suitable. Theoretical calculations of laser processing of initial surface, which contained defected area were done. Calculations were provided for the cases, when the defect is placed near center and near the edge of the laser spot. Temperature distribution for two laser processing regimes are presented for deeper understanding of physical background of ASG structures suppression. One shot mode calculations are presented in comparison with burst double shot mode. It was shown that residual temperature field after first laser pulse shot in the burst mode has vanished small affection from initial defect.

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