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Application of laser surface alloying for improvement of wear resistance of bearing steels working at severe conditions and of light titanium alloys

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ABSTRACT

The task of wear resistance improvement for bearing steels working at high loads in water medium was solved by laser alloying with Sn. The modified zone contains up to 22 wt.% Sn, which is used as a solid lubricant during exploitation. As a result the bearing race's durability is increased 2.5 times.

The combination of laser alloying from a nitrogen jet with surface plastic deformation (SPD) was used to produce Titanium nitride layers with minimum roughness, no cracks, and no residual stresses. The wear resistance tests showed the real possibility of using the developed method to manufacture friction joints from light Titanium alloys.

1. INTRODUCTION

Recently, many methods are used to overcome wear problem. However, a number of applied tasks concerning with reliability and durability are not solved up to now. For example, there are no satisfactory methods to improve wear resistance of friction joints working at severe conditions : high loads and contact pressures, wash-out of lubricant from the contact area, corrosive medium, etc. In this case, the nature of a friction surface interaction is closed to dry friction. It leads to high linear wear and fast destruction of mechanical parts. The wear behaviour of friction joints of an oil-drilling equipment (bearings, seals, gates, etc) are a typical illustration of the mentioned problem. For example, the durability of turbo-drill multirows bearings is only 4-6 hours. Tribotechnical joints working at severe conditions have, as a rule, high wear tolerance : from some hundreds microns up to several millimetres. Consequently, the thickness of modified layer must be comparable with the wear tolerance.

Sn is a well-known component of anti-friction alloys. However, the low melting point and high vapour pressure make difficulties for laser alloying with Sn.

Titanium alloys have a high strength and corrosion resistance at low specific weight. High friction coefficient, low wear resistance and a tendency to galling, however, limit their widespread use in industry. The formation of Titanium nitride on the surface of Titanium alloys is the most popular way to improve their tribological properties. Solid state nitriding by CVD processes, ion plating, magnetron sputtering, plasma spraying, or other similar methods are widely used for this purpose. All these methods have two main drawbacks : (1) these processes need the whole piece to be heated, which leads to grain's growth, thus impairing mechanical properties; (2) the coatings are formed on the whole surface and this leads to a decrease in fatigue resistance. Both these reasons make the treatment of parts submitted to cyclic loads impossible by conventional methods.

2. EXPERIMENTAL PROCEDURE

2.1. Laser alloying of bearing steels with Sn. A 2.5 kW CO₂ laser and Nd:YAG pulse-periodic (pulse duration $\tau=1-10$ ms, pulse energy $E=1-30$ J) were used. Argon with flow rate 50 l/min was directed coaxial with laser beam to protect metals from oxidation during laser treatment. The steel used for samples and bearing rings has the following composition : 0.5% C, 0.8-1.0% Si, 0.5-0.6% Mo, 0.1% V.

Sn coatings were covered by galvanic Cr shielding coatings and this double-layers' system on steel base was remelted by laser action. Two systems have been chosen for investigations : (1) 50 μm Cr layer on 70 μm Sn layer; (2) 50 μm Cr layer on 50 μm Sn layer. The energy and pulse duration were varied from 5 to 8 J, and from 6 to 14 ms, respectively.

The cross-sections of the treated samples were metallographically polished and etched to allow microstructural examination and microhardness measurements. The distribution of Sn in the laser treated regions was examined by CAMEBAX X-ray microprobe.

The scheme "pin-on-disk" was used for wear tests at sliding friction (dry and oil lubricant). Disk flat surfaces were alloyed with Sn by pulse-periodic Nd:YAG laser. The test conditions were the following: (1) pin material - high alloyed steel with 60 HRC hardness and 6 mm diameter; (2) load - 2 MPa for dry friction, and 4 MPa for friction with oil lubricant; (3) sliding velocity - 0.2 m/s for dry friction, and 0.8 m/s for friction with oil lubricant; (4) test duration - 1 hour; (5) lubricant - paraffin oil. The friction coefficient was measured as the main parameter of the tests.

The wear velocity and service life time were investigated for multirows turbo-drill bearings after CO₂ laser alloying of their races. All the experiments were carried out at conditions closed to the real exploitation parameters : axis load - $F=15$ kN; startup contact pressure - $\sigma=2500$ MPa; frequency of rotation $\omega=700$ min⁻¹; ambient medium - water at temperature $T=300$ K.

2.2. Laser nitriding and subsequent SPD. The disks from commercial Titanium alloy VT23 (4.5% Al, 2.0% Mo, 4.5% V, 0.6% Fe, 1.0% Cr) were treated by pulse-periodic Nd:YAG laser with power density $(2-3)10^5$ W/cm², pulse duration 5 ms, and nitrogen flow rate 40 l/min. SPD was produced by using a lathe and special hard cylinder roller (load: 200 kg; rotation: 100 turns per minute). Disk surfaces were analysed by Auger electron spectroscopy. Residual stresses were measured by X-ray diffraction. Disk-on-disk wear tests were used. The disks before being weighed with a precision balance, were cleaned in alcohol and dried in a furnace at 100 °C. Wear tests were performed in water at 27°C maintaining both disks rotating in opposite directions with a contact pressure of 400 MPa, rotating frequency 1000 min⁻¹, sliding speed 0.4 m/s. After each test, disks were cleaned again in alcohol, dried once in a furnace at 100°C and the decrease in diameter was measured together with the weight loss. The total number of tests was 20. Each test had a duration of 4 hours. As a result the wear intensity (defined as the ration between the linear wear and the friction distance) was determined.

3. RESULTS AND DISCUSSION

The peculiarities of convective mass transfer in case of alloying from predeposited coatings, and from gas phase are discussed in [1-3]. Among a number of influencing factors the following ones can be mentioned : energy input per pulse; pulse duration; diameter of zone of action; spatial distribution of the beam; influence of surface evaporation; surface thermo-chemistry, etc. As a result, chemical composition of alloyed zone is determined by the above mentioned factors and by the method of alloying elements inserting into the melt. In case of predeposited coatings, final result of alloying strongly depends on coating's preparation and properties.

3.1. Laser alloying of bearing steels with Sn. Laser alloying of required quality could not be reached for any variations of treatment conditions (pulse-periodic Nd:YAG laser) for 70 μm Sn layer thickness. On the contrary, decrease of Sn layer thickness to 50 μm permits to optimise alloying (Fig. 1,2). The maximum Sn concentration (22 wt.%) exceeds of that predicted by equilibrium phase diagram (equilibrium solubility of Sn in Fe is 18 wt.% at 900°C and 7 wt.% at 600 °C). The other feature of laser alloying from double layer coating is large depth of melted zone, which reaches about 800 μm for $E=8$ J, and $t=6$ ms (150 μm for the uncovered substrate).

The main task of "pin-on-disk" wear test is to study a friction behaviour of alloyed layers at no-lubricant (dry friction). In this case, the steady state is observed from the beginning of the test (Fig. 3a). The average value of friction coefficient (0.232) is low enough to avoid galling and adhesive wear during one hour. The mechanism of friction behaviour is the following : Sn emerges at contact area as a result of precipitations from

intermetallic compounds or solid solution, and of small inclusion's outlet on the disk surface. The first process is caused by high temperature at contact area. The second one concerns with mechanical destruction of thin solid layers. The steady state for friction coefficient behaviour is explained by intensive Sn transfer from one point of the disk surface to another. It keeps the friction coefficient at a low level due to Sn solid lubricant properties.

The wear test with oil lubricant, under the conditions of increased load and sliding velocity, leads to the total wear of modified layer after 30 minutes. As a result, the friction coefficient sharply increases from very low value (0.08) up to 0.45 (Fig.3b).

Based on the results of above mentioned tests, optimum parameters of laser alloying were chosen for treatment of turbo-drill external and internal races. The first (short) stage of bearing wear test (Fig. 4, curve 2) corresponds to the alignment of mating parts. The wear rate stability (second stage) is guaranteed by solid lubricant feed from alloyed layers and Sn intensive transfer between friction parts. Geometry of laser traces (width, thickness and position on bearing races) was chosen to provide a good lubrication within the required wear tolerance. The sharp increase of wear velocity is observed only after total wear of Sn-containing zones. The comparison with the conventional method of induction hardening (Fig. 4, curve 1) have shown 2.5 times increase of service life time and 3 times decrease of wear velocity.

2.2. Laser nitriding and subsequent SPD. The alloyed zone consists of surface layer of TiN (thickness about 5 μm) and a subsurface layer of nitrogen solid solution in Titanium (thickness about 100 μm). This kind of structure is best suited to the SPD treatment because the hard nitride layer may be easily pressed on a plastic layer of solid solution without generating cracks. As a result of SPD surface roughness R_a decreased from 1.6-2 μm (after laser treatment with $2 \cdot 10^5 \text{ W/cm}^2$) to (0.1-0.7 μm); or from 5.3-9.9 μm (after laser treatment with $3 \cdot 10^5 \text{ W/cm}^2$) to 1-1.9 μm . Residual stresses varied over a wide range ($-400 < \sigma_{\text{res}} < +1000 \text{ MPa}$) according to the laser power density. Close to zero residual stresses correspond to laser power density $2.5 \cdot 10^5 \text{ W/cm}^2$.

Figure 5 shows the dependence of wear intensity on time. At the beginning, wear is severe because thin surface defects are easily worn out. The steady state of the wear process is reached after the first hour of test and is due to high microhardness, low friction coefficient of TiN, and plasticity of the sublayer of the solid solution of nitrogen in Ti. The catastrophic wear stage was not observed because it requires a longer time and implies the destruction of the TiN surface layer.

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Fig.1. Diameter (curves 1,3) and maximum depth (2,4) of laser alloyed zone versus pulse duration. Pulse energy: (1,2) - 8 J; (3,4) - 5 J.

Fig. 2. Cr (curves 1,2) and Sn (3,4) maximum concentrations inside the alloyed zone versus pulse duration. Pulse energy: curves (1,3) - 5 J; (2,4) - 8 J.

Fig. 3. Friction coefficient versus time for "pin-on-disk" test. Bearing steel alloyed with Sn by pulse-periodic Nd:YAG laser.
(a) dry sliding friction (b) oil lubricant sliding friction

Fig. 4. Wear velocity versus time for turbo-drill race. Curve (1) - induction hardening; (2) - laser alloying with Sn.

Fig. 5. Wear intensity versus time for "pin-on-disk" test. Laser alloying of Ti from a nitrogen jet plus subsequent surface plastic deformation.