Original Article

Microstructure and mechanical properties of doped and electron-beam treated surface of hypereutectic Al-11.1%Si alloy

Dmitrii Zaguliaev\textsuperscript{a,b}, Sergey Konovalov\textsuperscript{a,c,*}, Yurii Ivanov\textsuperscript{d}, Victor Gromov\textsuperscript{b}, Elizaveta Petrikova\textsuperscript{d}

\textsuperscript{a} Wenzhou University Institute of Laser and Optoelectronic Intelligent Manufacturing, Wenzhou, 325024, China
\textsuperscript{b} Siberian State Industrial University, Novokuznetsk 654007, Russia
\textsuperscript{c} Samara National Research University, Samara 443086, Russia
\textsuperscript{d} Institute of High Current Electronics of the Siberian Branch of the RAS, Tomsk 634055, Russia

\section*{A R T I C L E   I N F O}

Article history:
Received 6 May 2019
Accepted 26 June 2019
Available online 16 August 2019

Keywords:
AI-Si hypereutectic alloy
Electron beam
Electroexplosive doping
Microstructure
Wear resistance
Microhardness

\section*{A B S T R A C T}

The effect of electroexplosive doping in two modes with subsequent intense pulsed electron beam treatment of hypereutectic Al-11.1%Si alloy (silumin) on the change of its structure and phase composition, mechanical and tribological properties has been investigated. Methods of methods of scanning electron microscopy, electron microprobe and X-ray diffraction analysis were used to analyze changes of the structure, phase composition, and morphology of the modified surface of hypoeutectic silumin subjected to a complex treatment. Change of tribological and mechanical properties after the complex energy deposition is evaluated: the microhardness increases by 3.2 times (2.34 GPa in contrast to 0.73 GPa in the as-cast state), the wear parameter (inverse to the wear resistance) decreases by 18–20 times (from 49\textsuperscript{−}\textsuperscript{4} mm\textsuperscript{3}/N m to 2.5\textsuperscript{−}\textsuperscript{4} mm\textsuperscript{3}/N m) and the friction coefficient decreases by \textasciitilde1.5 times (from 0.55 to 0.36). It is revealed that a complex treatment mode hardly affects the studied properties but it has a strong effect on the phase composition of a modified layer (the content of the aluminum-based solid solution is reduced by 2.5 times, and the relative content of silicon oxide grows by \textasciitilde2.2 times). The multiphase submicro- and nanocrystalline structure formed in the surface layer is responsible for changes in the wear resistance and microhardness, and special features of the thermal action by an intense pulsed electron beam on the surface govern a decrease in the friction coefficient.

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\* Corresponding author at: Doctor of Engineering Sciences, Professor Sergey Konovalov Wenzhou University Institute of Laser and Optoelectronic Intelligent Manufacturing, Ocean Science and Technology Innovation Park, No. 19 Binhai 3rd Road, Yongxing Street, Longwan District, Wenzhou, Zhejiang 325024, China.

E-mails: zagulyaev_dv@physics.sbsiu.ru (D. Zaguliaev), ksv@ssau.ru, ksv@wzu.edu.cn (S. Konovalov), yuf55@mail.ru (Y. Ivanov).

https://doi.org/10.1016/j.jmrt.2019.06.045
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1. Introduction

Aluminum is known to combine the whole range of valuable properties (electrical conductivity, corrosion resistance, lightness, ductility, thermal conductivity, etc.), which make it a unique metal applicable in almost any technical field [1].

In electronics, aluminum successfully replaces copper in the production of massive conductors. High corrosion resistance of aluminum (about 40 times the resistance of steel) is decisive for its use in shipbuilding. Good thermal conductivity causes its application in cooling systems. Due to its low density and high plasticity, aluminum is widely used in aviation and aerospace industries. It contains no harmful elements, being an ecologically safe metal. However, aluminum alloys, not pure metal, are often employed [2–6]. Al-Si alloy (silumin) is a very lightweight material; it is characterized by low hardness and consequently by low wears resistance, which reduces its prospects.

A method of surface doping of metallic materials is electric explosion of conductors [7–9]. Electroexplosive doping (EED) allows improving strength, durometer and tribological properties in the modified material. Hardening is provided by the formation of a hardening coating consisting of finely dispersed phases. The coating properties are usually highly dependent on the microstructure, phase composition, porosity, and its distribution.

However, the properties resulting from such modification are not enough in the current conditions of rapidly developing equipment and technology. In this regard, scientists are looking for combined actions to achieve the required functional characteristics [10–23].

For elimination of coating defects formed by the electroexplosive method, the subsequent treatment by an intense pulsed electron beam (IPEBT) appears to be very promising [10,11]. This treatment causes remelting of surface layers of the material at superhigh heating and cooling rates, resulting in a homogeneous structure of submicron- and nanosized range [24–28].

In electroexplosive method a stronger material was used as a component of the coating, namely, a powder of yttrium oxide (Y2O3). As know, yttrium oxide is a compound possessing a number of unique properties, among them—an ability to form a protective film when heating in air medium as well as an ultimate tensile strength of metallic yttrium ≈300 MPa.

The aim of the present work is to analyze changes in the structure, phase composition, tribological properties, and microhardness of hypoeutectic silumin subjected to electroexplosive doping with the Al–Y2O3 system and the subsequent intense pulsed electron beam treatment in optimal modes.

2. Material and methods of investigation

The investigation is performed on Al–Si alloy (hypoeutectic AK10M2N silumin); its chemical composition is determined from the analysis of X-ray spectra (Table 1) [29].

Silumin specimens shaped to plates measuring 20 × 20 × 10 mm³ were subjected to a complex treatment (Fig. 1d).

The treatment was carried out on a flat with dimensions 20×20 mm². This flat of the sample was grinded and polished.

At the first stage, an Al–Y2O3 composite coating was deposited by the method of electroexplosive doping on an EVU 60/10 installation (Siberian State Industrial University, Novokuznetsk). To intensify thermal effects on the material surface prior to its melting and to ensure the deposition conditions, an end pattern of explosion were used [29]. The spraying technology was as follows: an aluminum foil was clamped between the coaxial electrodes, to which an adjustable voltage was applied through a vacuum gap. Due to the storage capacitor discharge, high-density electric current flows through the conductor, thus causing it to explode. Explosion products rush towards the specimen to was treated and catch powder particles, the Y2O3 powder in this case (Fig. 1a).

As a result, the electric explosion products present a multiphase system including both the plasma component (Al) and condensed particles of different size (Y2O3), which are deposited on the specimen surface, thus forming a multicomponent coating (Fig. 1b). At the second stage, the formed multicomponent coating was subjected to the intense pulsed electron beam treatment (Fig. 1c). The surface is modified using the SOLO installation (Institute of High-Current Electronics, Siberian Branch of Russian Academy of Sciences, Tomsk) [30].

The optimal parameters of electroexplosive doping and intense pulsed electron beam treatment to form gradient, multielement, multiphase, nanostructural states with unique properties in the modified layer were previously determined for each type of energy deposition [29,30].

In the present paper, we continued the earlier investigations [29,30] and used optimal parameters of each action as the combined treatment modes (Table 2).

In the table, m (Al) is the mass of the aluminum foil, m (Y2O3) is the mass of powder Y2O3, U is the discharge voltage, Es is the energy density of the electron beam, Ef is the energy of accelerated electrons, f is the duration of the electron beam pulse, and N is the number of pulses.

The elemental and phase composition, the state of the defect structure were studied using scanning electron microscopy (Philips SEM-515 microscope with an EDAX ECON IV microanalyzer) and X-ray diffraction analysis (Shimadzu XRD 6000 X-ray diffractometer). Tribological properties (wear resistance and friction coefficient) are studied on a Pinon Discand Oscillating TRIBO tester (TRIBOtechnic, France) with the following parameters: a ShKh15 steel ball is 6 mm in diameter, the track radius is 4 mm, the indention load and track length vary depending on the wear resistance of the material.

Microhardness was measured by the Vickers method in accordance with International Standard ISO 6507:2005, the indentation load is 50 mN (HVS-1000 microhardness meter). The loading time was 10 s, and the unloading time −5 s.
Tribological properties and micro-hardness were examined in the central part of the modified surface; no preliminary sample preparation was required.

3. Results and discussion

It was found that hypoeutectic silumin in the as-cast state is a multiphase, morphologically heterogeneous aggregate that contains inclusions widely varying in size and shape [29]. Typical electron microscopic images of the surface structure of silumin subjected to the complex treatment (EED + IPEBT) by mode No. 1 are shown in Fig. 2.

It is clearly seen that the complex treatment forms a surface relief with a large number of microcraters (shown by arrows in Figs. 2a and b) and particles of droplet fraction (shown by arrows in Fig. 2c). The formed surface layer is divided into regions less than 1 μm in size (Fig. 2d). The regions are of a polycrystalline structure; the crystal size varies from 60 to 100 nm (the insert in Fig. 2d).

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>EED parameters</th>
<th>IPEBT parameters</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>m(Al), mg</td>
<td>m(Y₂O₃), mg</td>
</tr>
<tr>
<td>1</td>
<td>58.9</td>
<td>58.9</td>
</tr>
<tr>
<td>2</td>
<td>58.9</td>
<td>88.3</td>
</tr>
</tbody>
</table>
Fig. 2 – Surface structure of silumin subjected to the complex treatment by mode 1. Scanning electron microscopy. The arrows point to microcraters (b) and particles of droplet fraction (c).

Fig. 3 – Surface structure of silumin subjected to the complex treatment by mode No. 2. The arrows point to thin-film formations (c) and to particles of a circular droplet fraction (b). Scanning electron microscopy.
Fig. 3 presents typical electron microscopic images of the structure of the silumin surface subjected to the complex treatment by mode No. 2.

The comparison of the results presented in Figs. 2 and 3 allows us to conclude that a 50% increase in the mass of the Y2O3 powder weighed sample and a 7% decrease in discharge voltage (Table 2) causes a significant decrease in the number of microcraters on the modified surface, a formation of fragmentary thin-film inclusions on the surface (indicated by arrows in Fig. 3a) and regions with a submicrocrystalline structure with the average crystallite size 0.83 μm in the surface layer (Fig. 3c and d).

The results performed by the electron microprobe analysis methods exhibit that in the surface layer of silumin treated by mode No. 1 the average concentration of yttrium atoms is 14.3 wt %; of oxygen atoms, 6.7 wt % (Fig. 4). In the surface layer of silumin treated by mode No. 2, the average concentration of yttrium atoms is 12.5 wt %; of oxygen atoms, 5.1 wt % (Fig. 4).

The complex treatment, in comparison with electroexplosive doping alone, leads to a significant decrease in the average concentration of yttrium and oxygen atoms, which may indicate their more uniform distribution throughout the modified surface.

For treatment mode No. 1, the concentration of yttrium atoms and oxygen (Y = 71.88 wt % and O = 13.64 wt %) in the droplet fraction particles is significantly higher (Fig. 5a and b) than their average concentration (Y = 14.3 wt % and O = 6.7 wt %) (Fig. 4).

For mode No. 2, the concentration of yttrium atoms in films (83.69 wt %) and in microdroplets (92.67 wt %) (Fig. 5c and d) also exceeds the average yttrium concentration (12.5 wt %) (Fig. 4). However, the oxygen concentration in the droplets is close to zero (Fig. 5c and d) in contrast to 13.64 wt % for mode No. 1 and to the average concentration 5.1 wt % in the chosen region. The minimum concentration of yttrium atoms (3.5 wt % at the oxygen atom concentration 2.5 wt %) is found in regions with a submicrocrystalline structure presented in Fig. 3c and d.

The Table 3 results of the X-ray diffraction analysis of the surface layer of the modified silumin show that, regardless of the complex treatment mode, a multiphase structure is formed in the surface layer of silumin.

The complex treatment mode significantly affects the phase composition of the material. When treated by mode No. 1, the main phase of the modified layer is an aluminum-based solid solution (±71.2 wt %), the SiO2, YAlO3 and YSi2 phases are present in a smaller amount. The transition to mode No. 2...
is accompanied by an increase in the number of phases, a 2.5-fold decrease in the relative content of the aluminum-based solid solution, an ≈2.2-fold increase in the relative content of silicon oxide, and the presence of yttrium oxide and metallic yttrium.

Tribological tests are performed for silumin in the as-cast state, after intense pulsed electron beam treatment and after the complex treatment by EED and IPEBT (Table 1). The test results are shown in Fig. 6.

The tribological tests demonstrate that the wear parameter (inverse to the wear resistance) and the friction coefficient of silumin weakly depend on the complex treatment mode. In comparison with the initial silumin, the wear resistance increases by 18–20 times and the friction coefficient decreases by ≈1.5 times. With respect to silumin irradiated with an intense pulsed electron beam, after the complex modification, the wear resistance increases by 2.6–2.8 and the friction coefficient decreases by ≈1.3 times.

As the mechanical properties we take the microhardness variation depending on the method and mode of modification (Fig. 7).

The analysis of the diagram gives grounds to say that, regardless of the parameters of modification separately by EED or IPEBT, the microhardness increase is 97% (0.71 GPa). The complex treatment, independently of the mode, leads to an increase in microhardness by 3.2 times (2.34 GPa as compared to 0.73 GPa in the as-cast state), which correlates with the data of tribological tests.

The comparison of the structural investigation results with the changes in tribological and mechanical properties suggests that the microhardness and wear parameter increase due to a multiphase submicro- and nanocrystalline structure formed in the yttrium-enriched surface layer during the complex treatment. It is known that the electron beam can be used as a surface polishing method [31,32]. In this regard, the friction coefficient decrease can be related to the IPEBT, during which the electron beam acting on the surface melts a thin surface layer with subsequent crystallization. This reduces roughness and consequently the friction coefficient.
4. Conclusions

The complex treatment by electroexplosive doping of hypoeutectic silumin with yttrium oxide and subsequent irradiation with an intense pulsed electron beam were accompanied by the formation of a multiphase submicro- and nanocrystalline layer enriched with yttrium and oxygen atoms and characterized by a significant improvement in the tribological and mechanical properties.

A variation in the complex treatment mode, namely, a 50% increase in the mass of the $Y_2O_3$ powder weighed sample and a 7% decrease in discharge voltage, alters the morphology of the treated surface and decreases slightly the average concentration of yttrium and oxygen atoms in the surface layer of the material.

Changes in tribological and mechanical properties are related to a multiphase and morphologically heterogeneous submicro- and nanocrystalline structure formed in the yttrium- and oxygen-enriched surface layer during the complex treatment.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgements

This work was supported by the Ministry of Science and Higher Education of the Russian Federation (state contract No. 3.1283.2017/4.6) and partially supported by the Russian Foundation for Basic Research (project No. 19-52-04009_Bel_mol_a). The authors are grateful to the engineer Teresov A.D. for assistance in obtaining results and discussing them and Irina Egorova for assistance in translating the article.

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