

EFFECT OF YTTRIUM OXIDE MODIFICATION OF Al-Si ALLOY ON MICROHARDNESS AND MICROSTRUCTURE OF SURFACE LAYERS

Received – Primljeno: 2018-03-10

Accepted – Prihvaćeno: 2018-06-02

Original Scientific Paper – Izvorni znanstveni rad

Microhardness, structure and phase state of silumin modified by coating with yttrium oxide when electroexplosive alloying were analyzed. Appropriate processing modes were estimated according to the results of research. The study on the structure and phase composition was carried out for the processing mode, which increases microhardness of the surface layer more than twice. A complex of research procedures was used to analyze the structure and phase composition. As revealed in the study, the coatings with a thickness of 50 – 80 μm are highly rough and porous, they have a sub-micro- and nano-scaled multiphase structure with particles of silicon, Y_2O_3 , YSi_2 and $\text{Y}_2\text{Si}_2\text{O}_7$, as strengthening phases, and alloying elements (silicon, yttrium, and oxygen) don't tend to spread homogeneously in them.

Key words: Al-Si alloy, yttrium oxide, structure, microhardness, wear resistance.

INTRODUCTION

To date, alloys of non-ferrous metals are widely used instead of steel alloys. Their physical and mechanical properties are similar to those of steel, some of them are even better. It is said that the most prospective alloys are those on the base of aluminum and silicon (silumin). Since silumin has good plasticity, the alloy can follow the most complex shapes, filling casts evenly. As a consequence, casting of silumin is simplified, reducing, therefore, production costs [1-3]. The main advantage over other aluminum alloys, including other types of silumins is quite good casting properties, first of all high fluidity. These casting alloys are suitable for casting of thin-walled, complex and leak-proof products, which are resistant to vibration and impact loads [4, 5].

The dominating trend to make motors economically and ecologically compatible is the reason for attempts of designers, who modify the rod and piston group, e.g. reduce its weight, and change their geometry, making the shape of pistons more complex, this way. However, the loads on the rod and piston group are not reduced, since the capacity of motors is the same, deteriorating significantly the resource, as a consequence. Therefore, it is urgently needed to find new and efficient methods to improve properties of silumins, which involve modifying, micro-alloying, and surface treatment [8-16]. The promising procedure of outer energy impacts, conditioning serious changes in the structure, phase composition, physical and mechanical properties of the sur-

face layers of metals and alloys is electroexplosive alloying. Using this method, coatings with high quality, functional characteristics, and sufficient adhesion with the substrate as well, can be produced. Due to this technique it is possible to produce coatings from conductor explosion products, and form composite surfaces with qualities better than those of the initial material [17].

To sum up, this work aims at modification of surface layers in alloy Al-Si with yttrium oxide particles in electroexplosive alloying with the consequent analysis of the structure, phase composition and mechanical properties of produced coatings.

EXPERIMENTAL

Plates of eutectic Al-Si alloy (silumin) (11,1 Si, 0,58 Mg, 2,19 Cu, 0,92 Ni, 0,25 Fe, 0,029 Mn, 0,047 Ti, 0,005 Cr, balance Al (wt. %)) were analyzed. The samples under consideration were 20 × 20 × 10 mm and oriented perpendicular to the plasma jet axis. Electroexplosive alloying was carried out using a laboratory pulse-discharging electroexplosive equipment EVU 60/10 [15]. Electrical current with a high density ($\sim 10^{10}$ A/m²) passes through the conductor when a capacity storage discharges, resulting this way, in electrical explosion. We used aluminum foils to explode conductors and Y_2O_3 as a weighted portion of powder. The treatment was carried out in three processing modes, which differ in discharge voltage, weights of foils to be exploded and powder portions. All processing modes are listed in Table 1.

The measurement of micro-hardness was used to describe mechanical properties of the surface layers. The difference in micro-hardness before and after treatment can be considered to indicate strengthening of the sur-

S. V. Kononov (ksv@ssau.ru). Wuhan Textile University, Wuhan, China, Samara National Research University, Russia;

D. V. Zagulyaev, V. E. Gromov, Siberian State Industrial University, Novokuznetsk, Russia;

Y. F. Ivanov, Institute of High Current Electronics Siberian Branch of Russian Academy of Sciences, Tomsk, Russia

Table 1 Processing modes of electroexplosive alloying

| Processing mode | Weight of aluminum foil / g | Weight of powder Y_2O_3 / g | Discharge voltage / kV |
|-----------------|-----------------------------|-------------------------------|------------------------|
| 1 | 0,0589 | 0,0589 | 2,6 |
| 2 | 0,0589 | 0,0589 | 2,8 |
| 3 | 0,0589 | 0,02945 | 2,6 |
| 4 | 0,0589 | 0,02945 | 2,8 |
| 5 | 0,0589 | 0,0883 | 2,6 |
| 6 | 0,0589 | 0,0883 | 2,8 |

face layers in metals and alloys. Micro-hardness was determined using the device to measure micro-hardness HVS-1000 and Shimadzu DUH-211S to estimate ultra-micro-hardness according to Vickers method.

Scanning electron microscopy (SEM) with the help of SEM-515 Philips, toolled with micro-analyzer EDAX ECON IV was the technique to analyze the element and phase composition, and defect substructure of the modified layer. The phase composition of modified layers, that is, qualitative and quantitative characteristics of various phases in case there are any, their content, dispersion, structure and chemical composition were assessed using electron diffraction microscopy and X-ray spectrometry (diffractometer XRD-7000s, Shimadzu). The defect structure of samples was studied via STEM-analysis of thin foils (JEM-2100F, JEOL). The data on thin structure of the material were used to classify morphological characteristics of the structure.

All data obtained were processed statistically, taking into account at least 10 measurements in each mode.

RESULTS AND DISCUSSION

Micro-hardness in the sprayed layer and in the substrate of samples treated in electroexplosive alloying was measured in different points from the treated surface. Micro-indentation was carried out on crosscut sections. Analyzing the change in micro-hardness as far from the treated surface, it was identified that processing modes 2 and 5 (Figure 1a) provide optimal characteristics (thickness and micro-hardness of the alloyed layer) in the treated surface.

As seen in Figure 1(a), micro-hardness of the material is maximal in the surface layer and exceeds that of the initial material more than twice. As far from the modified surface, the drop of micro-hardness is registered and at a depth of $\approx 90 \mu\text{m}$ micro-hardness equals that of silumin in the initial state. The sprayed layer, processed in Mode 2 is $50 \mu\text{m}$ thick (Figure 1b), and in Mode 5 – $80 \mu\text{m}$.

As revealed, the optimal processing modes are Mode 2 and Mode 5. For the further analysis samples processed according to mode 2 were used to identify their phase composition and structure.

The structure of silumin volume after electroexplosive alloying was analyzed by the method of sections using optical (Figure 1b) and scanning electron microscopy (Figure 2). Studying the data in Figure 2, one can

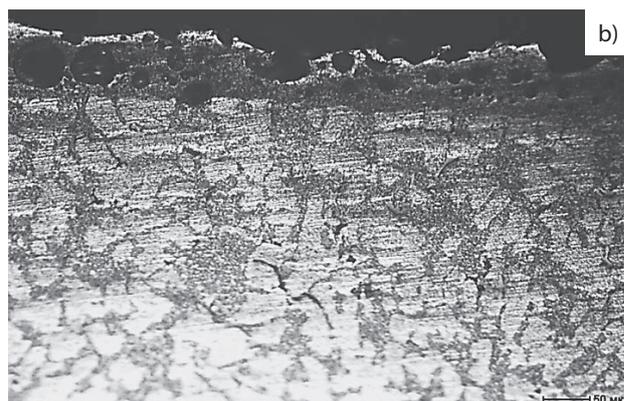
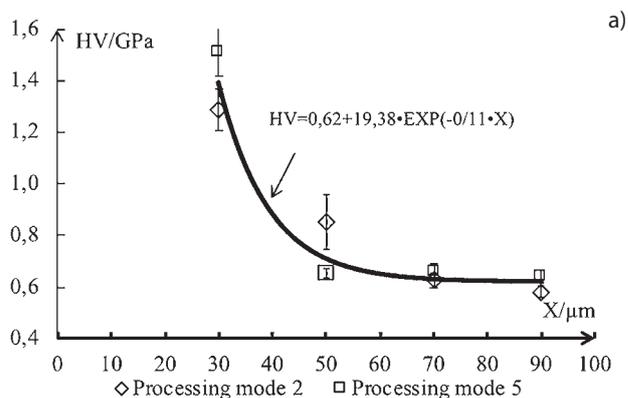


Figure 1 a) Micro-hardness profile of silumin after electroexplosive alloying (the load on indenter 50 mN). b) The coating of the system $Al-Y_2O_3$ produced by the method of electroexplosive alloying (zooming 20 X optical microscopy – processing mode 2).

note that the thickness of the modified layer varies in the range 30 - 50 μm , and the level of porosity is high. The pores are throughout the modified layer; their sizes are ones to tens of micrometer.

The phase composition of silumin modified via electroexplosive alloying was studied by the methods of X-ray analysis. The data on the phase analysis of the material are given in Table 2.

Considering the results given in Table 2, first, a rather high amount of silicon is registered in the surface layer of

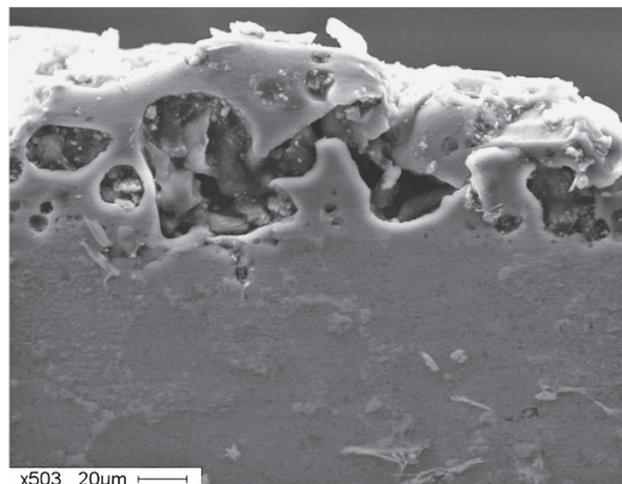


Figure 2 SEM - The structure of silumin section after electroexplosive alloying.

Table 2 **The results of X-ray analysis of eutectic silumin after electroexplosive alloying**

| Phase | Content, rel. / % | Parameter of the lattice / nm | D (CSZ) / nm | $\Delta d/d / 10^{-3}$ |
|-------------------------------|-------------------|-------------------------------|--------------|------------------------|
| Al | 68,2 | 0,40485 | 75,01 | 0,24 |
| Si | 30,1 | 0,54231 | 16,4 | 0,80 |
| Y ₂ O ₃ | 1,7 | 1,06010 | 16,6 | 7,88 |

CDZ – coherent scattering zone

silumin that might be caused by emission of some aluminum layer when electroexplosive alloying. Secondly, there is Y₂O₃ phase, maybe, due to particles of initial powder of yttrium oxide, penetrating into the surface layer of silumin when electroexplosive alloying. The findings of X-ray micro-spectral analysis, in particular, the element composition in the surface layer of silumin after electroexplosive alloying are given in Table 3.

Analyzing the results given in Figure 3 and Table 3, it should be noted that after electroexplosive alloying the surface layer is formed with a high level of alloying elements distributed non-homogeneously, it is most visible in spreading of yttrium and oxygen atoms. To be more precise, there are zones with concentration of yttrium and oxygen exceeding the average one twice and more. These results confirm that in the plasma flow of powder particles there is an alloying material identified in some studies before. Furthermore, the surface layer with a high level of roughness containing a lot of micropores, micro-craters and micro-cracks is formed in electroexplosive alloying.

The defect sub-structure, element and phase composition of the surface layer in silumin after electroexplosive alloying were also analyzed using the methods of transmission electron diffraction microscopy of thin foils. As revealed, a structure with cellular crystallization of aluminum is formed in the surface layer because the modified layer gets cooled at a high-speed when electroexplosive alloying. The sizes of cells vary from 200 to 450 nm. On borders of the cells there are interlayers of the second phase. X-ray micro-spectrum analysis showed that the interlayers are formed by silicon and yttrium atoms.

The phase composition of silumin after electroexplosive alloying was studied by the methods of transmission diffraction electron microscopy using the procedure of dark-field analysis and indentation of respective electron-diffraction micro-patterns (Figure 4).

Analyzing Figure 4, it is obvious that the surface layer of silumin after electroexplosive alloying has a structure of cellular crystallization. The cells are of a clearly oval form. Their sizes vary from 150 nm to 350 nm. According to the micro-diffraction analysis the cells are a solid solution based on aluminum.

In the volume of cells particles of the second phase are identified with the help of dark-field analysis; the sizes of particles are in units of nanometers (Figure 4c).

With respect to electron-diffraction micro-pattern (XRD) (Figure 4b) we can say with a good reason that

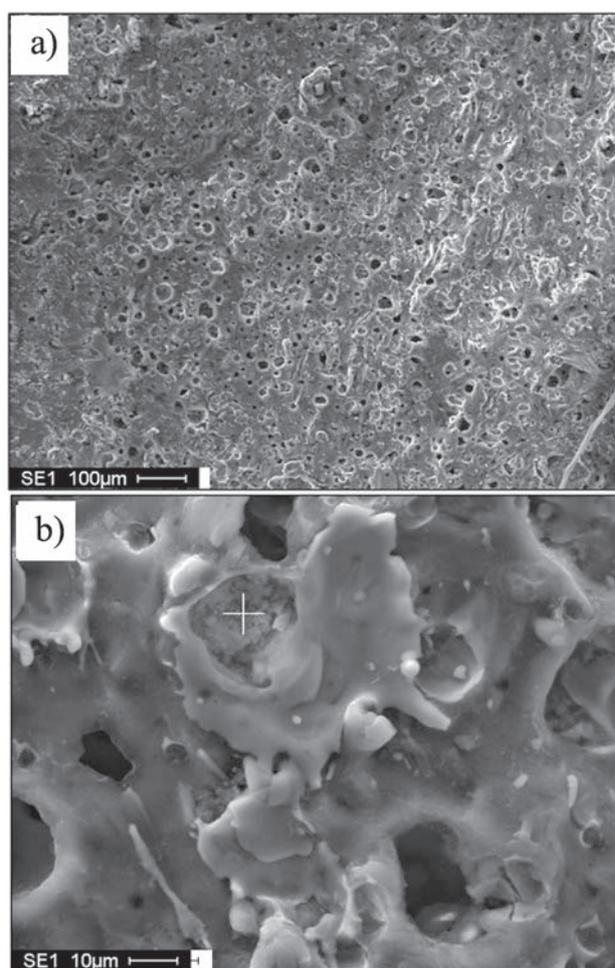


Figure 3 SEM data on the structure of silumin surface treated by the electroexplosive method: a), b) see Table 3

Table 3 **The element composition of the surface layer in silumin after electroexplosive alloying, identified by the methods of X-ray micro-spectral analysis of zones shown in Figure 3 / wt. %**

| Zone | Al | Si | Mg | Ti | Fe | Ni | Cu | Y | O | C |
|-----------|------|-----|-----|-----|-----|-----|-----|------|------|------|
| Figure 3a | 47,2 | 3,0 | 0,6 | 1,0 | 0,7 | 1,3 | 1,8 | 16,2 | 10,8 | 17,4 |
| Figure 3b | 0,8 | 0,0 | 0,0 | 0,2 | 0,7 | 0,5 | 0,7 | 34,0 | 28,1 | 35,0 |

these particles are yttrium silicide of the composition YSi₂. The aluminum cells are distributed as interlayers of the second phase. As seen in the electron-diffraction micro-pattern (Figure 4b), the interlayers are formed by silicon and yttrium silicate of the composition Y₂Si₂O₇.

CONCLUSION

The surface layer in eutectic silumin was modified with yttrium oxide using the method of electroexplosive alloying. The appropriate processing modes were revealed: Mode 2 (discharge voltage – 2,8 kV, weight of aluminum foil – 0,0589 g, weight of yttrium powder Y₂O₃ – 0,0589 g.), and Mode 5 (discharge voltage – 2,6 kV, weight of aluminum foil – 0,0589 g, weight of yttrium powder Y₂O₃ – 0,0883 g.). It was revealed that as a result of electroexplosive alloying of silumin a highly-porous surface layer is formed with a thickness from 50

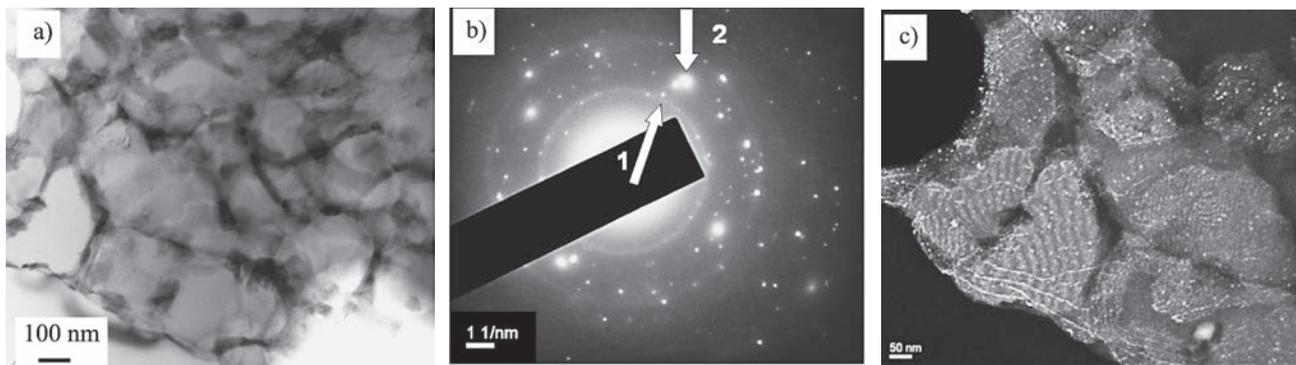


Figure 4 XRD data of the silumin structure after electroexplosive alloying; a) bright field; b) electron-diffraction micro-pattern, arrows indicate reflexes, where dark fields were obtained; c) dark field obtained in reflexes 2 $[111]\text{Al} + [112]\text{YSi}_2$.

to 80 μm ; alloying elements (Si, Y and O) don't tend to spread homogeneously in this layer, it also has sub-micro- and nano-scaled multiphase structure with particles of silicon, Y_2O_3 , YSi_2 and $\text{Y}_2\text{Si}_2\text{O}_7$ as strengthening phases, its wear resistance and micro-hardness are high.

Acknowledgments

This work was financially supported by the state task of Ministry of Education of Russian Federation No. 3.1283.2017/4.6 to perform research work and RFBR research project No. 16-43-700659.

REFERENCES

- [1] Zolotarevskiy V S, Belov N A, Glazoff M V. Casting aluminum alloys [M]. Amsterdam: Elsevier, 2007.
- [2] Mamuzić I, Trebuña F, Šimčák F, Buršák M., Tomčík J. Investigation of reasons and possibility of parameters elimination influencing cracking of leaf springs on continuous casting machine. *Metalurgija* 46(2007)4, 267-271.
- [3] Lipinski T. Influence of surface refinement on microstructure of Al-Si cast alloys processed by welding method. *Manufacturing Technology* 15(2015)4, 576-581.
- [4] Władysław R, Kozuń A. Structure of AlSi20 alloy in heat treated die casting[J]. *Archives of Foundry Engineering* 15(2015)1, 113-118.
- [5] Javidani M, Larouche D. Application of cast Al-Si alloys in internal combustion engine components [J]. *International Materials Reviews* 59(2014)3, 132-158.
- [6] Ivanov Y, Alsaraeva K, Gromov V, Konovalov S, Semina O. Evolution of Al-19.4Si alloy surface structure after electron beam treatment and high cycle fatigue. *Materials Science and Technology (United Kingdom)* 31(2015)13a, 1523-1529.
- [7] Ivanov Y F, Alsaraeva K V, Gromov V E, Popova N A, Konovalov S V. Fatigue life of silumin treated with a high-intensity pulsed electron beam. *Journal of Surface Investigation. X-ray, Synchrotron and Neutron Techniques* 9(2015)5, 1056-1059.
- [8] Zeren M, Karakulak E. Influence of Ti addition on the microstructure and hardness properties of near-eutectic Al-Si alloys [J]. *Alloys and compounds* (2008)450, 255-259.
- [9] Hernandez R C, Sokolowski J H. Thermal analysis and microscopical characterization of Al-Si hypereutectic alloys [J]. *Alloys and compounds* (2006)419, 180-190.
- [10] Zeren M. The effect heat-treatment on aluminum-based piston alloys [J]. *Materials and design* (2007)28, 2511-2517.
- [11] Taghiabadi R, Ghasemi H M, Shabestari S G. Effect of iron-rich intermetallics on the sliding wear behavior of Al-Si alloys [J]. *Mater. Sci. and Engineering A* (2008) 490, 162-167.
- [12] Li R X, Li R D, He L Z, Li C X, Gruan H R, Hu Z Q. Age-hardening behavior of cast Al-Si base alloy [J]. *Materials Letters* (2004) 58, 2096-2101.
- [13] Mohamed A M A, Samuel A M, Samuel F H, Doty H W. Influence of additives on the microstructure and tensile properties of near-eutectic Al-10.8%Si cast alloy [J]. *Materials and Design* (2009)30, 3943-3957.
- [14] Budilov V, Vardanyan E, Ramazanov K. Deposition of Functional Coatings Based on Intermetallic Systems TiAl on the Steel Surface by Vacuum Arc Plasma. *Journal of Physics: Conference Series* 652(2015)1, 012053.
- [15] Deev V B., Degtyar V.A, Kutsenko A I, Selyanin I F, Voitkov A P. Resource-saving technology for the production of cast aluminum alloys. *Steel in Translation* 37(2007)12, 991-994.
- [16] Wong T T, Liang G Y. Effect of laser melting treatment on the structure and corrosion behavior of aluminium and Al-Si alloys [J]. *Materials Processing Technology* (1997)63, 930-934.
- [17] Romanov D A, Gromov V E, Glezer A M, Panin S V, Semin A P. Structure of electro-explosion resistant coatings consisting of immiscible components [J]. *Materials Letters* (2017)188, 25-28.

Note: Responsible person for English translation Tatyana Kust, Yurga Institute of Technology, TPU, Russia