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Changes in surface structure and mechanical characteristics of Al–5 wt% Si alloy after irradiation by electron beam

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ABSTRACT

The modification of Al–5 wt%Si alloy surface by electron beam in the regimes being different in the energy density of electron beam (10, 20, 30, 40 and 50 J/cm^2) and the pulse duration (50 and 200 µs) was performed in the research. It was established that the maximum increase in microhardness was observed at electron beam parameters of 30 J/cm^2, 200 µs and 50 J/cm^2, 50 µs; and microhardness values for each regime amounted to 860 MPa and 950 MPa, respectively. The microhardness value of the cast alloy equals to 520 MPa. The irradiation surface morphology at beam parameters of 30 J/cm^2, 200 µs is characterised by numerous micropores and microcracks. The irradiation regime of 50 J/cm^2, 50 µs leads to complete dissolution of intermetallide and silicon particles in surface layer; the crack density per unit of sample surface decreases in comparison with the regime of 30 J/cm^2, 200 µs. The surface layer is characterised by the high-speed cellular crystallization structure with dimensions from 500 to 800 nm formed in grain volume that may be the reason for the increase in strength properties of the material.

1. Introduction

Due to the extensive application of internal combustion engines the technical progress leads to their steady improvement directed to the decrease in fuel consumption and toxic exhaust emissions with simultaneous increase in power and ecological safety. All novelties in engine-building rest mainly on new materials.

Nowadays one can hardly imagine the production of internal combustion engines without the use of aluminium alloys [1]. Moreover, both the external parts of engines such as the heads of cylinder block, the blocks themselves, valve caps, bodies of attached implements and the internal high loaded parts such as pistons [2] are manufactured from aluminium and Al-based alloys. Every year more and more aluminium and Al-based alloys are used in the process of engine creation. Primarily, it is connected with the combination of its unique properties such as the low density (as a consequence – a small weight of product) and the coefficient of thermal expansion, excellent wear resistance and ability to casting, high strength and thermal resistance [3,4].

It is known that the inclusions of silicon and intermatallides of different shapes being formed in the structure of aluminium with silicon as well as porosity affect adversely the strength and plasticity of a finished product [5–8]. In this connection, many scientists work in the direction of eutectic refinement and the decrease in porosity of alloy structure [9,10]. A perspective method of aluminium-silicon alloy modification is the pulse electron beam processing in the melting mode [11–13]. The melting of surface layers by electron beam followed by crystallization is accompanied by a more careful mixing of aluminium with silicon and the filling the pores with a melt that results in the decrease in degree of inhomogeneity in distribution of chemical elements and phases in material surface layers.

In this context, the purpose of the research is to analyse the morphological changes and microhardness of Al–5 wt%Si alloy surface layer subjected to intense pulsed electron beam irradiation of various duration and the value of beam energy density.

2. Materials and methods

Hypoeutectic alloy of Al–5 wt%Si was used as the material under study. Its elemental composition, determined as a result of

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Table 1
X-ray spectral analysis results of the alloy (mass %; Al – the balance).

Si	Cu	Fe	Mn	Mg	Ni	Ti	Cr	Zn	Pb
5.39	1.33	0.64	0.24	0.64	0.07	0.03	0.03	1.07	0.04

X-ray spectral analysis of the alloy in the cast state, is shown in Table 1.

The material irradiation by intense pulsed electron beam was performed on setup SOLO whose general view is presented in Fig. 1a. [14].

The electron beam parameters being used in the research are the following: the energy of accelerated electrons – 17 kV, the energy density of electron beam – 10, 20, 30, 40 and 50 J/cm^2, the pulse duration 50 and 200 μs, the pulse number 3, the pulse repetition rate – 0,3 s^{-1}; the residual gas (argon) pressure in the working chamber of the setup – 2 × 10^{-2} Pa.

The samples were in the shape of parallelepiped with 15 × 15 × 15 mm^3 dimensions. The electron beam was perpendicular oriented to sample surface 15 × 15 mm^2 in sizes, the beam diameter was selected with the conditions of covering the whole area of sample surface (Fig. 1b).

The morphology and structural components of the surface layer were determined by the methods of scanning electron microscopy on the device Philips SEM-515 with microanalyzer EDAX ECON IV.

Microhardness was measured by the method of recovered imprint (Vickers) immediately on the surface subjected to irradiation in the accordance with the International Standard ISO 6507:2005, the indenter load amounted to 1 N (microhardometer HVS-1000). The loading time was 10 s, and time of load removal – 5 s (the average value of microhardness was determined using 10 imprints).

3. Results and discussion

The results of microhardness measurement for different values of energy density of electron beam and pulse duration are shown in Fig. 2.

When analysing the results presented in Fig. 2 it may be noted that the microhardness value of alloy surface layer depends on pulse duration of electron beam. At pulse duration of 50 μs the surface layer microhardness increases with the growth of energy density of electron beam reaching the maximum value of 950 MPa. At energy density of electron beam of 50 J/cm^2 it exceeds the initial material microhardness by 83%. At pulse duration of electron beam of 200 μs the surface layer microhardness reaches the maximum value at energy density of electron beam of 30 J/cm^2 and amounts to 860 MPa that exceeds the initial material microhardness by 65%. Therefore, on the basis of microhardness variation analysis depending on energy density of electron beam and pulse duration the optimal modes may be considered those of 50 J/cm^2, 50 μs and 30 J/cm^2, 200 μs. In this context, the surface morphology and its structural analysis were carried out by the methods of scanning electron microscopy for the denoted modes.

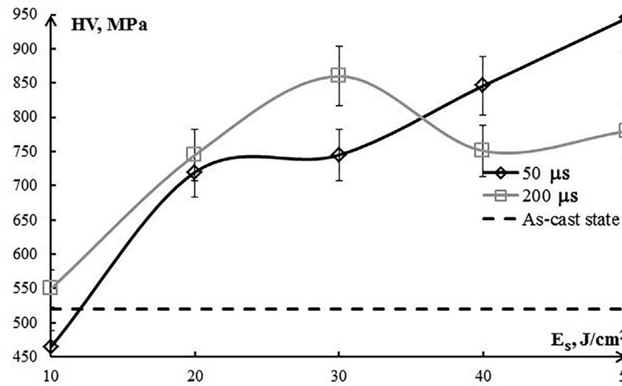

Fig. 2. Dependence of irradiation surface microhardness of Al–5 wt%Si alloy on energy density of electron beam. Initial state microhardness is designated by dotted line.

The alloy irradiation in the mode of 30 J/cm^2, 200 μs results in the formation of numerous micropores and dissolution of initial intermetallide inclusions (Fig. 3 a, c) in the surface layer. The reason for micropore formation may be the material shrinkage at its speed crystallization. In some instances, the islands containing the rounded-shape particles whose dimensions vary in the limits of 2–3 μm are observed on the irradiated surface. In should be noted that alloy irradiation by pulsed electron beam at energy density of electron beam of 30 J/cm^2 is accompanied by the formation of microcracks (Fig. 3 c) in surface layer. As a rule, microcracks locate along grain boundaries. The dimensions of the areas limited by microcracks vary in the limits from 100 μm to 200 μm. It may be suggested that microcrack formation is caused by the formation

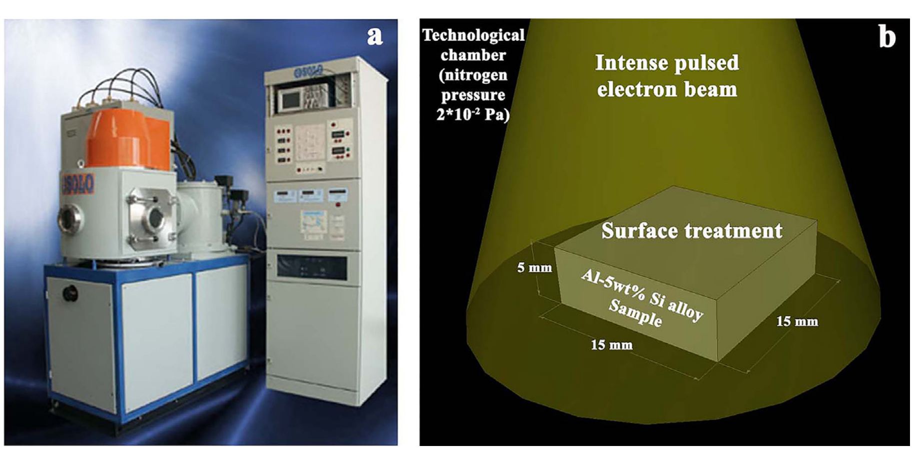

Fig. 1. External view of setup SOLO (a), dimensions and orientation of sample relative to electron beam (b).

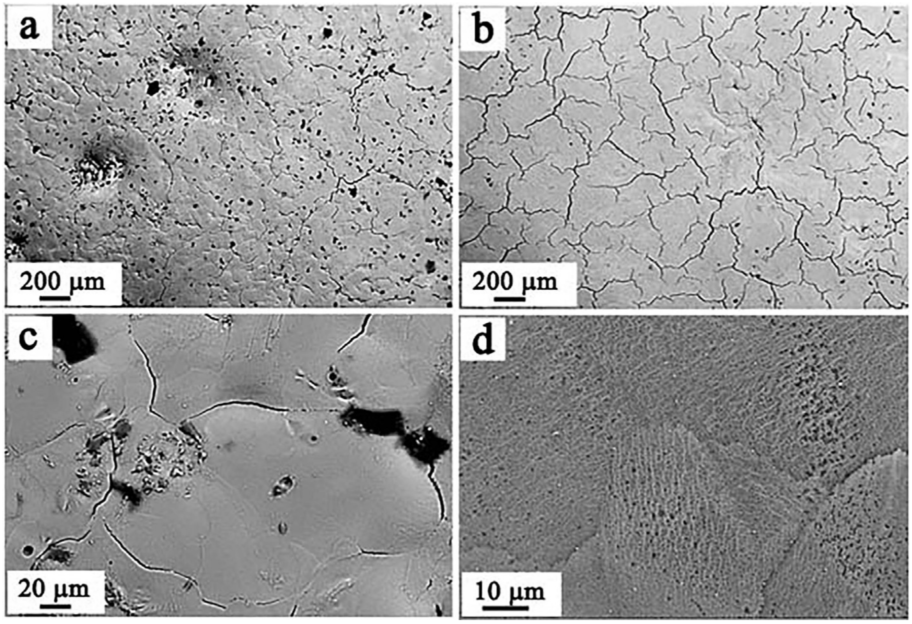

Fig. 3. Structure of Al–5 wt%Si alloy surface subjected to pulsed electron beam irradiation at the following parameters: a,c – 30 J/cm^2, 200 μs; b, d – 50 J/cm^2, 50 μs.

of tensile stresses in surface layer being the consequence of high cooling rates of material surface layer from the molten state.

At energy density of electron beam of 50 J/cm^2 the crack density per unit of sample surface decreases and the areas limited by cracks increase to 250–380 μm (Fig. 3 b), respectively. The latter may be indicative of the tensile stress value decrease in comparison with the samples irradiated at energy density of electron beam of 30 J/cm^2. The irradiation mode being considered results in the complete dissolution of intermetallide particles (Fig. 3 b, d) in the surface layer. In the bulk of grains the structure of high speed cellular crystallization whose dimensions vary in the limits of 500–800 nm (Fig. 3 d) is formed. It may be stated that the detected changes in the structure are the factors leading to 83% increase in microhardness.

4. Conclusions

It has been shown that microhardness value of Al–5 wt%Si alloy surface layer is dependent on the irradiation parameters and at 30 J/cm^2 and pulse duration of 200 μs reaches the value of 860 MPa that exceeds the initial material microhardness by 65%. The morphology of irradiation surface is characterised by numerous micropores and microcracks.

The maximum microhardness value (950 MPa) is observed at pulse duration of 50 μs and energy density of electron beam of 50 J/cm^2 that exceeds the initial material microhardness by 83%. The irradiation mode results in the complete dissolution of intermetallide and silicon particles in the surface layer. In the bulk of grains a structure of high-speed cellular crystallization whose dimensions vary in the limits of 500–800 nm is formed that, in our opinion, is the reason for the increase in the strength properties of the material layer.

CRediT authorship contribution statement

Yu.F. Ivanov: Conceptualization, Formal analysis, Writing - original draft. **D.V. Zaguliaev:** Project administration, Writing - review & editing. **A.M. Glezer:** Formal analysis. **V.E. Gromov:** Methodology. **A.A. Abaturova:** Visualization. **A.A. Leonov:** Data curation. **A.P. Semin:** Resources. **R.V. Sundeev:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M. Javidani, D. Larouche, Application of cast Al-Si alloys in internal combustion engine components, Int. Mater. Rev. 59 (2014) 132–158, https://doi.org/10.1179/1743280413Y.0000000027.
[2] N.A. Belov, V.D. Belov, S.V. Savchenko, M.E. Samoshina, V.A. Chernov, A.N. Alabin, Piston silumins, Ore and Metals, Moscow, 2011.
[3] W. Yan, W. Chen, S. Zhang, B. Li, J. Li, Evolution of solidification structures and mechanical properties of high-Si Al alloys under permanent magnetic stirring, Mater. Charact. 157 (2019), https://doi.org/10.1016/j.matchar.2019.109894 109894.
[4] J.G. Kaufman, E.L. Rooy, Aluminum Alloy Castings: Properties, Processes, and Applications, ASM International, 2004.
[5] H. Choi, X. Li, Refinement of primary Si and modification of eutectic Si for enhanced ductility of hypereutectic Al-20Si-4.5Cu alloy with addition of Al2O3 nanoparticles, J. Mater. Sci. 47 (2012) 3096–3102, https://doi.org/10.1007/s10853-011-6143-y.
[6] M. Okayasu, K. Ota, S. Takeuchi, Influence of microstructural characteristics on mechanical properties of ADC12 aluminum alloy, Mater. Sci. Eng. A 592 (2014) 189–200.
[7] S. Hegde, K.N. Prabhu, Modification of eutectic silicon in Al–Si alloys, J. Mater. Sci. 43 (2008) 3009–3027, https://doi.org/10.1007/s10853-008-2505-5.
[8] T.H. Ludwig, J. Li, P.L. Schaffer, Refinement of eutectic Si in high purity Al-5Si alloys with combined Ca and P additions, Metall. Mater. Trans. A 46 (2015) 362–376, https://doi.org/10.1007/s11661-014-2585-6.
[9] K.J. Kim, C.-Y. Jeong, High temperature mechanical properties of AlSiMg(Cu) alloys for automotive cylinder heads, Mater. Trans. 54 (2013) 588–594, https://doi.org/10.2320/matertrans.M2012285.

[10] O. Kogtenkova, B. Straumal, A. Korneva, T. Czeppe, A. Wierzbicka-Miernik, M. Faryna, P. Zięba, Grain boundary complexions and phase transformations in al- and cu-based alloys, Metals 9 (1) (2019) 10, https://doi.org/10.3390/met9010010.
[11] Y. Hao, B. Gao, G.F. Tu, H. Cao, S.Z. Hao, C. Dong, Surface modification of Al-12.6Si alloy by high current pulsed electron beam, Appl. Surf. Sci. 258 (2012) 2052–2056, https://doi.org/10.1016/j.apsusc.2011.04.104.
[12] D.V. Zaguliaev, S.V. Konovalov, Yu.F. Ivanov, V.E. Gromov, E.A. Petrikova, Microstructure and mechanical properties of doped and electron-beam treated surface of hypereutectic Al-11.1%Si alloy, J. Mater. Res. Technol. 8 (2019) 3835–3842, https://doi.org/10.1016/j.jmrt.2019.06.045.
[13] L. Zhao, S. Wang, Y. Jin, Y. Chen, Microstructural characterization and mechanical performance of Al-Cu-Li alloy electron beam welded joint, Aerosp. Sci. Technol. 82–83 (2018) 82–83, https://doi.org/10.1016/j.ast.2018.08.030.
[14] D.V. Zagulyaev, S.V. Konovalov, V.E. Gromov, A.M. Glezer, Yu.F. Ivanov, R.V. Sundeev, Structure and properties changes of Al-Si alloy treated by pulsed electron beam, Mater. Lett. 229 (2018) 377–380, https://doi.org/10.1016/j.matlet.2018.07.064.