IOP Conf. Series: Materials Science and Engineering **447** (2018) 012061 doi:10.1088/1757-899X/447/1/012061

Mechanisms of nanoscale structure formation during electron beam treatment of silumin

V D Sarychev[1], Yu F Ivanov[2], S A Nevskii[1], Yu S Serenkov[1], E A Vysotskaya[1], V E Gromov[1]
[1] Siberian State Industrial University, Novokuznetsk, Russia 654007
[2] Institute of High Current Electronics SB RAS, Tomsk, Russia 634055

E-mail: nevskiy.sergei@yandex.ru

Abstract. The effect of low-energy high-current electron beams on the structure of silumin has been studied. It has been found that the electron beam treatment leads to the formation of a heterogeneous multi-layer structure in the material. A columnar crystallization structure has been observed in the surface layer. The transverse dimensions of the columns are between 400 and 600 nm, whereas the second phase interlayer dimensions are between 80 and 100 nm. The transverse dimensions of the columns at a depth of 80 to 100 μm are 1.0-1.2 μm. The cause of the columnar structure is the thermoconcentration-capillary instability, which leads to the formation of vortices and the displacement of the second phase particles to the columnar boundaries. The considerable thickness of the columnar crystallization layer is caused by the fact that silicon and other alloying elements influence the dependence of liquid aluminum surface tension on temperature by introducing nonlinearity. As a result, there is an effect of the "thermal drill", i.e. the formation of vortices. The formed vortices stir the melt throughout the depth, and the downward flow of the liquid moves to the center of the bath at the cooling stage, which is manifested in an increase in the thickness of the columnar crystallization layer. It manifests itself in an increase in the thickness of the columnar crystallization layer. At depths over 100 μm, the fracture of silicon particles is observed as a result of differences in the elastic moduli and linear expansion coefficients of the aluminum matrix and the silicon plate.

1. Introduction

Aluminum and silicon based alloys are increasingly used in a number of industries, for example, in the engine building industry for the manufacture of pistons. Studies of the structure of piston materials after their operation, shows that damaged layers with a thickness from 10 to 20 μm [1] are formed there. In this regard, it is necessary to develop technologies for surface modification of aluminum alloys, which would provide thickness of the hardened layer larger than that of the damaged layers formed during operation. Recently, different ways and methods of surface modification have been suggested, and one of the prospective methods is the low energy high current electron beam treatment [2]. The advantage of this treatment method is that its periodic pulsed character allows, on the one hand, increasing the time interval of the molten state of surface layers and, on the other hand, providing hardening effects leading to the formation of sub-micro and nanoscale structures [3]. The disadvantage of the electron beam treatment is the formation of craters on the surface of the material, which become dangerous stress concentrators under cyclic loading [4, 5]. Therefore, it is necessary to choose treatment modes that minimize the influence of craters. To find such modes, one needs information on the mechanisms of the influence of electron beam treatment on the structure of

materials. As was shown in earlier studies [4-9], the effect of the electron beam on materials has a diverse character. It involves heating, melting and vaporization of the surface of materials. Electron beams also generate thermoelastic waves that affect the mechanical properties of the radiation-exposed material. During the melting of metals under the action of electron beams, convective flows are formed in the melt. The intensity and character of these flows determine the features of heat and matter transfer, which affect the physical and mechanical properties of materials. The present article aims at the study of the mechanisms of the effect of electron beam treatment on the structure of silumin.

2. Material and methods of investigation

The Al–12% Si silumin, which is widely used in the engine building industry for the manufacture of pistons, was studied. The sample for studies had dimensions of 20×20×10 mm^3. Surface modification was accomplished by means of the electron-beam treatment technique. The energy density of the beams was 35 J/cm^2, the pulse duration was 150 μs, the number of pulses was 3, and the pulse repetition frequency was 0.3 s^{-1}.. Transmission electron microscopy (TEM) was used to study the structural and phase states of the modified silumin at different distances from the irradiated surface.

3. Results and discussion

Analysis of the TEM images of the cross-section of the samples has shown that the electron beam treatment leads to the formation of a gradient structure. At a depth of 10 to 100 μm from the radiation-exposed surface, the structure of columnar crystallization is observed. The layers of the second phases are located on the boundaries of the columns. The transverse dimensions of the columns are from 400 to 600 nm; the transverse dimensions of the second-phase interlayers are from 80 to 200 nm. Apparently, the columnar crystallization structure appears due to thermoconcentration-capillary instability, which leads to the formation of a vortex and the displacement of the second-phase particles to the boundaries [10-12]. At depths from 80 to 100 μm, one can observe a transition layer, extending from the crystallization zone to the thermal effected one. The transverse dimensions of the columns at this depth are 1.0-1.2 μm. Such an increase in the size of the columns can be explained by the transformation of the interlayers into sphere-shaped particles. The large depth of the columnar crystallization layer is due to the fact that silicon and other alloying elements affect the dependence of the surface tension of liquid aluminum on the temperature [13]. As a result, the “thermal drill” effect appears, which consists in the formation of a vortex structure that mixes the melt throughout the depth, as well as of a downward flow of liquid moving towards the center of the bath during the cooling stage. This explains the increase in the thickness of the columnar crystallization layer. To confirm the proposed mechanism, the mathematical problem of the temperature distribution in a silumin sample in the form of a plate has been solved. Following [12, 14], the enthalpy approach can be used for this purpose. In this approach, the heat conduction equation can be written as follows:

$$\rho\frac{\partial H}{\partial t}=\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \tag{1}$$

where z is the coordinate, ρ is the density, k is the coefficient of heat conductivity, and H is the enthalpy. Phase transitions under the effect of electron beams are taken into account as follows:

$$\rho H(T)=\begin{cases}\rho_s C_s T,\ T<T_L;\ \rho_L\dfrac{L_L}{\Delta T_L}T,\ T_L\le T\le T_L+\Delta T_L;\rho_L C_L T,\ T_L+\Delta T_L\le T<T_V,\\ \rho_V\dfrac{L_V}{\Delta T_V}T,\ T_V\le T\le T_V+\Delta T_V;\ \rho_V C_V T,\ T_V+\Delta T_V\le T\end{cases} \tag{2}$$

where C_p is the coefficient of heat capacity, indices S, L, V stand for solid, liquid and vaporous states. On the surface of the sample z =0 the heat flow is given by

$$-k\frac{\partial T}{\partial z}=q_0(t),\ q_0(t)=\begin{cases}\dfrac{E_S}{t_0}, 0\le t\le t_0\\ 0, t>t_0\end{cases} \tag{3}$$

On the bound of plate $z = h$ there is no heat flow

$$\partial T/\partial z=0 \tag{4}$$

The initial temperature is equal to $T(0,z)=T_0$ at any depth of the plate 0<z<h, h is the thickness of plate. The numerical solution of equations (1)-(4) was obtained by means of an implicit difference scheme using the double-sweep method. The thermal and physical constants of silumin were computed using the mixture principle. The computations were carried out for beams with a power density ranging from 15 to 35 J/cm^2 and a pulse duration t_0 =150 μs. Figure 1 shows the temperature distribution in the sample at different time moments for materials exposed to an electron beam with an energy density of 35 J/cm^2. One can see that at t = 150 μs, i.e. at the end of the pulse, the temperature of the material surface is equal to T = 900 K (curve 2), which is above the melting temperatures of aluminum and silicon, but lower than the temperature of vaporization. This is due to the high thermal conductivity and vaporization heat of silumin. At the end of the pulse, the processes of cooling and crystallization are started. Calculations of the fusion penetration depth (table 1) show that the thickness of the melted layer increases with the energy density of the electron beam. Its values agree with the experimental data [15]. At t =200 and 300 μs (curves 3 and 4, respectively), gradual temperature equalization across the depth is observed. At distances from 80 to 100 μm from the surface, the temperature increases. As mentioned above, at these distances, the process of transformation of the second-phase interlayers to sphere-shaped particles, i.e. spheroidization process, dominates. According to the literature data [16], this process has a diffusion origin, though recently mechanisms alternative to diffusion have been proposed as well.

For instance, in [17] a mechanism was proposed according to which the spheroidization occurs as a result of failure of silicon plates due to the difference in the coefficients of linear thermal expansion of the matrix and inclusion. Since the volume fraction of silicon plates is small compared to that of the aluminum matrix, the latter makes the main contribution to thermal expansion. The linear expansion coefficient of aluminum is four times higher than that of silicon. Therefore, thermal expansion (contraction) of the two phases in most cases is incompatible, which leads to the inevitable appearance of mechanical stresses between the phases. Silicon inclusions can accept only a quarter of the thermal expansion (contraction) from the aluminum matrix by means of their own thermal expansion (contraction). Cracks are formed at the non-homogeneities of the surfaces of the inclusions. They play the role of capillaries for aluminum atoms. Mechanical stresses generated by the cracks cause capillary forces that move the atoms of the matrix into the gaps formed between inclusions. The flows of vacancies and silicon atoms occur in the opposite direction.

Table1. Dependence of the thickness of the melted layer in aluminum and silicon samples

E_s, J/cm^2	Silumin d, μm	Aluminum d, μm	Experiment d, μm
15	23	18	23
20	39	39	30
25	54	57	55
35	80	-	80

4. Conclusions

The mechanisms of the effect of electron beams on the structure of silumin have been established. It has been demonstrated that electron beams with an energy density of 35 J/cm^2, and a pulse duration of

150 μs lead to the formation of a heterogeneous multi-layer structure. The surface layer has a columnar crystallized structure. Its depth is 80 μm. Mathematical modeling of the heating operation shows that the depth of fusion is also 80 μm. One of the reasons for the formation of a columnar crystallized structure is thermoconcentration-capillary instability appearing as a result of the temperature gradient occurrence, which, in turn, leads to the formation of vortices and the second-phase particles expulsion to the boundaries of columns. At depths over 100 μm, the process of spheroidization of silicon plates is observed.

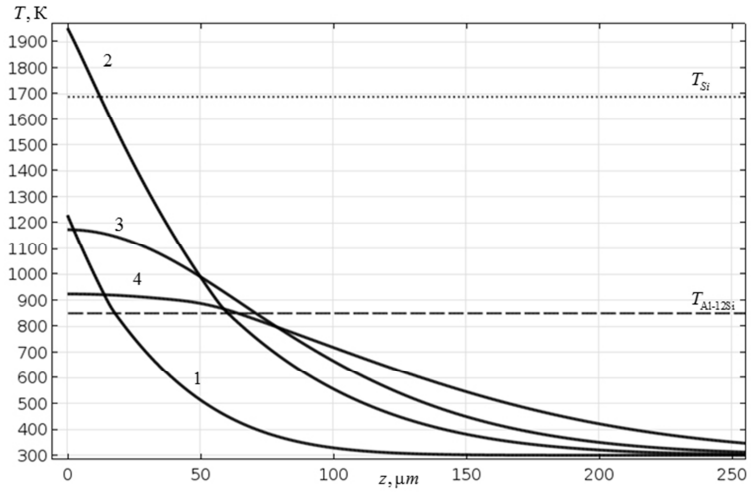

Figure1. Distribution along the depth at different instants of time t 1 - 50 μs, 2 - 150 μs, 3 - 200 μs, 4 - 300 μs. $T_{Al\text{-}12Si}$- eutectic temperature for silumin, T_{Si} – melting temperature for unblended silicon.

Acknowledgement
The study was carried out with the financial support of Ministry of Education and Science of Russian Federation within the framework of the state task # 3.1283.2017/4.6 and Russian Foundation of Basic Research (project # 18-48-420001).

References

[1] Fadeev A V, Bazhenov V E, Koltygin A V 2015 *Russian J. Non-Ferr. Metals* **56** 26
[2] Shulov V A, Gromov A N, Teryaev D A and Engel'ko V I 2016 *Russian J. Non-Ferr. Metals* **57** 256
[3] Novikov A S, Shulov V A and Engel'ko V I 2012 *Sil'notochnye Impul'snye Elektronnye Pushki dlya Aviatsionnogo Dvigatelestroeniya* (Pulsed High-Current Electron Beams for Aviation Propulsion Engineering) (Moscow: DIPAK) (In Russian)
[4] Markov A B, Meisner L L, Yakovlev E V, Meisner S N, Gudimova E Y, Petrov V I 2015 *Izvestiya Vuzov. Fizika* **58** 9/3 173 (In Russian)
[5] Ozur G E, Proskurovsky D I and Rotshtein V P 2016 *Techn. Phys. Lett.* **42** 328
[6] Bleicher G A, Krivobokov V P, Pashchenko O V 2014 *Erosiya Poverkhnosti Tverdogo Tela pod Deistviem Moshnykh Puchkov Zrayagennykh Chastits* (Erosion of the surface of solids at power charged particles beams action) (Novosibirsk: Nauka) (In Russian)
[7] Khaimzon B B, Sarychev V D, Soskova N A and Gromov V E 2013 *Steel in Trans*. **43** 55
[8] Sarychev V D, Khaimzon B B, Gromov V E and Soskova N A 2012 *Titan* **1 (35)** 4 (In Russian)
[9] Volkov N B, Leivi A Ya, Talala K A and Yalovets A P 2010 *Tech. Phys*. **55** 484
[10] Nevskii S, Sarychev V, Konovalov S, Kosinov D, Komissarova I 2016 *Mater. Sci. Forum* **870** 34

[11] Berg J, Acrivos A 1965 *Chem. Eng. Sci.* **20** 737
[12] Konovalov S, Chen X, Sarychev V, Nevskii S, Gromov V, Trtica M 2017 *Metals* **7** 1
[13] Traidia A, Roger F *2011 Int. J. Heat Mass Transfer* **54** 2163
[14] Samarskii A A, Vabishchevich P N 2003 *Vychislitel'naya Teploperedacha (Computational Heat Transmission)* (Moscow: URSS) (In Russian)
[15] Ivanov Y F, Petrikova E A, Ivanova O V, Ikonnikova I A, Tkachenko A V 2015 *Russian Phys. J.* **58** 478
[16] Courtney T H, Kampe J C M 1989 *Acta Metall*. **37** 1747
[17] Liu X, Beausir B, Zhang Y et al. 2018 *J. All. Comp.* **730** 208