Structure of Silumin Surface Layer Modified by Compression Plasma Flow[1]

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Abstract – In this work the structure of the Al–20%Si hypereutectic alloy surface layer modified by compression plasma flows (CPF) was investigated. CPF were generated in nitrogen atmosphere by a magnetoplasma compressor of compact geometry. CPF impact led to dissolution of Si crystals, intermetallides and structure refinement of the surface layer. An additional modification of the surface layer was carried out by means of titanium coating preliminary deposition and subsequent CPF treatment. Structure changes provided an aluminium alloy microhardness increase.

1. Introduction

Aluminium alloys with a high concentration of silicon (> 20%) are supposed to be widely spread in automobile industry. Hypereutectic Al–Si cast alloys are especially suitable to use for tribological parts. Silicon can enhance strength and hardness of an aluminium alloy, but large primary silicon crystals result in surface cracking and degradation of chemical properties [1]. Refinement of silicon precipitates provides the wear resistance increase [2].

That is why a lot of techniques including mechanical vibration, electromagnetic mixing, ultrasonic treatment, variation of thermal parameters of the melt are applied to change morphology of the Si phase [3, 4]. Fluxes of high energy particles are also used for the silumin surface layer modification [1, 5–8].

High speed cooling is one of the main reasons for the surface properties change after treatment. Cooling from the melt results in homogenization and refinement of the structure. This approach was used in this work to modify the surface layer of the Al–20%Si hypereutectic alloy by compression plasma flows. CPF can also be applied for alloying the surface layer by means of preliminary deposition of the coating containing alloying elements and subsequent CPF treatment.

A high concentration and temperature gradients in the melted layer due to the dependence of the surface tension on the concentration and temperature led to concentration-capillar and thermo-capillar convection and mixing of the coating and substrate elements in the melt. Ti was chosen in this work as an alloying element because it improves silumin wear resistance [9, 10].

2. Experimental

The samples used were made of hypereutectic silumin (19.7% Si, 1.54% Mg, 0.55% Cu, 0.26% Fe, 0.19% Ni, 0.13% Mn in at.%, Al – balance). Part of samples were coated with titanium (~1 μm) using cathodic arc vapour deposition with the following process parameters: the arc current of 100 A, the bias voltage of –120 V, the deposition time of 5 min.

CPF were obtained using a gas-discharge magneto-plasma compressor of compact geometry. The pressure of the plasma forming gas was 400 Pa during the discharge. The discharge duration in the MPC was around 100 μs. Treatment of the silumin samples was carried out by five pulses while treatment of the Ti coated samples – by three pulses to provide homogeneity of the mixed layer. The time interval between pulses was 20 s. The energy density absorbed by the surface layer changed in the range of 10–27 J/cm^2 per pulse.

The phase composition of the samples was investtigated by the X-ray diffraction analysis (XRD) in Bragg-Brentano geometry and CuKα-radiation using a DRON 4-13 diffractometer.

Surface and cross section morphology as well as samples element composition was analyzed by means of scanning electron microscopy (SEM) using a LEO1455VP device equipped with an energy-dispersive X-ray Röntec detector. The microhardness of the samples was tested by means of a PMT-3 microhardmeter with a Vickers indenter under the load ranging from 0.5 to 2.0 N. After that the microhardeness value at the indenter penetration depth of 4 μm was chosen for comparison.

[1] This work was partially supported by the grant of Fund of Fundamental Investigations of Belarus.

3. Results

The investigation of the silumin phase composition after CPF treatment at 19 J/cm^2 (Fig. 1) showed the disappearance of Si diffraction lines in the diffraction pattern.

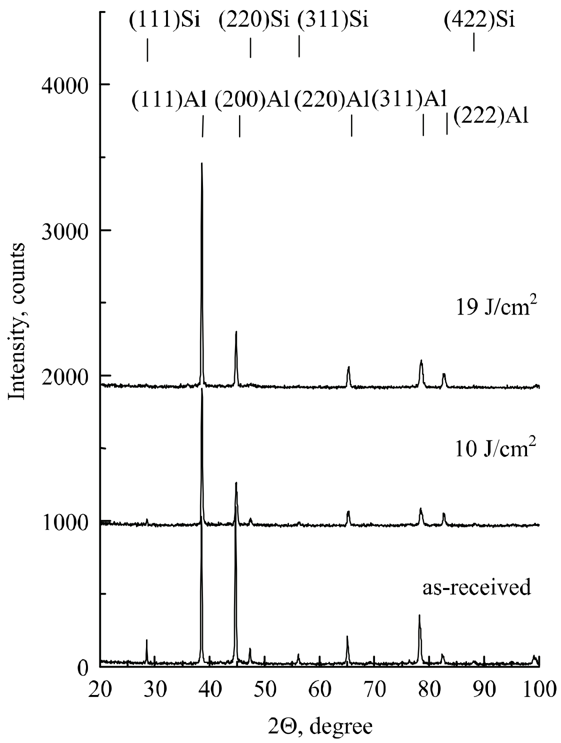


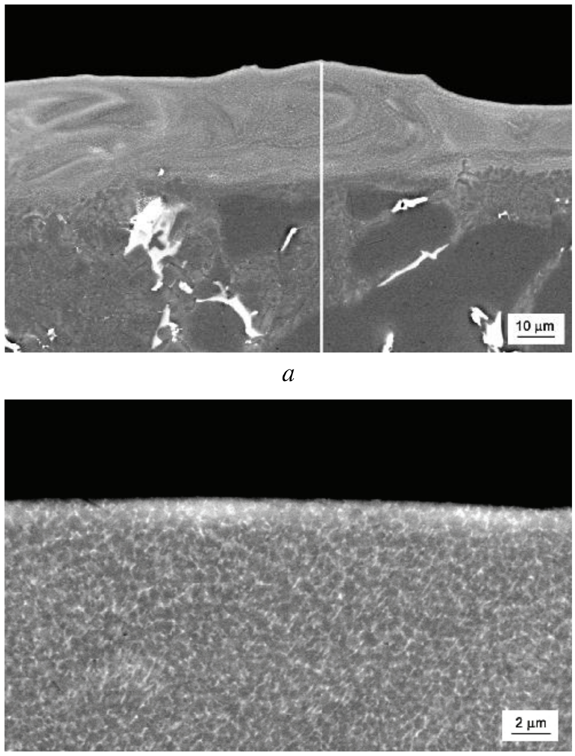
Fig. 1. XRD patterns of silumin treated by CPF

This effect can be connected with dissolution of large Si crystals in the melted layer during CPF impact. A high cooling rate can result in the precipitation of disperse Si particles undetectable by XRD. Some of Si atoms can also take part in the formation of an oversaturated solid solution on the basis of the f.c.c. Al lattice. A similar effect was observed in [1] after treatment of the Al–30Si alloy by an intense pulsed ion beam. The increase of the Si solution rate in the Al matrix up to 5.7 at.% was reported. This value exceeded the maximum solution rate of 1.59 at.% in thermal equilibrium. A shift of Al diffraction lines to greater diffraction angles indicated the formation of the oversaturated Al(Si) solid solution after CPF treatment (see Fig. 1). According to the data presented in [1] the concentration of Si in the solid solution formed can be roughly estimated as 7 at.% in our case.

Dissolution of Si crystals during CPF impact can be illustrated in Fig. 2.

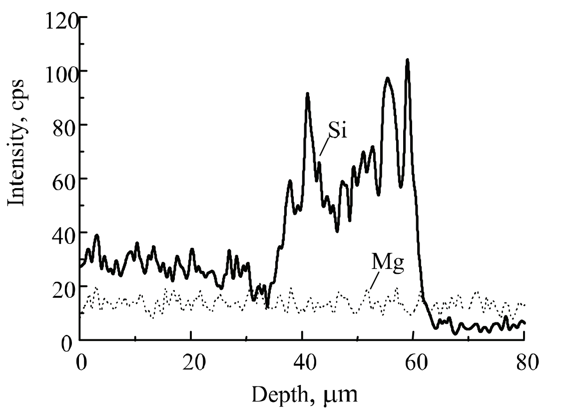
In Figure 2, *a* one can see a layer melted by CPF with the thickness of ~30 μm. Al–Si eutectic containing other alloying elements (grey areas) and phases with alloying elements (precipitates of white colour) can be specified in the underlying layer. The melted layer (Fig. 2, *b*) consists of cells with the boundaries enriched with alloying elements (elements heavier than Al according to the element contrast). The size of cells is ≤ 1 μm, that is why it is hard to determine elements distribution in the cell and its boundary. The Si atoms have a uniform distribution inside the melted layer (Fig 2, *c*).

The Si concentration in this layer is equal to the average concentration of Si in the alloy ~20%. The Si concentration has increased up to ~35% in the underlying layer and has a non-uniform character, which is connected with scanning of the electron beam along the area containing Al–Si eutectic and Si primary crystals. With the increase of the scanning depth the Si concentration drops to background level (Fig. 2, *c*).



a

b



c

Fig. 2. Cross section morphology (*a*, *b*) and distribution of Si and Mg along the corresponding white line (*c*) of silumin sample treated by CPF at 19 J/cm^2

The findings showed that CPF treatment of silumin led to dissolution of Al–Si eutectic, primary Si crystals, intermetallides and formation of the surface layer with a more uniform and disperse structure.

The phase composition analysis of the silumin samples alloyed with Ti atoms showed the same regularities that were described earlier (Fig. 3).

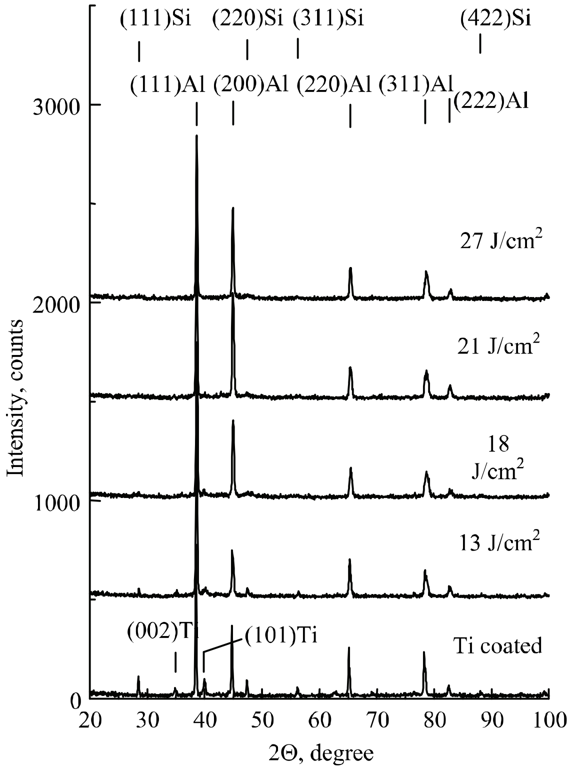


Fig 3. XRD patterns of silumin preliminary coated by Ti and treated by CPF

The increase of energy deposited in the surface layer resulted in dissolution of Si primary crystals and eutectic. Si diffraction lines disappeared in diffraction patterns beginning from 21 J/cm^2. Al diffraction lines were shifted to greater diffraction angles indicating the formation of the Al(Si) oversaturated solid solution. Ti diffraction lines can be seen in the pattern up to 18 J/cm^2. This is the evidence of non-uniform mixing of Ti in the aluminium alloy that occurred due to a significant difference in physical characteristics of Ti and Al (especially melting temperature).

Mixing is not observed at 13 J/cm^2 according to the data of SEM analysis (Fig. 4).

The increase of energy deposited in the surface layer leads to formation of a more uniform mixed layer. At the energy of 18 J/cm^2 the surface layer contains small precipitates with the size of 100–500 nm and has a structure close to cellular (Fig. 4, *b*). A clear cellular structure is formed at the energy of 21 J/cm^2 (Fig. 4, *c*). A similar structure was observed in Fig. 2, *b*. At the same time cells observed in Fig. 4, *c* contain small precipitates with the average size of ~150 nm. A further increase of deposited energy and cooling speed as a consequence leads to the dendritic structure formation (Fig. 4, *d*).

The energy growth leads to diminishing the Ti concentration in the mixed layer due to the growth of the melted layer thickness. It varies from 3 at.% at 18 J/cm^2 to 0.7 at.% at 27 J/cm^2.

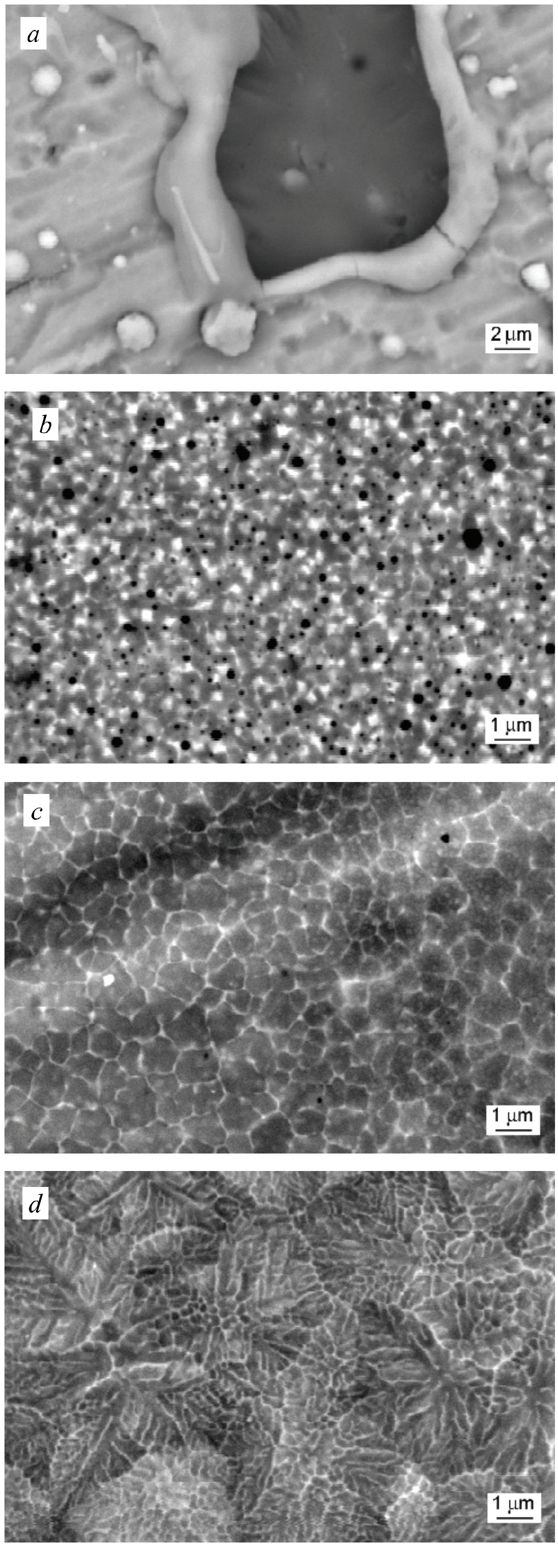


Fig. 4. Surface morphology of silumin samples coated with Ti and treated by CPF at 13 (*a*), 18 (*b*), 21 (*c*), and 27 J/cm^2 (*d*)

The observed surface structure changes strongly influence the microhardness value (Fig. 5). The formation of a more dispersed structure in case of silumin treatment at 18 J/cm^2 leads to 1.3 times microhardness increase. Alloying with Ti atoms provides a greater microhardness value ($H/H_0 = 1.6$). This effect can be attributed to possible formation of disperse Al_3Ti precipitates or to additional refinement of the structure due to Ti alloying.

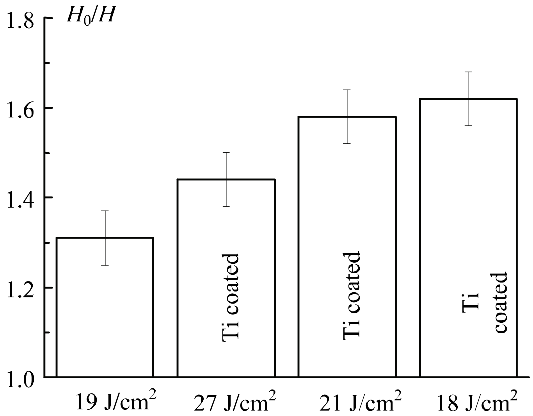


Fig. 5. Relative microhardness of silumin treated by CPF

Though Al_3Ti formation was not detected by the XRD analysis the previously received data showed its synthesis in technically pure aluminium by CPF [11]. Moreover, the dependence of microhardness on the energy deposited in the surface layer is correlated with the Ti concentration.

The maximum microhardness is achieved at the maximum Ti concentration.

4. Conclusion

The findings showed that compression plasma flows treatment of the Al–20%Si alloy led to dissolution of Si crystals, intermetallides and structure refinement of the surface layer. These changes led to 1.3 times microhardness increase at the energy deposited in the surface layer 19 J/cm^2.

An additional microhardness increase can be obtained by alloying the surface layer with Ti atoms. The maximum microhardness (1.6 times) is achieved at the maximum Ti concentration (3 at.%). The energy growth results in diminishing the Ti concentration in the mixed layer and changing surface morphology: cellular like → cellular → dendritic. The minimum size of surface structure components detected by SEM is ~ 100 nm.

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