Effect of ion implantation on the properties of implantable aluminum alloys

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Abstract. The effect of ion-implantation processing of N$_2^+$ ions in aluminum alloys 1160, 1190 and 1420 on their microhardness, stresses of II type and microstructure is discussed in this article. During research, prototypes of aluminum alloys were hardened by ion implantation in the accelerator. The implantation mode, selected from literature, was used to test the possibility of hardening aluminum alloys by implantation with N$_2^+$ ions. The ion beam was scanned in a horizontal plane at a beam height of 400 mm. The residual pressure in the working chamber was maintained 5·10$^{-5}$ mm Hg. The parameters of the irradiation regime are the following: energy - 5 keV, dose - 10$^{18}$ ion/cm$^2$, temperature - 200 °C. The strength characteristics were studied by the methods of measuring microhardness, residual voltage in the surface layers of implanted samples. A micro X-ray diffraction analysis was also performed.

1. Introduction
For a long time, it has been of great interest to study the structure and properties of various metals and alloys subjected to ion implantation (II). Due to the fact that II, as a way of targeted influence on the microstructure and properties of materials, is a relatively new and still little studied method of hardening, the general laws of changes in the microstructure and properties of metallic materials have not been identified. The effect of II on various properties of metals and alloys is very different and ambiguous [1, 2, 3, 4].

So, in the process of II, implantable ions penetrating into the surface layers of metals or alloys cause the formation of a significant number of so-called radiation defects, spraying the surface, changing and moving structural elements, etc. All of this leads to profound changes in the composition and microstructure and, as a result, the properties of the surface layer of the material [5, 6]. This, in turn, explains the increase in hardness, strength, fatigue characteristics, wear resistance, corrosion resistance, improved surface quality of the metal material and many other things. Considerable attention is paid to the detailed study of materials with a special microstructure and desired properties.

In this regard, the study of the effect of II on the structure and properties of aluminum and its alloys is of great scientific and practical interest. The studies conducted and presented in this article were made with the aim of analyzing the strength characteristics after II of the following aluminum alloys:

- 1160 (chemical composition of alloy: Al – 90,9 ÷ 94,7 %; Cu – 3,8 ÷ 4,9 %; Mg – 1,2 ÷ 1,8 %; Mn – 0,3 ÷ 0,9 %; Fe – до 0,5 %; Si – up to 0,5 %; Zn – up to 0,25 %; Ti – up to 0,15 %; Cr – up to 0,1 %);
• 1190 (chemical composition of alloy: Al – 91.095 ± 94 %; Cu – 3.8 ± 4.3 %; Mg – 1.7 ± 2.3 %; Mn – 0.5 ± 1 %; Fe – up to 0.5 %; Si – up to 0.5 %; Zn – up to 0.1 %; Ti – up to 0.1 %);
• 1420 (chemical composition of alloy: Al – 90.55 ± 92.9 %; Mg – 5 ± 6 %; Li – 1.9 ± 2.3 %; Mn – up to 0.3 %; Fe – up to 0.3 %; Si – up to 0.3 %; Ti – up to 0.1 %; Zr – up to 0.15 %; Cu – up to 0.05 %).

2. Microhardness
The studies of microhardness of the surface layers of samples of alloys 1160, 1190, and 1420 after II were carried out in the direction from the surface to the center using the Neophot-2 instrument on transverse metallographic thin sections cut perpendicular to implantation. There was nitrogen implantation mode: $E = 5$ KeV, $D = 10^{18}$ ion·cm$^{-2}$, $t = 200$ °C. Microhardness measurements over the layer depth were carried out from the surface of the sample to the center after 10 - 20 μM. The results of the study after mathematical processing are presented in the form of graphs of the change dependency in microhardness on the layer depth (figure 1).

![Figure 1](image-url)

**Figure 1.** Changes in microhardness from the core to the surface of aluminum alloy samples after ion implantation with nitrogen.

During II process of sample 1190, the alloy softens, and the hardness at the surface is about 65 MPa, which is significantly lower than the hardness of the substrate (110 MPa). It seems probable that this softening of the alloy is associated with its recrystallization process during implantation, which creates a certain hardening and at the same time occurs at a sufficiently high temperature (200 °C) for this alloy.

The properties of sample 1160 under the same conditions are slightly different, namely, the alloy surface hardens, and at a distance of 30 - 70 μM from the surface of the aluminum alloy sample, gradual softening occurs and the microhardness of the alloy gradually decreases to the base hardness of 100 MPa. This nature of the surface microhardness dependence of this aluminum alloy is associated with the features of its chemical composition, which differs from the composition of alloy 1160.

Alloy 1420 as a result of II is hardened, while its microhardness at the surface is 410 MPa, followed by a gradual decrease in this characteristic at a distance of 40 - 50 μM from the surface up to the microhardness of the base 110 MPa. Apparently, this is due to the formation of radiation defects at the surface of this alloy.

Analyzing the results obtained, we can conclude that the applied II mode for hardening aluminum alloys 1160 and 1190 is not advisable, because the recrystallization temperature of these alloys is quite
low and is approximately at the level of implantation temperature, which indicates that these alloys are softened during II.

3. Residual stresses in the surface layer of implantable samples

The II process is associated with the incorporation of atoms or molecules of an implantable substance into the crystal lattice of a base metal material. As a result, the base metal, supersaturated with the atoms of the implanted substance, undergoes structural transformations in the surface zone, the specific volume of the surface layer changes with respect to the bulk of the metal, in consequence of which there are micro distortions that are balanced in the volume of individual crystals, i.e. stresses of II type.

The occurrence of residual stresses is associated with a change in many physicochemical and physicochemical properties of a metal material and, above all, its strength characteristics. Fatigue failure is known to occur in connection with the accumulation of micro-failures, and primarily in the surface zone of a metal sample, which is the most loaded during torsion and bending. The formation and development of microcracks, which subsequently leads to the destruction of samples, occurs in areas that were not subject to II, i.e. below the implantation layer [1]. An increase in microhardness is also associated with the presence of residual strength [1]. The main goal of these studies is an attempt to determine the microstresses of the crystal structure using a general-purpose diffractometer “DRON-3” in samples of three aluminum alloys 1160, 1190, and 1420 after II with nitrogen. Focusing control was carried out from a flat sample according to Bragg-Brentano.

Diffractograms were taken from implanted sections of samples of aluminum alloys. Non-implanted areas of the same aluminum samples were used as a model. The recordings were carried out at the same intensity of Fe-H$_2$ radiation and the same speed of movement of the paper structure, which made it possible to compare and analyze the obtained diffraction patterns without additional recalculations. For the two crystallographic planes 111 and 311 of each aluminum sample, interference maxima were recorded.

As far as is known, the shape and width of interference lines are determined by the following factors: 1) crystallite size; 2) microdistortions of crystallites (stresses of II type); 3) the presence of packing defects in crystallites.

The line broadening associated with the above factors is called physical broadening and, therefore, may be a consequence of the presence of stresses of II type. Also, the width of the interference line is affected by the conditions of the x-ray and the intrinsic width of the spectral line of the characteristic radiation (geometric radiation). Simultaneous imaging of interference lines from the studied sample and a model makes it possible to eliminate the influence of characteristic factors. The obtained diffraction patterns are presented in figures 2, 3 and 4.

![Figure 2. Diffractogram of alloy 1160: a) crystallographic plane 111; b) crystallographic plane 311; 1 – model, 2 – implanted sample.](image-url)
Figure 3. Diffractogram of alloy 1190: a) crystallographic plane 111; b) crystallographic plane 311; 1 – model, 2 – implanted sample.

Figure 4. Diffractogram of alloy 1420: a) crystallographic plane 111; b) crystallographic plane 311; 1 – model, 2 – implanted sample.

Comparing the diffraction patterns of the studied samples of aluminum alloys with the diffraction patterns of the corresponding standards, it can be concluded that the indicated method of any physical broadening, and hence significant micro-distortions in the II zone, cannot be detected. From the above results it follows that the diffraction patterns of the aluminum alloy sample and the standard of identical crystallographic planes are almost identical, and the difference between the half-widths of the lines of the studied sample and the standard is within the measurement errors.

4. X-ray microanalysis

It is possible to determine the local chemical composition of inclusions, phases, grains, and also to study the distribution of individual elements between the structural components using a local X-ray microanalysis. The distribution of aluminum alloy elements after II with nitrogen was studied using the CamecaMS-4 instrument, consisting of a microanalyzer and a scanning electron microscope. The resolution of X-ray microanalyzer is 70A˚.

The analysis method consisted of using the spectrum of characteristic x-rays excited in the studied aluminum sample during its bombardment by a focused electron beam. The present elements were determined by the movement of the crystal analyzers over the entire range of radiation reflection units. The analysis included a qualitative determination of the contents of Al, Mg, and Cu during scanning along the cross-sectional line of metal samples. The studies were carried out on samples of aluminum alloys 1160, 1190, as well as 1420, cut perpendicular to the implantation surface, i.e. redistribution of elements from the surface to the center of the metal sample was used. Present elements in the analyzed microvolume gave intensity peaks in the radiation spectrogram. The results are presented in the form of graphs of changes in the relative intensity of the characteristic radiation of the corresponding element of Al, Mg and Cu from the surface to the center of aluminum samples (figures 5, 6, 7).
After implantation at a distance \(\approx 100\mu M\), a decrease in the content of aluminum elements was observed in the sample of alloy 1160 after implantation, and an increase in the content of magnesium and copper elements at a distance of \(\approx 150\mu M\).

After II, an increase in the content of copper elements at a distance of \(\approx 150\mu M\) and magnesium elements at a distance of \(\approx 50\mu M\) was observed on a sample of 1190 aluminum alloy. The content of aluminum elements in the surface layer decreased at a distance of \(\approx 100\mu M\).

After II, a redistribution of the base elements was observed on the studied sample of aluminum alloy 1420, while magnesium and aluminum, which have a lower nitride formation energy compared to copper, were most actively involved with the formation of nitrides (table 1). An increase in the
number of magnesium elements at a distance of \( \approx 80 \mu \text{M} \) and aluminum elements at a distance of \( \approx 200 \mu \text{M} \) in the surface layer and a slight decrease in copper elements at a distance of \( \approx 50 \mu \text{M} \) were also observed.

According to the above, it can be concluded that the most “active” elements to nitrogen are magnesium and aluminum.

It follows that in the surface layer of all the studied aluminum alloys the redistribution of the base occurs, which is probably mainly due to the interaction of the base elements with nitrogen with the formation of nitrides. The prevalence of certain nitrides in the surface layer of alloy samples is determined by the chemical content of each aluminum alloy.

5. Conclusion

The studies on surface hardening of aluminum alloys 1160, 1190, and 1420 by implantation with nitrogen ions suggest that aluminum alloys 1160 and 1420 have surface hardening and the microhardness of the surface layers of these alloys gradually decrease from 400 MPa to 80 - 110 MPa, and alloy 1190 as a result of II softens from the surface: its hardness is 80 MPa, while in the core of the alloy it is 100 MPa.

With that in mind, it is necessary to conduct additional studies on the variation of the II modes and pay special attention to the implantation temperature.

The II process can be recommended for hardening products from aluminum alloys that operate in various operating conditions. But the industrial implementation of this process should be preceded by a serious design study of equipment for the implementation of II.

Given the above, ion implantation can be considered one of the promising methods of hardening the surface of products made from aluminum alloys.

References

[1] Hirvonen J K 1985 Ion implantation (Moscow: Metallurgy)
[2] Usanova O Yu, Savelyev I L and Kazantsev A Yu 2015 Collection of conference reports Scientific space of Europe. Prospects for the use of ion implantation to enhance the heat transfer process (Poland: Nauka i studia Przemysl)
[3] Usanova O Y, Fukalova E V and Gushchin N S 2005 Wear resistance of cast iron with different shapes of graphite inclusions Litejnoe Proizvodstvo 5 4-5
[4] Usanova O Yu, Maryushin L A, Kazantsev A Yu и Dyukova A I 2017 Corrosion resistance study of grey cast iron implanted with C, N, Cr and Cu ions IOP Conf. Series: Earth and Environmental Science 87 (9) 092030
[5] Myers S M 1985 Implant metallurgy of equilibrium alloys (Moscow: Metallurgy) pp 47-71
[6] Komarov F F 1990 Ion implantation in metals (Moscow: Metallurgy) p 216