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Improving the performance characteristics of grey cast iron parts via ion implantation

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ABSTRACT

Introduction. Cast iron is a material that is widely used in various industries. It possesses high heat capacity, relatively high hardness, and a number of other physical, mechanical and technological properties. Due to the significant operational stress experienced by the working surfaces of cast iron parts and its frequent exposure to aggressive environments, additional surface treatment is required to enhance wear resistance, corrosion resistance, and other properties. There are many different methods of surface modification. One of the most promising and modern ones is ion implantation with various ions. The **purpose of the work** is thus to study the effect of ion implantation on the surface of cast iron and the resulting changes in its mechanical properties. **Methods.** Cast iron samples were implanted with nitrogen ions of different doses (optimal dose of implanted nitrogen ions as a nitride-forming element). The surface microstructure of cast iron samples was investigated using a scanning electron microscope *Stereoscan S-180* at a magnification of ×2,900 and ×5,000. Microdurometry analysis of the samples was carried out using a *Neophot-2* metallographic microscope equipped with an attachment for measuring microhardness, at a load of 10 g after implantation of cast iron samples with various doses of nitrogen ions. In addition, X-ray diffraction analysis was performed on a *DRON-3* diffractometer to determine the phase composition and fine structure of modified cast iron samples. **Results and Discussion.** Ion implantation of cast iron samples significantly increases microhardness. Thus, the conducted study reveals that the best mechanical properties (specifically microhardness) are observed in cast iron samples after implantation by N^+ ions with a dose of 5×10^{17} ions/cm^2 with energy of 40 KeV. X-ray diffraction analysis demonstrated that the ion implantation with nitrogen results in the formation of Fe_2N and Fe_2N nitrites, and also revealed changes in fine structure (average dislocation density and size of mosaic blocks).

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Introduction

Cast iron has a number of properties that make it indispensable in the manufacture of various parts [1], such as piston rings, bushings, turbine parts, etc.

The strength characteristics of cast iron enable its use in manufacturing components subjected to heavy loads and parts that can withstand water and steam. However, there is a problem of improving the surface properties of cast iron (wear resistance, corrosion resistance, etc.).

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Numerous methods exist to further improve the properties of cast iron using various technologies [2–4], for example, applying a protective titanium nitride coating [5], normalizing the cast iron [6], and applying diffusion carbide-containing coatings [7] among others. However, these methods have the disadvantage of poor adhesion of the coating with the substrate material (cast iron) [8–10].

To improve the properties of cast iron and harden its surface, as well as to create a quality bond between the surface layer and the base material, it is proposed to employ the method of ion implantation [11–13]. Ion implantation is a technology that allows for modifying materials properties by "bombarding" its surface with high-energy ions. In the case of cast iron, ions of various elements are used as "projectiles" which become embedded in its surface layer. As a result of ion implantation, not just a coating is formed, but a deeply modified alloy with variable composition. This alloy differs from conventional coatings in that there is no clear boundary between the original material and the modified layer. Instead of an abrupt transition, a gradual change in composition and properties is observed into the depth of the material. This gradual change enables a more uniform distribution of improved properties throughout the depth of the modified layer. Studies indicate that the thickness of such a modified layer can reach 150–200 µm, which makes ion implantation an excellent tool for improving the wear resistance and strength of parts [14, 15].

The use of the ion implantation method ensures improvement in the mechanical properties of the material, increasing its hardness, strength and wear resistance. This process also facilitates improved adhesion between the surface layer and the base material, which increases the resistance to corrosion and external factors [16–18]. Ion implantation is widely used in industry to modify the properties of various materials such as different steels and alloys including cast iron. This method is an effective way to improve surface quality and overall material performance, making it an attractive choice for use in various industries that require improved wear resistance, hardness, fatigue resistance, corrosion resistance and other surface properties of materials [19–22].

While effective, ion implantation is not without its challenges. One of the key problems is the unpredictability of its results. Unlike other methods of materials processing, where the effect of parameters on properties is easily modelled, ion implantation is characterized by significant variability in outcomes. This is due to the fact that in the process of implantation ions interact with the material at the atomic level, and its behavior under various conditions can be quite complex. To date, no universal model fully describes the mechanism of strengthening resulting from ion implantation, nor does one accurately predict the results. Frequently, ions do not behave as expected, necessitating careful experimental verification for each specific case [23]. However, it should be noted that the process success hinges on process parameters such as ion dose and energy. Despite the difficulties related to the predictability and results of the process, ion implantation remains an important technique for improving material properties and creating new functional surfaces. It is important to choose the right process parameters to achieve the desired results and further application of this technique [24, 25].

To solve the problem of hardening the surface layer of cast iron products and parts, it is necessary to conduct preliminary studies that will show the regularities of formation of the structure and properties of implanted surfaces. **The aim of this work** was to determine the technological parameters of surface treatment of cast iron workpieces using ion implantation (optimal radiation dose and beam energy) that allow for increasing the strength properties of the surface layer. ***To achieve this aim, a number of objectives were accomplished***:

1. The optimum mode of nitrogen ion implantation in grey cast iron was determined, and the optimal radiation dose and beam energy for achieving maximum strength of the surface layer were established.
2. The effect of ion implantation on the microstructure of gray cast iron was studied, and an analysis of changes in the microstructure was performed, including the fragmentation of pearlite colonies, the formation of a diffusion layer, and the burnout of graphite inclusions.
3. An assessment of the change in microhardness of the cast iron surface after implantation was performed, the dependence of microhardness on the implantation dose was determined, and an analysis of its distribution over the depth of the modified layer was conducted.

4. The phase composition and fine structure of the implanted layer were determined, the phases formed as a result of implantation were identified, and an analysis of changes in the average dislocation density and the size of mosaic blocks was performed.

Methods and materials

Microstructural analysis of the experimental cast iron

The microstructure of implanted grey cast iron (type *CI20* pearlitic structure, chemical composition is shown in Table 1) was analyzed using a *Stereoscan S-180* scanning electron microscope with resolution up to 60 Å on 10×10×10 mm samples (Fig. 1) after etching in 3 % HNO_3. The samples were cut in a direction perpendicular to the implanted layer and examined at magnifications of ×2,900, 5,000.

Table 1

The composition of cast iron

Element	C	Si	Mn	Cr	P	S
Percentage content, %	3.45	2.2	0.8	0.32	0.1	0.12

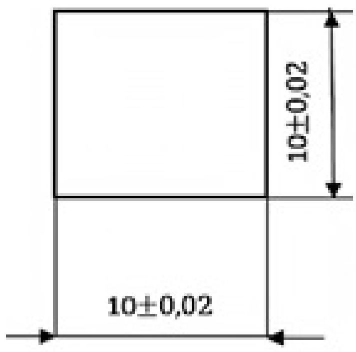


Fig. 1. Gray cast iron sample diagram

Microdurometry analysis of cast iron after implantation

For microdurometry studies, samples obtained using three different treatment modes were used (with doses of 10^{17}, 2×10^{17} and 5×10^{17} ions/cm^2 and with implantation energy of 40 KeV). The studies were carried out on the *Neophot-2* metallographic microscope equipped with an attachment for measuring microhardness (with a load of 10 g).

Microhardness was measured in the direction from the implanted surface to the centre on samples cut perpendicular to the implanted layer. Microhardness values along the depth of the layer were determined as the arithmetic mean of 5 measurements.

Phase Composition Analysis of the Cast Iron Surface after Implantation

X-ray diffraction studies were conducted using a *DRON-3* diffractometer. X-ray analysis was carried out using *Co K*α radiation.

It is known that the implanted layer itself has a thickness of only about 1,000 Å [26–28]. In addition to specifically applicable imaging devices, the phase analysis was facilitated by the fact that the most intense lines of the phases expected in the implanted layers (nitrides, carbides, etc.) are located in the range of small reflection angles. Due to the geometry of imaging at small angles X-rays travel a longer path in the surface layer than at angles close to 90°, thereby increasing the reflecting volume of the phases formed.

Despite the fact that the intensity of the diffraction lines of the phases in the implanted layers is many times lower than the intensity of the matrix lines, it was possible to identify the phases.

Results and Discussion

Microstructure of the Experimental Cast Iron

The microstructure of implanted metals and alloys is controlled by processes occurring in any supersaturated solid solution and by specific effects characteristic of the implanted metal surface.

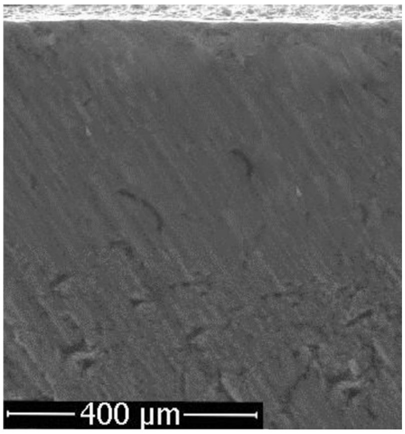
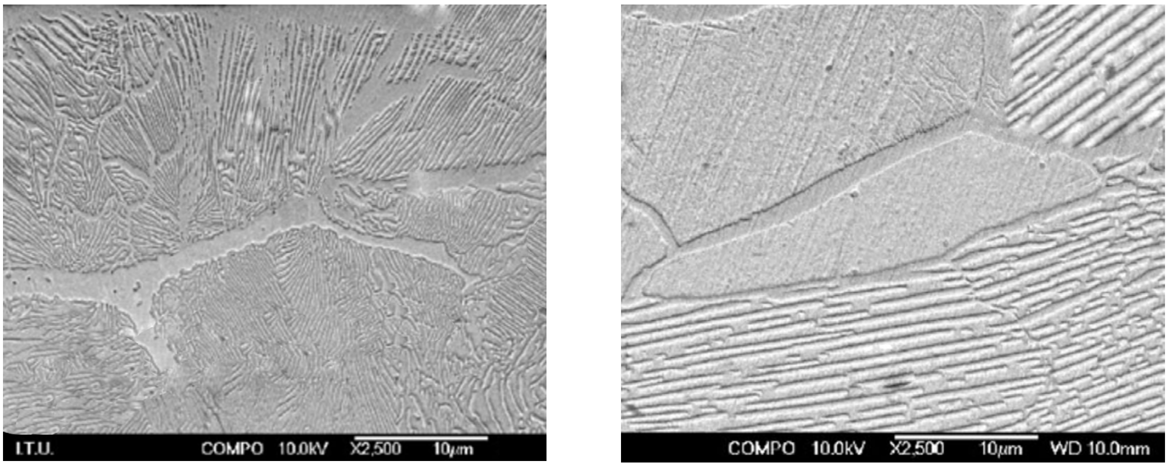


Fig. 2. Microstructure of the surface layer of cast iron implanted with N^+ ions

As a result of ion implantation, there is not just a simple surface coating, but a profound change in the structure of the material. Instead of a clear boundary between the new layer and the original material, as is typical with conventional deposition, a transition zone is formed. In this zone, the composition of the material gradually changes from the original cast iron to a modified layer enriched with nitrogen atoms. This changing composition creates a gradient of properties, where hardness and other mechanical characteristics smoothly transition from the initial values to the improved parameters achieved through ion implantation (Fig. 2). Nevertheless, from the photographs of the microstructure of the surface layer it is evident that a diffusion layer with a thickness of approximately 400 μm was formed on the surface of the implanted sample. Graphite inclusions are almost completely absent within this layer. These inclusions begin to appear only at the end of this layer and in small quantities. In the structure of grey cast iron graphite burnout occurs under the influence of nitrogen ions. Similar results were also obtained by the authors of the work [29]. In this work, nitriding of the surface of grey cast iron under different modes also led to the burnout of graphite inclusions in the surface layer of the samples.

Implantation of nitrogen ions (N^+) into the near-surface region of grey cast iron leads to significant changes in its microstructure. Firstly, fragmentation and disorientation of pearlite colonies occur, which are a characteristic feature of the microstructure of gray cast iron. The microstructure of the implanted cast iron is shown in Fig. 3.



a *b*

Fig. 3. Microstructure of the surface layer of cast iron implanted with N^+ ions:
a – 2×10^{17} ion/cm^2; b – 1×10^{17} ion/cm^2

The changes in the microstructure of the surface layer after ion implantation are crucial for determining various surface properties (microhardness, wear resistance, etc.).

Microdurometry Analysis of Cast Iron after Implantation

Microdurometry analysis showed that an increase in microhardness occurs as a result of ion implantation (Table 2, Figs. 4, 5, 6).

Table 2

Results of microdurometry analysis of cast iron after implantation

Radiation dose, ion/cm^2	Hardness, MPa
0	2,500
10^{17}	18,500
2×10^{17}	20,500
5×10^{17}	24,000

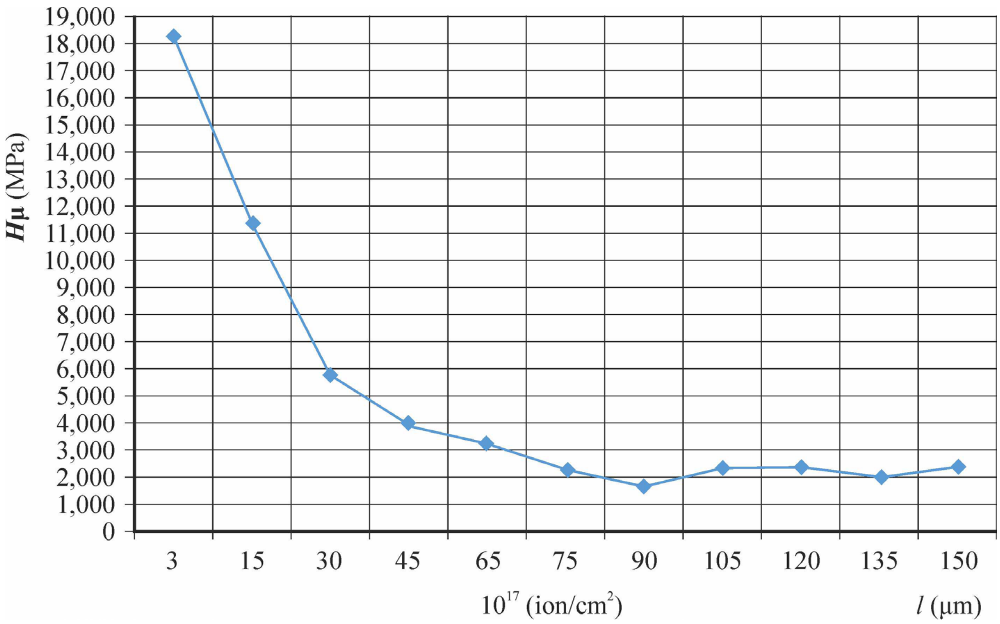


Fig. 4. Change in microhardness of cast iron implanted with nitrogen ions at a dose of 10^{17} ion/cm^2

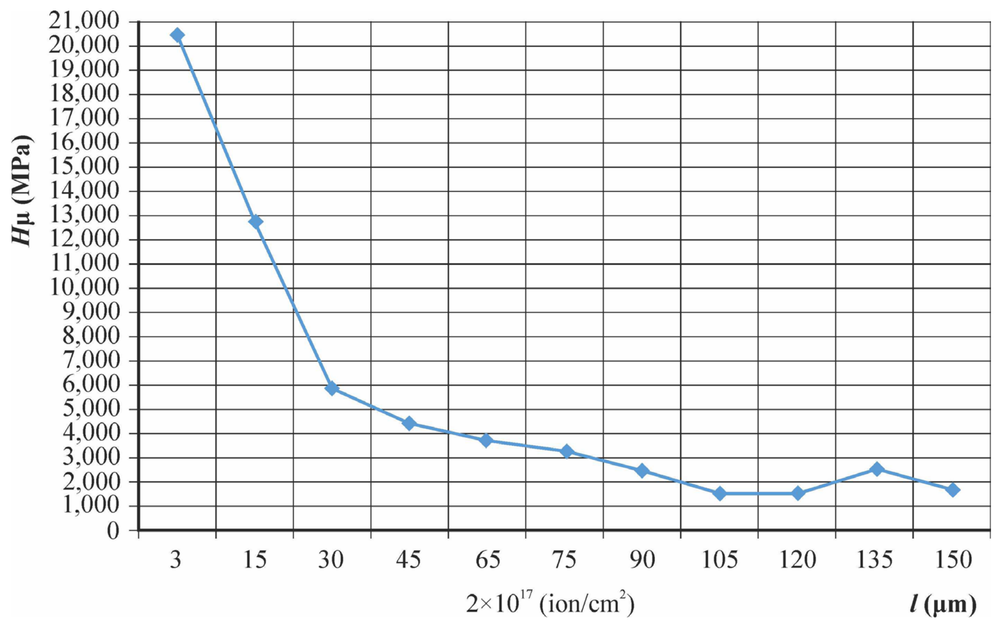


Fig. 5. Change in microhardness of cast iron implanted with nitrogen ions at a dose of 2×10^{17} ion/cm^2

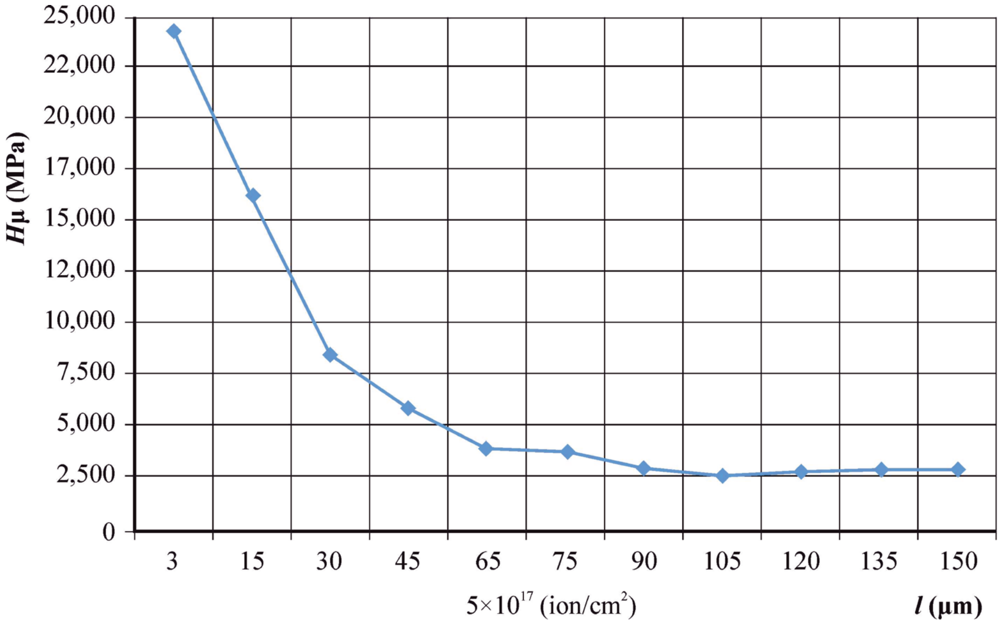


Fig. 6. Change in microhardness of cast iron implanted with nitrogen ions at a dose of 5×10^{17} ion/cm^2

From Table 2 and the graphs (Figs. 4, 5, 6), it is evident that the hardness at the surface increases significantly and gradually decreases to 2,500 MPa as the distance from the surface increases. The decrease continues until it reaches the value characteristic of the initial state, before implantation.

Thus, the maximum value of surface microhardness is observed in the samples after implantation by nitrogen ions at a dose of 5×10^{17} ions/cm^2. This, consequently, is the most optimal dose of ion implantation for cast iron samples (type *CI20*), which is shown under the given conditions of research.

The increase in microhardness at the surface layer is related to the formation of a large number of specific radiation defects in the near-surface layer (such as, for example, *Frenkel* pairs) and the formed phases, in this case nitrides, which are known to have a high hardness (microhardness) value.

Analyzing the obtained data on the hardness of the surface layer of the samples and the data obtained from the microstructural analysis results (obtained at different radiation powers), it can be seen that the thickness of the implanted nitrogen layer in our grey cast iron samples directly depends on the implantation dose. The higher the radiation dose, the wider the layer. However, the dependence is not linear. Apparently, with an increase in the implantation dose, the layer thickness may reach saturation, when all available interstitial sites in the crystal lattice of iron are filled with nitrogen atoms. For example, the increase in hardness for the implanted layer at a dose of 1×10^{17} ion/cm^2 starts from approximately 75 μm from the surface; for 2×10^{17} ion/cm^2 it starts from approximately 90 μm from the surface and for 5×10^{17} ion/cm^2 it starts from approximately 90–100 μm from the surface. A similar pattern is observed for the hardness of the layer closest to the surface. Increasing the radiation power from 10^{17} ions/cm^2 to 2×10^{17} ions/cm^2 resulted in an increase in its hardness by approximately 2,000 MPa. Further increase of radiation power from 2×10^{17} ion/cm^2 to 5×10^{17} ion/cm^2 resulted in an increase in hardness of this layer by 3,500 MPa.

X-ray Diffraction Analysis Results

X-ray analysis was conducted to determine the phase composition and study the fine structure (average dislocation density and the size of mosaic blocks). This analysis demonstrated that during ion implantation of nitrogen into grey cast iron new phases are formed. The nitrogen ions, penetrating into the material, enter into chemical reactions with iron (*Fe*) atoms, which constitute the cast iron matrix. As a result of these interactions, iron nitrides are formed. Among it, the Fe_3N phase, iron (III) nitride, predominates. In addition, iron (II) nitride, Fe_2N, is present in smaller quantities. The formation of these nitrides is a consequence of the ion implantation process and has a significant impact on the properties of the surface layer of cast iron, increasing its hardness and wear resistance. Increasing the dose of N^+ from 10^{17} to 2×10^{17} does not lead to a change in the phase composition.

The studies also showed that after implantation, the size of mosaic blocks (*C.S.R.*) decreases compared to the initial untreated state. Moreover, the most pronounced decrease is observed in samples after implantation with a dose of 2×10^{17} ion/cm^2 (Table 2).

Nitrogen ion implantation introduces significant changes in the structure of cast iron, specifically in its near-surface layer. One of the key changes is an increase in the dislocation density in this layer compared to the initial material, which was not treated. Dislocations, which are defects in the crystal lattice, affect the mechanical properties of materials. Its increased concentration, resulting from ion implantation, leads to an increase in hardness and strength. This is confirmed by observations showing that the highest average dislocation density is found in samples implanted with the highest nitrogen dose – 5×10^{17} ions/cm^2 (Table 3). It is important to note that this dose is considered optimal in this study, as it provides the most effective increase in strength properties without deterioration of other characteristics.

Table 3

Results of X-ray diffraction analysis of samples before and after implantation with N^+ ions

Cast iron type	Radiation power (ion/cm^2)	Coherent scattering region ($D \pm \Delta D$) (cm$\times10^{-4}$)	Average dislocation density ($\rho \pm \Delta\rho$) $\times 10^9$ (cm^{-2})	Phase composition
CI	0 (original sample)	2.0 ± 0.12	0.75 ± 0.5	α-Fe
	10^{17} ion/cm^2	1.5 ± 0.08	1.3 ± 0.1	α-Fe, Fe_3N, Fe_2N
	2×10^{17} ion/cm^2	0.9 ± 0.03	3.7 ± 0.6	α-Fe, Fe_3N, Fe_2N
	5×10^{17} ion/cm^2	0.6 ± 0.03	4.8 ± 0.6	α-Fe, Fe_3N, Fe_2N

Thus, X-ray diffraction analysis showed that, after implantation with nitrogen ions, an increase in the average dislocation density and a decrease in the size of mosaic blocks occur. Ultimately, these structural changes explain the improvement in surface properties observed in the investigated type of cast iron.

Conclusion

As a result of the conducted research it is established that nitrogen ion implantation is an effective method for increasing the strength properties of parts made from grey cast iron.

1. According to the results of the work it is shown that the optimal mode of implantation in the conditions of this study is a dose of 5×10^{17} ion/cm². At this dose, the maximum increase of microhardness is observed, reaching 24,000 MPa, which significantly exceeds the initial value (2,500 MPa).

2. Ion implantation leads to significant changes in the cast iron microstructure. A diffusion layer about 400 μm thick is formed, in which graphite inclusions are almost completely absent. Fragmentation and disorientation of the pearlite colonies, characteristic of the initial structure of gray cast iron, occur.

3. As a result of nitrogen implantation, the phase composition of the surface layer is changed, and nitrides Fe_2N and Fe_3N are formed. An increase in the average dislocation density and a decrease in the size of mosaic blocks are observed.

Therefore, the application of nitrogen ion implantation with an optimal dose allows obtaining a hardened layer on the surface of cast iron while maintaining the specified dimensions of parts. The obtained results open up opportunities for practical application of ion implantation in industry to improve the durability and reliability of grey cast iron parts used in various fields of engineering.

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Conflicts of Interest

The authors declare no conflict of interest.