Wear behaviour of austempered, ductile iron microalloyed with boron under different contact load by dry sliding wear conditions

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Abstract. In the preformed work were studied the characteristics of Ni, Mo and Cu – free austempered ductile iron microalloyed by Boron under different contact load. For microalloying liquid cast iron with boron, the ferroboron by synthesized SHS - innovation technology was used. The upper and lower bainitic austempered ductile irons were studied with different content of metastable retained austenite. The experimental samples were tested with a fixed linear sliding speed of 2 m / s at a different contact load values, which were changed in the range of 25, 50 and 100 Newtons. It was defined that the value of the contact load has a significant effect on the tribotechnical characteristics of bainitic cast irons in conditions of dry sliding friction. Particulary, they determine the structural changes character and the degree of surface layers degradation of friction. High strength cast irons with the lower bainite structure are more resistant to adhesive wear. According to the obtained data, the presence of up to 80% metastable retained austenite in the metal matrix structure of the of experimental cast irons makes it possible to stabilize the friction coefficient under the investigated contact loads. Thus, to ensure maximum wear resistance, the isothermal quenching of high-strength cast irons must be carried out in the temperature range 220-280 °C with a minimum treatment time.

1. Introduction
It is known that the tribotechnical properties of constructional materials are largely determined by their phase composition and microstructure, also by singularities of their production technology. The main task of increasing reliability and durability of parts under friction and wear conditions is the microstructure formation of surface layer, which makes it possible to prevent or slow down the formation processes of deformation defects in materials and afterward increase their strength and tribotechnical properties [1-5].

During developing wear-resistant materials, it is necessary to take into account not only the mechanics of contact interaction, but also the microstructure transformation processes of surface layers under various contact loads. This fully applies to high-strength bainitic cast irons, in which it's possible to regulate the relation of structural components, differing by level of physical and mechanical parameters, which have various effects on the formation the functional properties of
bainitic cast irons. This refers to the amount of upper and lower bainite, martensite and retained austenite, the stability of which can be varied within wide range.

The task of structure optimization is more and more complicated when microalloying a melt of bainitic cast irons, for example, with boron micro additive [6-9].

In this case, the interphase boundaries are strengthened by dispersed inclusions of borides, carbides and boron nitrides, the hardness of metal matrix increases about 5-7 HRC units, also the plastic deformation resistance is improved. At the same time, boron microadditives accelerate the carbon diffusion and contribute increasing in the amount of retained austenite, which can cause decreasing wear resistance of these alloys [10]. Thus, boron has a multi-vector effect on the formation of bainitic cast irons exploitation characteristics and therefore it's necessary to carry out additional researches in order to use it effectively.

In the presented work, the wear out processes have been studied of high-strength cast irons microalloyed by boron and with various types of bainitic matrix under dry sliding friction, depending on the values of contact load, which is known [11-12], as significantly effects on the features of interaction and destruction of friction surfaces in the process of frictional loading. During researches, the effectiveness of method of formation the metastable retained austenite structure was tried out in bainitic cast irons, which can be subjected to phase transformations under contact load influence.

2. Experimental procedures

2.1 Microalloyed by Boron austempered ductile iron elaboration

The cast iron was produced in an induction furnace by melting raw materials consisting from 3.62% C, 2.00% Si, 0.35% Mn, 0.03% S, 0.06% P and about 10% steel scrap. For receiving high strength cast iron the modification procedures were carried out with metallic Mg vapour and 0.5 % Fe-Si ligature. For microalloying liquid iron with boron, the 10% ferroboron was used, which was synthesized by SHS - an innovative technology [13]. That was ensuring high (92% B) assimilation and equable distribution of Boron. The ductile iron was poured at 1400 °C into Y block ingots (30 mm). The Chemical composition of melted ductile iron is shown in the Table 1.

| Table 1. Chemical composition of experimented ductile irons (wt, %) |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Element   | C   | Si  | Mn  | S   | P   | Mg  | B   | Fe  |
| Weight (%) | 3.47| 2.10| 0.27| 0.003| 0.035| 0.037| 0.03| bal |

2.2 Heat treatment

The samples were austenitized at 900 °C in a thermal furnace for 60 min, then soaked in a melted metal bath at 280 °C and 400 °C temperature under 10- 40 sec time range for receiving the metastable austenite. The samples were austenitized at 900 °C in a thermal furnace for 60 min, then soaked in a melted metal bath at 280 °C and 400°C temperature under 10- 40 sec time range for receiving the different amount of metastable austenite with lower and upper bainite.

For microstructural and phase composition studies was used the metallographic, scanning electron microscopy and X-ray diffraction analysis methods. Optical microscopy gave us the qualitative picture of received phases. Quantitative study was carried out by X-Ray diffraction technique. X-ray diffractometer (model ДРОН-4) with Cu Kα radiation (λ=1.54 Å) was used as the source.

Hardness was measured for all the heat treatment conditions before and after wear test. Hardness values were taken on a Rockwell hardness testing machine in Rc scale for a load of 150kg.
2.3. Block-on-Ring Wear Testing
Dry sliding wear testing procedures were performed using the CMII-2 tribometer (block-on-ring) model, capable of maintaining a constant unidirectional, sliding velocity between the block and ring. Wear tests were carried out at 25, 50 and 100 N contact loads, under 2.3 m/s sliding speed. The test specimens were subjected to a cyclic load with a total sliding distance of 6.280 m. The sample mass loss calculations and working surfaces topographic analyses was performed after each 1256-meter continuous sliding. The quenched carbon steel (0.9% carbon content) disk with 62 HRC hardness was used as a counter-body (Figure 1).

![Figure 1. Schematic diagram of the block-on-ring friction and wear test](image)

During each test, the evolution of the friction coefficient was recorded. The worn out surfaces of specimens were studied by Energy Dispersive X-ray (EDX) microanalysis using scanning electron microscope. Friction-induced vibration caused by dry sliding were defined using vibrometer El-Calc during wear tests.

3. Results and discussion
In the presented work, 4 groups of samples were studied, which differed in the type of metal matrix and the amount of metastable retained austenite. The formation of various amounts of metastable retained austenite in the structure was achieved by interrupting the bainitic transformation at different time intervals. As a result of researches, it was determined that, under contact load of 25 N, isothermally quenched at 280 °C and 400 °C cast irons have practically same coefficient of friction (Figure 2 a, b).
Figure 2. The friction coefficient evolution of ADI under sliding distance a – Isothermal quenched at 400°C; b – Isothermal quenched at 280°C;

The cast irons with a content of ≈ 75% metastable retained austenite are characterized by most stable values of this parameter during tribological testings. In the cast irons with a lower amount (≈ 60%) of retained austenite, a cyclic fluctuation of friction coefficient is observed in the range 0.22 ... 0.45. During sliding, the periodic decreases of the friction coefficient reflects the self-hardening processes of the material surface layers and allows us to conclude, that under load, the partial γ → α' (martensitic) transformation is going on. Further mechanical-thermal action contributes the decomposition of surface martensite with the formation of high dispersed carbide particles, which causes relaxation of maximum internal stresses and ensures high wear resistance of bainitic cast iron. During the process of contact interaction under a load of 25 N, the temperature of investigated samples reached to 150, 200°C in the friction zone. With an increasing the contact load to 50 N, the temperature was risen to 350 ... 400°C, and under load of 100 N, the surface volumes of cast iron were heated to 700 ... 730°C.

Analysis of friction coefficient values change kinetics and the wear surface topography of experimental samples allows us to conclude, that the destruction of cast-irons surface layers, microalloyed with boron has a fatigue nature during the contact interaction process under a load of 25 N on the friction pair. The surface of the samples indicates a low wear intensity, are not observed the traces of selective transfer individual phases and overcovering of graphite inclusions, which effectively perform as a solid lubricant for a long time.

At higher contact loads (50 N and 100 N), the intensity of frictional interaction and power of formed heat flow increases. This contributes to an increase in the temperature of the sample's active volumes and the passing of plastic hardening processes of the surface layers. At the same time the range of oscillations and values of friction coefficient is increasing (Figure 3).
Figure 3. The friction coefficient of ductile iron isothermal quenched at 400°C (60% retained austenite) depending under different contact load: a- 25N; b-50N; c-100N;

Figure 4. Total wear volume of austempered ductile iron with 60% austenite content as the function under different loads

It should be noted that cast irons with a more content of metastable austenite at high contact loads are differed by stability of tribological properties and a low wear rate (Figure 5).
Figure 5. Total wear volume of austempered ductile iron with 75% austenite content as the function under different loads

Energy dispersive spectroscopy (EDS) analysis of friction surfaces showed that the structure of the upper bainite is oxidized more intensity under a contact load of 100 N and approximately 52% more oxygen (O) is defined in the surface layers of the experimental samples (Figure 6).

Spectrum: Point

| Element  | AN   | Series  | norm. C | Atom. C [wt.%] | Atom. C [at.%] |
|----------|------|---------|---------|----------------|----------------|
| Iron     | 26   | K-series| 83.20   | 60.16          |                |
| Oxygen   | 8    | K-series| 13.67   | 28.27          |                |
| Carbon   | 6    | K-series| 2.28    | 10.57          |                |
| Silicon  | 14   | K-series| 0.85    | 1.00           |                |
| Total:   |     |         | 100.00  | 100.00         |                |

Spectrum: Point

| Element  | AN   | Series  | norm. C | Atom. C [wt.%] | Atom. C [at.%] |
|----------|------|---------|---------|----------------|----------------|
| Iron     | 26   | K-series| 62.78   | 35.28          |                |
| Oxygen   | 8    | K-series| 33.67   | 58.55          |                |
| Carbon   | 6    | K-series| 2.29    | 4.92           |                |
| Silicon  | 14   | K-series| 1.26    | 1.25           |                |
| Total:   |     |         | 100.00  | 100.00         |                |

Figure 6. EDS spectrum of austempered ductile iron, isothermal quenched at 280°C (a) and 400 °C (b) with 60% retained austenite content

The datas of vibration-frequency studies show that during the testing of cast iron samples with a lower bainitic structure, the more low amplitude of frictional vibrations are defined and a noise level is 7 - 9 dB lower than in samples with an upper bainitic structure in the process of dynamic loading (Figure7).

So, we can conclude that bainitic cast irons microalloyed by boron have high wear resistance under rational structuring and investigated conditions of frictional loading.
Figure 7. Typical time-domain frequency spectrum induced by friction vibrations of ductile iron under dry sliding: a - isothermal quenched at 400°C; b - isothermal quenched at 280°C

This is explained by the fact that dispersed borides, carbides, and boron nitrides located along the grain boundaries strengthening the metal matrix and increase its resistance to plastic deformation. In addition, the formation in the structure optimal amounts of metastable austenite provides cyclic strengthening of surface layers under contact loads influence and slows down the process of internal stresses accumulation, which in accordance with the data of works [14, 15]. This also ensures the stability of tribological characteristics during long-term frictional interaction.

4. Conclusions

- It was defined that the value of the contact load has a significant effect on the tribotechnical characteristics of bainitic cast irons in conditions of dry sliding friction.
- High strength cast irons with the lower bainite structure are more resistant to adhesive wear.
- According to the obtained data, the presence of up to 80% metastable retained austenite in the metal matrix structure of the of experimental cast irons makes it possible to stabilize the friction coefficient under the investigated contact loads.
- Thus, to ensure maximum wear resistance, the isothermal quenching of high-strength cast irons must be carried out in the temperature range 220-280°C with a minimum treatment time.

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