

Effect of Boron on the Wear Behavior of High Chromium White Cast Irons

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Abstract. The wear behavior of high chromium white cast irons with composition: 2,6÷3,4% C; 0,9÷1,1% Si; 0,8÷1,1% Mn; 1,0÷1,3% Mo; 12,3÷13,4% Cr and 0,18 ÷ 1,25% B is investigated. The microstructure and tribological characteristics of six compositions of high chromium white cast irons (one without boron and with 0,18; 0,23; 0,59; 0,96; 1,25% boron) are studied.

After casting, heat treatment was carried out, including quenching at 950°C and tempering at 235°C for 1 h. The influence of the heating temperature in the interval 850÷1100°C, 25 min on the Rockwell hardness and the microstructure are studied.

The wear resistance during abrasive wear for samples after casting and after heat treatment is investigated as measured loss of mass in terms of dry friction under load of 1,5 kg during 10 min. The lowest mass loss during abrasive wear test in dry conditions friction is defined for cast irons alloyed with 0,18 % boron - $\Delta m = 0,1469$ g after casting and $\Delta m = 0,0022$ g after heat treatment. The highest mass loss is determined during abrasive testing of alloyed cast irons with 0,96 and 1,25% boron. The alloyed cast irons with 0,18 % boron show highest wear resistance.

Keywords: high chromium white cast iron, boron, carbides, hardness, wear resistance, microstructure.

I. INTRODUCTION

High chromium white cast irons are an important group of materials for engineering applications of which high wear resistance and corrosion resistance are required.

Depending on the chemical composition of these materials and their chromium content, their structure may contain the following carbides: M_7C_3 , M_3C and $M_{23}C_6$.

These carbide phases differ in a chemical composition and morphological characteristics. The operational properties of these cast irons are determined from a predominant carbide type in their structure to a significant extent [1–3]. For this reason, the research directed towards at controlling and improving the operational properties of high-chromium white cast irons includes studying the changes in the carbide phases as a function of the alloying elements present in the structure, including the element boron [1–6].

Austempered ductile irons (ADI) with structure of lower and upper bainite, additionally alloyed with boron from 0,03 to 0,135%, become carbide austempered ductile irons (CADI). The structure of these cast irons (CADI) consists of eutectic carbides from 9 to 27% and possess up to 3 times higher wear resistance during abrasive wear compared to this one without boron (ADI) [7].

The wear resistance and strength of high chromium white cast irons depends on both the size, type and morphology of the carbide phases and on the microstructural characteristics of these alloys. The metal matrix in them can be regulate by the chemical composition and by conducting heat treatment after casting the alloy. Most of these alloys, in addition to high chromium (>10%),

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also contain nickel, molybdenum, copper or combinations of these alloying elements in order to prevent the formation of pearlite in the microstructure. After properly conducted heat treatment, these cast irons have a martensitic microstructure of the metal matrix for maximum abrasion resistance and toughness [8,9].

The alloying with boron and its influence on the microstructure and properties of high chromium white cast irons is poorly studied. The aim of the performed research is to determine the influence of the boron in an amount of 0,18 to 1,25% in the composition of high chromium white cast irons on their hardness and tribological characteristics.

II. MATERIALS AND METHODS

Samples of six high-chromium white cast iron melts with the following composition were examined: 2,6÷3,4% C; 0,9÷1,1% Si; 0,8÷1,1% Mn; 1,0÷1,3% Mo; 12,3÷13,4% Cr and 0,18 ÷ 1,25% B. One of the melts does not contain boron, and the other five compositions contain 0,18; 0,23; 0,59; 0,96 and 1,25% boron.

The microstructure of the samples after casting is studied by means of an optical metallographic analysis by MIT 500 microscope of the Coptic company. The test samples are processed in the reagent composition 1g KOH, 4g KMnO₄, 100 ml H₂O и 2g C₄H₆O₄ for 5 minutes at ambient temperature. This reagent shows carbide phases of type: M₆C, M₇C₃, M₂₃C₆ and M₃C.

The samples after casting are undergone to a quenching from 950°C with air cooling and following tempering at 235°C for 1 h. The study of the influence of the heating temperature in the interval 850÷1100°C on the hardness of the cast iron is conducted (Table 1, Fig. 1) to select the proper quenching temperature. Hardness test is carried out according to Rockwell's method for the samples with different boron content after heating at 850÷1100°C at an interval of 50°C, holding at these temperatures for 25 min and subsequent air cooling to room temperature (Fig. 2).

The performance of the samples of high chromium white cast iron alloyed with boron in as-cast condition and after heat treatment with quenching on air from 950°C, 25 min. and with tempering at 235°C, 1 h is studied during abrasive wear.

TABLE 1. HRC HARDNESS OF ALLOYED WITH BORON HIGH CHROMIUM WHITE IRONS, CAST AND QUENCHED FROM DIFFERENT TEMPERATURES

| № of sam-ple | HRC | | | | | | |
|--------------|-------|----------------------------|-------|-------|-------|-------|-------|
| | cast | Quenching temperature [°C] | | | | | |
| | | 850 | 900 | 950 | 1000 | 1050 | 1100 |
| 2 | 53,5 | 60,33 | 63 | 65 | 62 | 59,5 | 55 |
| 3 | 53,83 | 61 | 65,5 | 65,83 | 63,3 | 61,5 | 55,5 |
| 4 | 56,5 | 61,17 | 62,83 | 65,67 | 64,17 | 62 | 56,67 |
| 5 | 57,17 | 62,17 | 64 | 65,67 | 64,33 | 62 | 57,33 |
| 6 | 57,5 | 63,33 | 64,33 | 66,33 | 65,17 | 61,67 | 57,83 |

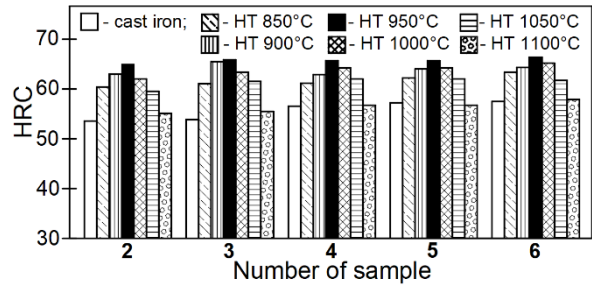


Fig. 1. Variation of HRC hardness of high chromium white cast irons depending on boron content and different heating temperatures.

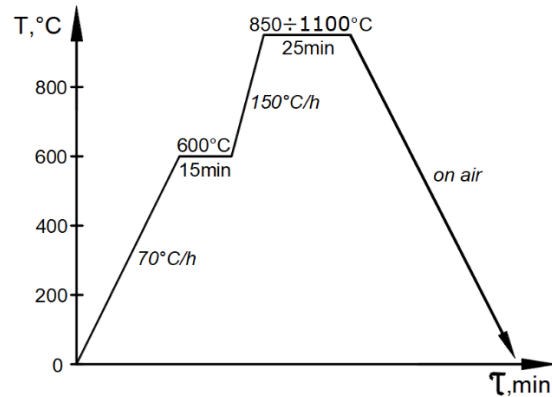


Fig. 2. Schematic diagram of the heat treatment cycle of the boron-alloyed high-chromium white cast irons.

The mass loss Δm is measured under the conditions of dry friction under a load of 1,5 kg for 10 min and the absolute wear resistance L was determined. A drill was used to study the wear of the different samples. The examined sample with dimensions $\varnothing 30 \times 40$ mm is fixed on a rod with a socket, and the distance between the axis of the sample and the axis of the three-jaw chuck of the drill is 60 mm. A weight with a mass of 1,5 kg is attached to the vertical feed lever. The sample is rotated with $n = 150 \text{ min}^{-1}$, pressed on an abrasive disk with dimensions of 250x20x20 mm. A disk 99BA60R7V is used for the experiment. An electronic balance WPS 180/C/2 with an accuracy of 0,1 mg is used to measure the mass of the samples.

The friction road L is:

$$L = 2 \cdot \pi \cdot R \cdot n \cdot t, [m] \tag{1}$$

where:

- $R = 60 \text{ mm}$ is distance between the axis of the specimen and the axis of the chuck;
- $n = 150 \text{ min}^{-1}$ is rotation speed.

The wear layer h is:

$$h = (m_0 - m_f) / \rho \cdot A_a = \Delta m / \rho \cdot A_a, [m] \tag{2}$$

where:

- m_0 – sample initial mass, [kg];
- m_f – final mass of the sample, [kg];
- $\rho = 7,8 \cdot 10^3 \text{ kg/m}^3$ is the density of the material;
- A_a - contact area of wear, [m²];
- Δm - loss of mass with wear, [kg].

Wear intensity i represents the material thickness destroyed per unit friction path:

$$i = h/L = \Delta m / (\rho \cdot A_a \cdot L) \quad (3)$$

The absolute wear resistance I is the reciprocal of the wear intensity:

$$I = 1/i = (\rho \cdot A_a \cdot L) / \Delta m \quad (4)$$

III. RESULTS AND DISCUSSION

In the structure of high chromium white cast irons with chromium about 13% the main carbide is M_7C_3 [1–3]. Carbides type M_3C и $M_{23}C_6$ also persist in the structure of these cast irons. The cast irons studied contain about 1% molybdenum, dew to carbides type M_6C и M_2C are possible in the structure. Microstructure of the cast irons without boron and with 0,18; 0,23 and 0,59% B is subeutectic, with 0,96 % B – with 0,96% B – close to the eutectic and with 1.25% B – supraeutectic [1]. Fig. 3 shows the microstructure of high chromium white irons without boron (a) and alloyed with 0,18% (b); 0,23 % (c) and 0,59% boron. The used reagent shows the carbide phases in the microstructure in dark color. The carbide phases in different compositions of cast iron differ in shape, size and quantity (Fig. 3).

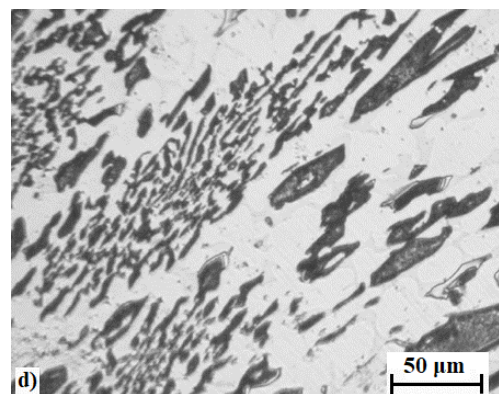
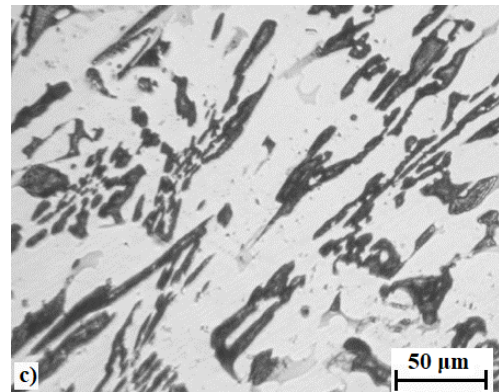
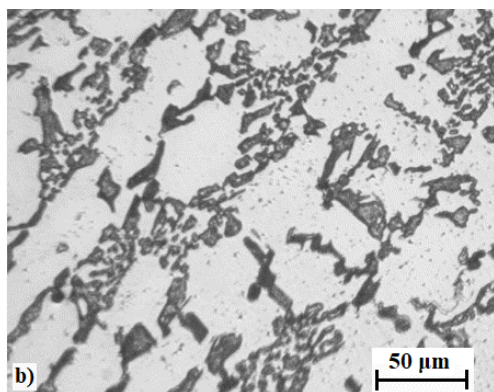
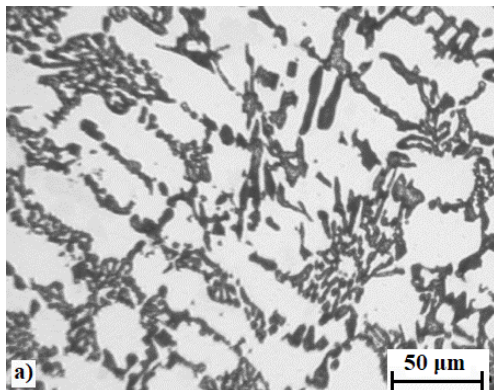


Fig. 3. Microstructure of boron-alloyed high-chromium white irons with 0% B (a); c 0,18% B (b); c 0,23% B (c) и c 0,59% B (d).

Fig. 2 shows a scheme of the tempering mode of the tested high chromium white cast irons alloyed with boron. The selected optimal mode of heat treatment of the samples for abrasive wear testing includes quenching from a temperature of 950°C with air cooling to room temperature and tempering at a temperature of 235°C, 1 hour. The heating at 950°C, 25 min and cooling in air, provides the highest hardness after quenching – 65÷67 HRC compared to the rest of the studied regimes in the temperature range 850÷1100°C. At heating temperatures of 850÷950°C for 25 min, secondary carbide phases are separated from the austenite. This leads to the impoverishment of austenite with carbon and alloying elements (the temperature M_s of the austenite-martensite transformation increases), which increases the amount of martensite in the structure of quenched cast irons and leads to an increase in hardness. At heating temperatures of 1000÷1100°C, the secondary chromium carbides dissolve in the austenite. This increases the resistance of the supercooled austenite to disintegration (the temperature of the M_s point of the austenite-martensite transformation decreases) and after quenching in the structure of the cast irons, the amount of retained austenite increases. The hardness of hardened cast iron after heating at a temperature of 1100°C decreases to 54÷58 HRC (Table 1, Fig. 1).

The data from the abrasive wear tests performed on the samples of alloyed with boron high chromium white iron in as-cast condition and after heat treatment are presented in Table 2 and 3.

TABLE 2. MASS LOSS AND WEAR RESISTANCE OF ALLOYED WITH BORON HIGH CHROMIUM WHITE IRONS IN AS-CAST CONDITION

| N ^o of sample | B, % | m ₀ , [g] | m _f , [g] | Δ m, [g] | I.10 ⁶ |
|--------------------------|------|----------------------|----------------------|----------|-------------------|
| 1 | - | 142,5032 | 142,2341 | 0,2691 | 1,069 |
| 2 | 0,18 | 147,4415 | 147,2946 | 0,1469 | 1,959 |
| 3 | 0,23 | 145,9076 | 145,7297 | 0,1779 | 1,617 |
| 4 | 0,59 | 143,6850 | 143,4546 | 0,2304 | 1,249 |
| 5 | 0,96 | 143,8705 | 143,5771 | 0,2934 | 0,980 |
| 6 | 1,25 | 147,6045 | 147,2214 | 0,3831 | 0,751 |

TABLE 3. MASS LOSS AND WEAR RESISTANCE OF ALLOYED WITH BORON HIGH CHROMIUM WHITE IRONS AFTER HEAT TREATMENT

| N ^o of sample | B, % | m ₀ , [g] | m _f , [g] | Δ m, [g] | I.10 ⁷ |
|--------------------------|------|----------------------|----------------------|----------|-------------------|
| 1 | - | 135,3652 | 135,3569 | 0,0083 | 3,467 |
| 2 | 0,18 | 142,7748 | 142,7726 | 0,0022 | 13,081 |
| 3 | 0,23 | 137,5008 | 137,4934 | 0,0074 | 3,889 |
| 4 | 0,59 | 136,4723 | 136,4627 | 0,0096 | 2,997 |
| 5 | 0,96 | 139,5951 | 139,5766 | 0,0185 | 1,555 |
| 6 | 1,25 | 140,5808 | 140,5520 | 0,0288 | 0,999 |

Fig. 4 shows the relation of the change of the mass loss Δm during wear test and the boron quantity.

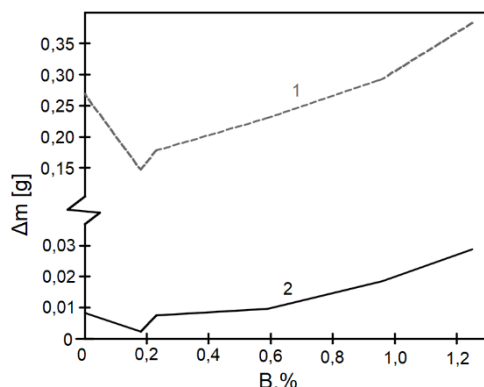


Fig. 4. Change in mass loss during wear Δm depending on the amount of boron in high chromium white cast irons: 1- in as-cast condition; 2- after heat treatment.

Fig. 5 and 6 show the absolute wear resistance I according to the boron quantity in the tested cast irons in as-cast condition and after heat treatment.

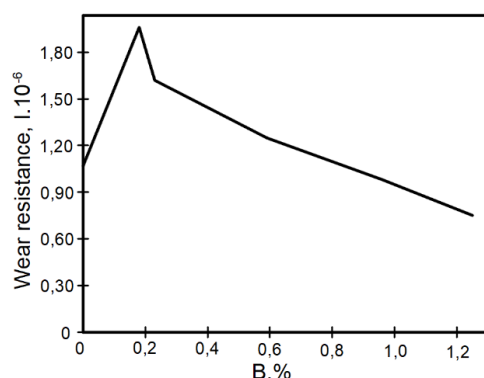


Fig. 5. Change in absolute wear resistance I depending on the boron quantity in high chromium white cast irons in as-cast condition.

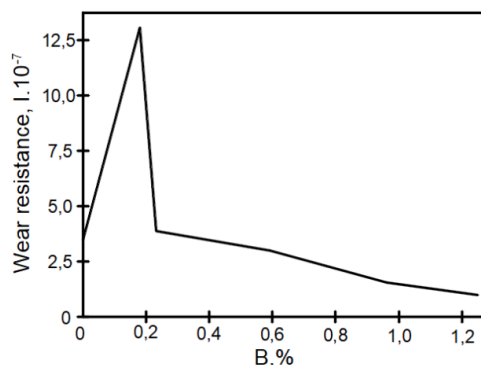


Fig. 6. Change in absolute wear resistance I depending on the boron quantity in high chromium white cast irons after heat treatment.

The lowest mass loss during wear Δm have alloyed cast irons with 0,18 % boron (Δm = 0,1469 g for cast irons in as-cast condition and Δm = 0,0022 g for cast irons after heat treatment). The cast irons in as-cast condition, alloyed with 0,18; 0,23 and 0,59% boron have smaller mass loss during wear Δm, the alloyed cast irons with 0,96 and 1,25% boron have bigger mass loss during wear Δm compared to Δm for cast iron without boron. The cast irons after heat treatment alloyed with 0,18 and 0,23 % boron have smaller mass loss during wear Δm, alloyed cast irons with 0,59; 0,96 and 1,25% boron have bigger mass loss during wear Δm, compared to Δm in the cast iron without boron. The cast irons alloyed with 0,18 % boron have highest wear resistance I (I = 1,959 .10⁶ for irons in as-cast condition and I = 13,081 .10⁷ for cast irons after heat treatment).

IV. CONCLUSIONS

The abrasion wear behaviour of high chromium white irons composition Fe-3,1C-13,1Cr-1,1Mo, additionally alloyed with 0,18; 0,23, 0,59, 0,96 and 1,25% boron is studied. It is concluded the lowest mass loss during wear Δm have cast irons alloyed with 0,18 % B – Δm = 0,1469 g for cast irons in as cast condition and Δm = 0,0022 g for cast irons after heat treatment. The same cast irons have highest wear resistance I – I=1,959.10⁶ for cast irons in as-cast condition and I =13,081.10⁷ for cast irons after heat treatment.

The investigation on the influence of the heat treatment in an interval 850÷1100°C for 25 min on the hardness of the quenched high chromium white irons alloyed with boron is performed. On the base of the results achieved the proper regime for the samples heat treatment is chosen for the tribological test. It includes quenching from temperature of 950°C, 25 min with air cooling to room temperature and tempering at 235°C, 1h.

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VI. REFERENCES

- [1] J. Kaleicheva, K. Kirov, V. Mishev and Z. Karaguiozova, "Microstructure and Properties of High Chromium White Cast Irons Alloyed with Boron", Proceedings of the 13th International Scientific and Practical Conference: Environment, Technology, Resources, Rezekne, Latvia, vol. 3, p.137-141, 2021. [Online]. Available: <http://journals.rta.lv/index.php/ETR> [Accessed March 25, 2023], <https://doi.org/10.17770/etr2021vol3.6656>
- [2] A. Nufal, "Metallurgical Aspects of High- Chromium White Irons", [Online]. Available: <https://www.foundry-planet.com/fileadmin/redakteur/pdf-dateien/13-Adel-Nofal.pdf> [Accessed: March 25, 2023].
- [3] Kh. Abdel-Aziz, M. El-Shennawy and Adel A. Omar, "Microstructural Characteristics and Mechanical Properties of Heat Treated High-Cr White Cast Iron Alloys", International Journal of Applied Engineering Research, vol. 12, Number 14, p. 4675-4686, 2017. [Online]. Available: ResearchGate, https://www.ripublication.com/ijaer17/ijaerv12n14_79.pdf [Accessed March 25, 2023].
- [4] S. Tomovic-Petrovic, S. Markovic and S. Zec, "The effect of boron on the amount and type of carbides in chromium white irons", Journal of the Serbian Chemical Society, vol. 67(10), p.697-707, 2002. [Online]. Available: ResearchGate, <https://www.doiserbia.nb.rs/img/doi/0352-5139/2002/0352-51390210697T.pdf> [Accessed March 25, 2023], <https://doi.org/10.2298/JSC0210697T>
- [5] A. Bedolla-Jacuinde, F. V. Guerra, I. Mejía, J. Zuno-Silva and C. Maldonado, "Boron Effect on the Precipitation of Secondary Carbides During Destabilization of a High-Chromium White Iron", 10th International Symposium on the Science and Processing of Cast Iron – SPCI10, 2014. [Abstract]. Available: ResearchGate, <https://www.researchgate.net/publication/271829525> [Accessed March 25, 2023], <https://doi.org/10.1080/13640461.2016.1142236>
- [6] F. Nurjaman, S. Sumardi, A. Shofi, M. Aryati, and B. Suharno, "Effect of molybdenum, vanadium, boron on mechanical properties of high chromium white cast iron in as-cast condition", AIP Conference Proceedings 1711, 020005, 2016, [Online]. Available: ResearchGate, <https://aip.scitation.org/doi/pdf/10.1063/1.4941614> [Accessed March 25, 2023], <https://doi.org/10.1063/1.4941614>
- [7] G. Rashev, V. Todorov, I. Bonev and R. Gagov, "Boron in Ductile Cast Irons". International Scientific Journal, Machines. Technologies. Materials. YEAR VI, Issue 3, pp. 8-12, 2012. (at bulgarian)
- [8] R.B. Gundlach, High alloy white irons, ASM Hand Book, Casting, 4th Edition, ASM International, 1998, pp.679-685.
- [9] J.R. Davis, Metallurgy and properties of high alloy white irons, ASM Specially Hand Book, Cast Irons, Materials Park, OH: ASM International, 1996, pp.107-30.