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Porosity and non-metallic inclusions in cast iron produced with a high proportion of scrap

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ABSTRACT

The work is devoted to the problem of an increase in the proportion of scrap metal in castings smelted and produced from wear-resistant chromium cast irons. Castings obtained with more than 60% of armor scrap and cracked during solidification and subsequent heat treatment were selected as research objects. Castings of similar mill armor after operation characterized with different wear resistance were selected to compare the characteristics of the structure and properties. The composition, structure, amount of non-metallic inclusion and porosity of samples cut from identical places of castings were studied with the help of the methods of optical and scanning microscopy, metallographic analysis, X-ray fluorescence analysis, and measurement of Vickers hardness. The characteristic localization of non-metallic inclusions of various types in the structure of cast iron samples was considered. An increase in the proportion of non-metallic inclusions in cast irons obtained using a high proportion of scrap was found, and it was shown that non-metallic oxide inclusions with a loose structure had the most negative effect. Along with porosity and primary crystals of carbide (CrFe)3Ctheydo not prevent the propagation of cracks caused by internal stresses arising during crystallization and subsequent polymorphic transformations in castings.

Keywords: wear-resistant chromium cast iron, casting, non-metallic inclusions, cracking, structure.

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Introduction

Currently, there is an increase in the proportion of scrap metal used in the iron foundry [[1], [2], [3], [4], [5]]. It is primarily due to economic and environmental considerations and is especially important in the case of products obtained from expensive wear-resistant high-alloy cast irons. Such products include parts of mills and crushers that can be remelted after their operational life to obtain similar products. It should be noted that the metal loss because of wear of such parts does not exceed 10%in some cases, especially if the destruction of the grinding body or armor occurs due to the formation of a crack. The amount of such scrap generated is large and its processing with the purpose to obtain similar products is relevant to the enormous amounts of such equipment annually used in the world.

It is known that it is recommended to use not more than 30% of scrap by the charge weight when cast iron is smelted [[6], [7]]. It is due to the need to reduce the contamination of the resulting castings with various impurities, including non-metallic inclusions and dissolved gases. An increase in porosity and the proportion of non-metallic inclusions results in a decrease in the resistance of castings to crack propagation caused by both shock loads and stresses that occur in the casting during the cooling stage and often lead to the formation of hot cracks. Hot cracks result in the rejection of a large number of castings. So, it is relevant to study the problem of the porosity formation and the accumulation of non-metallic inclusions and to evaluate their role in the cracking of castings obtained using a high proportion of scrap. For this purpose, it is required to estimate the quantity, composition, the sizes of pores and non-metallic inclusions and the place of their localization in the structure of such cast irons, and to compare them with the results of the study of cast iron obtained without the use of scrap metal.

Experimental part

A series of crusher armor samples made with a scrap proportion of more than 60% at a domestic enterprise and samples taken from similar parts obtained by various enterprises without the use of scrap were studied in this regard. All castings were made with sand casting molds. Samples of castings obtained with a high proportion of scrap were deliberately taken from castings damaged during the manufacture of products. The characteristics of the samples studied are shown in Table 1. They were taken from identical places of castings.

The composition of the castings was determined with an Axios X-ray fluorescence wave-dispersive combined spectrometer; the content of sulfur and carbon was determined with a Bruker G4 ICARUS TF analyzer. Metallographic analysis was performed using an inverted Leica DM IRM microscope and the VideoTest-Metal software package. Non-metallic inclusions were studied before etching; the structure of the phases forming cast irons was studied after etching. The number and proportion of non-metallic inclusions were determined under Interstate standard 1778-80 by method P1. The composition was studied with a JEOL JXA-8230 microprobe analyzer. The structure was found with a reagent having the following composition: 3% FeCl3 + 3% HCl in ethanol. Hardness was determined under the Vickers scale with an HBV-30A multifunctional stationary hardness tester.

Table 1 - Characteristics of armor casting samples

Sample No.	Characteristics of cast iron products	Characterization of alloy structure and matrix	Share of carbides, vol.%	Hardness, HV30
1	Crusher armor casting burst after heat treatment (HT). The share of scrap is over 60%	Hypereutectic P+A	48.6	746
2			39.2	671
3			31.4	752
4	Crusher armor casting burst after installation		26.7	698
5	High wear-resistance. Armor completed a full cycle		22.5	641
6	Low wear-resistance. Armor wears out quickly		34.3	436
7	Armor with high wear resistance. Worked full cycle	Hypereutectic P+A+M	22.4	665
8	Armor is characterized by the greatest wear resistance. Worked full cycle	Hypereutectic P+A	27.0	676
9	Armor with increased impact strength. Worked full cycle	Hypoeutectic P+A+M	22.2	710
10	Armor of the European manufacturer. Average wear resistance	Eutectic P+A	29.1	681

Table 2 - Composition of castings samples from wear-resistant chromium iron

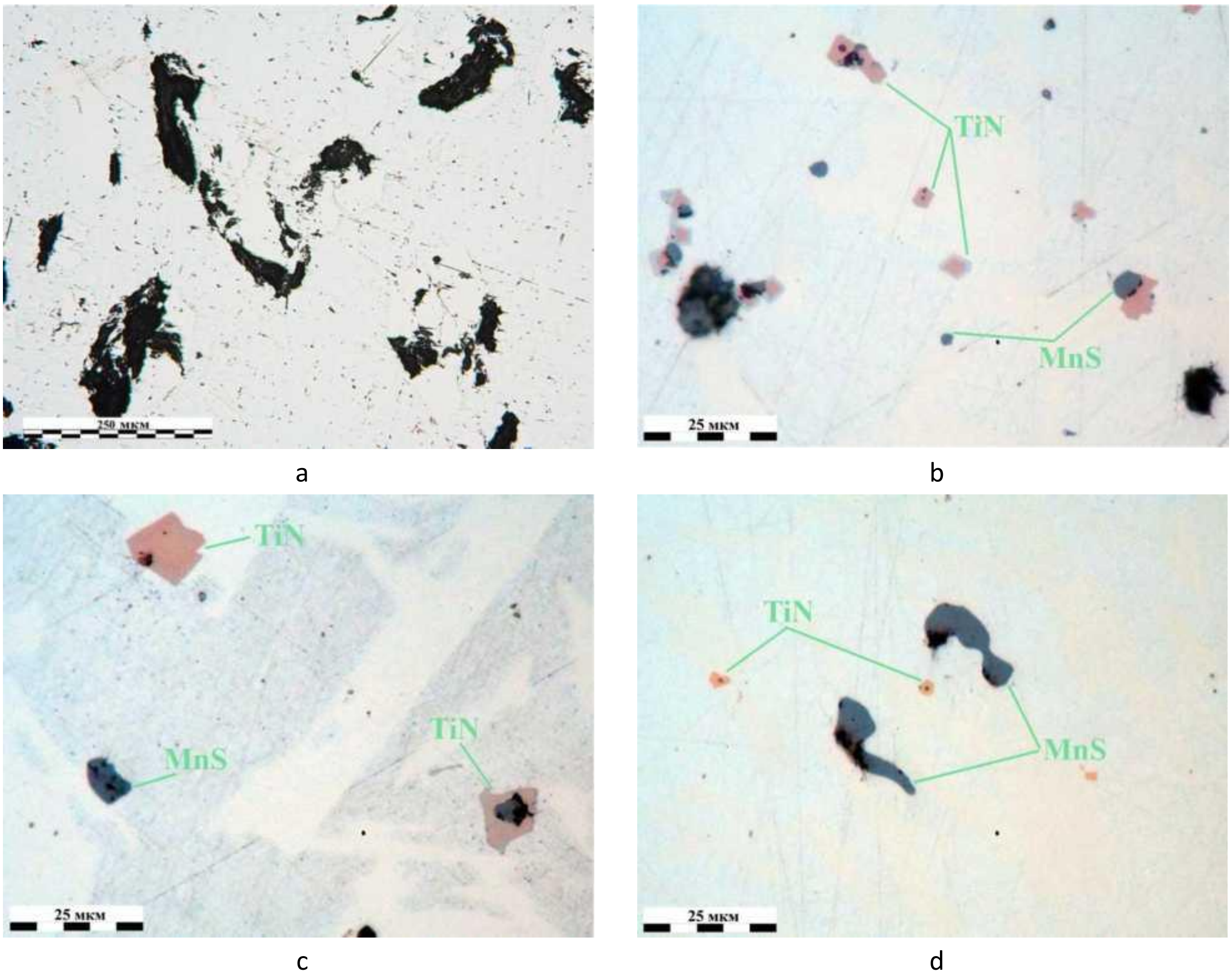
Sample No.	**Chemical composition, wt.%**										
	Fe	**Cr**	**Mo**	**C**	**Ni**	**Mn**	**Si**	**V**	**Co**	**Cu**	**Ti**
1	~70	21.8	0.74	4.05	0.62	1.14	0.7	0.15	0.12	0.16	0.23
2	70.2	19.63	0.56	3.26	0.38	2.2	0.85	0.09	0.13	0.26	0.32
3	70.3	21.7	0.65	3.81	0.33	1.39	0.56	0.1	0.09	0.18	0.04
4	69.5	23.04	0.29	3.35	0.38	0.67	0.66	0.13	0.15	0.07	0.26
5	69.1	22.79	0.33	2.96	0.37	0.86	1.48	0.1	0.14	-	0.27
6	69.1	22.97	0.31	3.23	0.46	0.82	1.18	0.12	0.14	0.07	0.19
7	67.3	24.89	0.59	3.20	0.69	0.61	0.24	0.12	0.10	0.16	0.05
8	65.5	27.08	0.41	3.34	0.74	0.87	0.4	0.07	0.11	0.1	0.08
9	75.5	16.5	1.27	2.83	0.28	1.02	0.43	0.07	0.2	0.12	0.04
10	67.9	25.7	0.23	3.0	0.54	1.14	0.58	0.04	0.14	0.16	-
	P	**Pb**	**S**	**Al**	**Mg**	**Zr**	**Ge**	**Nb**	**W**	**Zn**	**As**
1	-	0.012	0.04	0.08	-	-	-	-	-	-	-
2	0.032	-	0.042	0.6	0.31	0.01	0.01	0.007	0.05	-	-
3	0.034	-	0.049	0.19	0.15	-	-	0.005	-	0.01	-
4	0.030	-	0.054	0.2	0.28	-	-	-	-	-	0.027
5	0.026	-	0.031	0.14	0.09	-	-	-	-	0.08	-
6	0.026	-	0.044	0.08	0.09	-	-	-	-	0.16	-
7	0.017	-	0.027	0.43	0.19	-	-	0.048	0.27	-	-
8	0.025	-	0.058	0.24	0.09	-	-	-	-	-	-
9	0.03	-	0.05	0.17	0.2	-	-	0.005	-	-	-
10	0.035	-	0.036	0.055	0.08	-	-	0.06	-	-	-

The composition of Samples 2 and 4-7 is close (19.6-24.9 wt.% Cr and 2.96-3.35 wt.% C) according to the content of the main alloying elements (Table 2). Samples 7 and 9 contain more and less chromium, respectively (Table 2). Samples 1-7 can be attributed to ChKh22 cast iron, Sample 8 to ChKh28P cast iron, and Sample 9 to ChKh16M2 cast iron according to the chromium content under Interstate standards 7769-82. However, Samples 1-7 deviate from ChKh22cast iron according to the content of carbon (2.4-3.6 wt.%), manganese (1.5-2.2 wt.%), silicon (0.2-1.0), vanadium (0.15-0. 35 wt.%) and titanium (0.15-0.35 wt.%). Similarly, Samples 8 and 9 do not correspond to the specified grades under the content of other alloying elements. Besides, all samples contain micro additives of alloying elements - Al, Mo, Mg, Ni, Co, Ti, Zr, Nb, W. It enables us to conclude that the studied cast iron samples are made under the internal standards of enterprises and, probably, are foreign brands. The content of impurity elements, such as sulfur and phosphorus, in the studied samples, does not exceed the permissible level under Interstate standards 7769-82 (S<0.08%, P<0.1%).

The cast iron microstructure study shows that non-metallic inclusions are represented by manganese and iron sulfides, titanium nitrides, and oxides of the complex composition and confirmed by the microprobe analysis results. In some cases, nitrides and sulfides are found in intergrowths (Figure 1). The shape is predominantly polyhedral equiaxed. Samples 1-7 are characterized by inclusions shown in Figures 1 b and c. The sizes of non-metallic inclusions, both nitride and sulfide ones, are close and vary from 1 to 25 µm in the studied cast iron samples. The shape of sulfide inclusions differs in Samples 8-10 where they have a rounded surface (Figure 1d) not characteristic of the emerging crystal. It allows us to conclude that such inclusions crystallized after the alloy solidification. Oxide inclusions, predominantly with a loose structure, are found in the form of large inclusions associated with primary chromium carbide crystals (Figure 1 a).

The distribution of non-metallic inclusions of various types is not uniform (Figure 2). So, manganese sulfide inclusions are mainly localized in the places of eutectic crystallization (Figure 2 b) and are found intergrown with the surface of primary carbide crystals $(CrFe)_7C_3$ in some cases. Often, $(CrFe)_3C$ crystals are formed on the surface of this compound that precipitates during the eutectic crystallization. MnS inclusions are also found in conjunction with ligature fragments showing that the melt was contaminated with them during alloying. TiN inclusions are formed both in the structure of primary carbides (CrFe)3C and in the eutectic as independent phases (Figure 2c). The formation of such inclusions is caused by alloying cast iron with titanium that binds nitrogen diffusing into the melt from the atmosphere during the melting process.

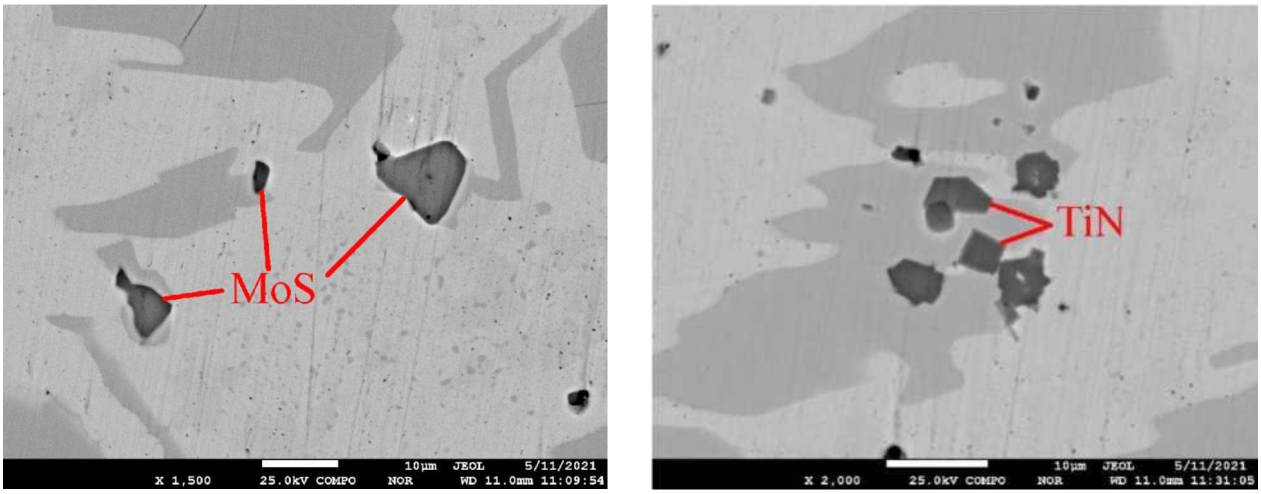
Inclusions of undissolved ferromolybdenum were found in the studied cast iron samples besides non-metallic inclusions (Figure 3). It proves the fact that the melt exposure duration after the ligature inclusion is insufficient for its complete dissolution. The mapping made to find the composition for the localization areas of ferromolybdenum inclusions shows that molybdenum alloys (CrFe)7C3 crystals when it is dissolved. At the same time, molybdenum dissolves in the cast iron matrix very little.



a b c d

a - Sample No. 1 oxide inclusions (dark areas); b - Sample No. 2; c - Sample No. 6; d - Sample No. 8

Figure 1 - Typical shape and dimensions of non-metallic inclusions in samples of wear-resistant chromium cast irons



a b

Figure 2 - The structure of various non-metallic inclusions in wear-resistant chromium cast iron

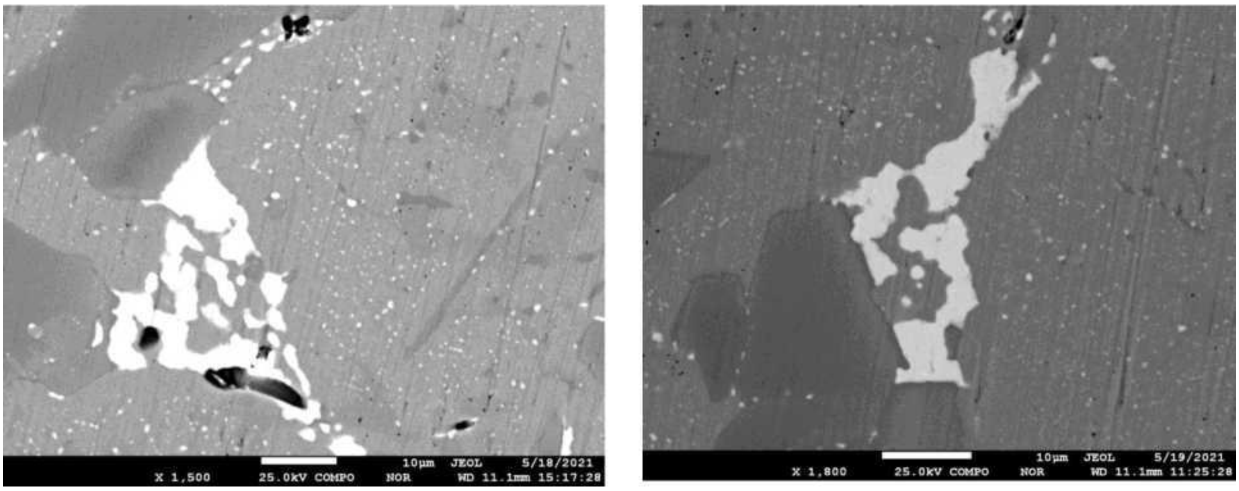


Figure 3 - Inhomogeneous distribution of molybdenum (light areas) in the cast ironstructure caused by incomplete dissolution of ferromolybdenum

Table 3 - Porosity and volume proportion of non-metallic inclusions and a group of inclusions in samples

Sample No.	Porosity, vol.%	Distribution density of non-metallic inclusions (NMI), pcs/mm2	Non-metallic inclusions, vol.%	Inclusion group							
				1	2	3	4	5	6	7	8/9
1	6.5	165	6.13	46.7	25.5	13.4	7.5	3.9	-	0.7	-
2	1.4	259	0.534	59.9	27.4	9.6	4.2	0.4	0.39	-	-
3	0.59	180	0.342	53.3	33.3	8.3	2.8	1.1	1.11	-	-
4	0.45	138	0.516	36.2	23.9	18.8	15.2	5.8		-	-
5	0.38	155	0.493	45.2	25.8	16.1	8.4	3.2	1.3	-	-
6	0.56	119	0.715	32.8	17.6	21.8	17.6	8.4	1.6	-	-
7	0.63	192	0.359	58.3	27.6	8.9	5.2	-	-	-	-
8	0.73	170	0.525	54.1	20	14.7	6.5	4.7	-	-	-
9	0.44	79	0.54	24.1	10.1	8.9	11.4	17.7	12.6	11	3.8/1.2
10	0.09	32	0.65	21.9	28.1	21.9	21.9	6.25	-	-	-

a b

Figure 4 - Formation of cracks in Casting No. 1

The discussion of the results

The analysis of the metallographic study results of samples suggests that an increase in the proportion of scrap in the production of castings results in an increase in the amount and dispersion of non-metallic inclusions in their structure. Only inclusions traditional for this type of cast iron are predominantly formed in this case. The formation of cracks in the volume of castings is not directly related to the presence and amount of non-metallic inclusions. A net of cracks was found near the surface (in 10-13 mm) in Castings 1, 2, and 3 obtained using a large proportion of scrap and destroyed at the cooling stage after crystallization and during subsequent heat treatment (Figure 4 a). The study of crack propagation suggests that they mainly pass through oxide inclusions, pores, and primary crystals of chromium carbide $(CrFe)_7C_3$, propagating between them along with the matrix alloy (Figure 4 b). Sulfide and nitride non-metallic inclusions rarely get into a crack, and in some cases, cracks stop on titanium nitride inclusions changing direction. It is due to the high hardness of the TiN compound. Besides, cracks in a smaller number and of a shorter extent were also found inside other studied castings. It suggests that their formation is primarily associated with the properties of such cast irons and, in particular, with the cooling modes for castings and the amount of carbon in their composition. It is known that an increase in the cooling rate and the availability of primary chromium carbides in the structure of alloys contribute to the occurrence of stresses exceeding the ultimate strength of the metal causing hot or cold cracking of the casting [[8], [9], [10], [11], [12], [13], [14]].

Thus, the study of samples of wear-resistant chromium cast irons cut from large-sized castings obtained in the factory by casting into a sand mold showed that the use of a high proportion (≥60%) of scrap metal in their production can increase the amount, dispersion and volume proportion of non-metallic inclusions in their structure, as well as porosity. The main non-metallic inclusions for such cast irons are crystals of manganese sulfide MnS (2-10 µm), and titanium nitride TiN (4-7 µm) typical for chromium cast irons, and oxide inclusions are introduced along with scrap metal. Meanwhile, internal stresses arising from violations of cooling regimes and a higher proportion of primary chromium carbide crystals are the main reasons for the increase in porosity, the formation of cracks, and accelerated wear of such castings [[15], [16], [17], [18], [19]].

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Сынықтардың жоғары үлесін пайдалану арқылы алынған шойындардағы кеуектілік және металл емес қосындылар

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ТҮЙІНДЕМЕ

Жұмыс тозуға төзімді хромды шойындарды балқыту және құю кезінде металл сынықтарын пайдалану үлесін арттыру мәселесіне арналған. Зерттеу объектілері ретінде құрыш сынықтарының 60% - дан астамын пайдалана отырып алынған, сонымен қатар қатаю және кейіннен термиялық өңдеу кезінде жарылған құймалар таңдалды. Құрылымы мен қасиеттерінің сипаттамаларын салыстыру үшін қолданыстан кейінгі диірмендердің ұқсас құрыштарының құймалары таңдалды және олар әртүрлі тозу төзімділігімен сипатталады. Оптикалық және растрлық микроскопия, металлографиялық талдау, рентгенофлуоресценттік талдау, Виккерстік қаттылықты өлшеу әдістерін қолдана отырып, құймалардың ұқсас орындарынан кесілген үлгілердегі металл емес қосындылардың құрамы, құрылымы, саны және кеуектілігі зерттелді. Шойын үлгілерінің құрылымындағы әртүрлі типтегі металл емес қосындылардың сипаттамалы локализациясы қарастырылды. Сынықтардың жоғары үлесін пайдалану арқылы алынған шойындардағы металл емес қосындылар үлесінің артуы анықталды және тығыз емес құрылымы бар металл емес оксидті қосылыстардың өте теріс әсер беретіндігі көрсетілді. Олар кеуектілік пен $(CrFe)_3C$ карбидтің бастапқы кристалдарымен бірге құймаларда кристалдану және кейінгі полиморфты өзгерістерден туындаған ішкі кернеулердің әсерінен пайда болатын жарықтардың таралуына кедергі келтірмейді.

Түйін сөздер: хромды тозуға төзімді шойын, құйма, металл емес қосындылар, сызаттану, құрылым.

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Пористость и неметаллические включения в чугунах, полученных с использованием высокой доли лома

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АННОТАЦИЯ

Работа посвящена проблеме увеличения доли использования металлического лома при выплавке и получении отливок из хромистых износостойких чугунов. В качестве объектов исследований выбраны отливки, полученные с использованием более 60% лома броней и растрескавшиеся при затвердевании и последующей термической обработке. Для сравнения характеристик структуры и свойств были выбраны отливки аналогичной брони мельниц после эксплуатации и характеризующиеся различной износостойкостью. С применением методов оптической и растровой микроскопии, металлографического анализа, рентгенофлуоресцентного анализа, измерения твердости по Виккерсу был изучен состав, структура, количество неметаллических включений и пористость образцов, вырезанных из идентичных мест отливок. Рассмотрено характерная локализация неметаллических включений различных типов в структуре образцов чугуна. Выявлено увеличение доли неметаллических включений в чугунах, полученных с использованием высокой доли лома, и показано, что наиболее отрицательное влияние оказывают неметаллические оксидные включения с неплотной структурой. Они наряду с пористостью и первичными кристаллами карбида (CrFe)3C не препятствуют распространению трещин, вызываемых внутренними напряжениями, возникающими при кристаллизации и последующих полиморфных превращениях в отливках.

Ключевые слова: износостойкий чугун, отливка, неметаллические включения, растрескивание, структура.

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