Influence of heat treatment modes on the formation of structure and physical and mechanical properties of cast blanks from the aluminothermic alloys

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Abstract. The production of aluminothermic alloys is accompanied by high temperatures of the reaction products, the control of which is difficult both by direct and indirect methods. Filling the metal into the mould without controlling the casting temperature provides a high gradient between the metal and the mould, which leads to the formation of quenching structures and, in some cases, structural heterogeneity of the blanks. To reduce the temperature of the reaction products, an introduction to the composition of mixtures of inert additives, which determine the change in the chemical composition of the alloys, is used. The removal of high internal stresses and the ordering of the structures of the experimental samples are carried out by using homogenizing annealing. Moreover, in typical structure characteristics of cast blanks, transformations occur, as well as the diffusion of individual chemical elements throughout the blank volume. The purpose of this work is to study the influence of the procedure of homogenizing annealing on the formation of the structure and physical and mechanical properties of aluminothermic cast blanks. This paper presents the results of the study of the effect of homogenizing annealing on the formation of a structure in iron-carbon alloy castings. Iron-carbon alloys were produced by means of a new casting technology – aluminothermy.

The growing rates of engineering and technology development around the world prompts the manufactures to use resource-saving technologies in all sectors of production, particularly in metallurgy, which is one way to reduce the cost of production [1]. This method also allows to get social and economic and environmental benefits in a competitive market economy. An example of such technologies is processes based on aluminothermy[2-6]. These technologies make it possible to obtain castings [7], with the required properties from machine-building and metallurgical wastes: dross, ferrous and non-ferrous metal shavings with concomitant savings in raw materials and energy resources. One of the most important products of an exothermic reaction is the metal phase, which is an iron-carbon alloy. The chemical composition of the specified alloy depends on the quantity and quality of the introduced components into the thermite charge, while they significantly affect the temperature of the reaction products, particularly, the temperature of the metal phase. The high casting temperatures of the resulting iron-carbon alloys, taking into account the effect of carbon chill moulds[8, 9], which provide intensive heat removal during the solidification of the castings, affect the formation of quenching structures of the resulting cast blanks, and also affect the formation of large internal stresses in them. The structure of cast steels obtained by aluminothermy, in some cases, is characterized by heterogeneity, as well as segregation of individual chemical elements. The obtained castings not always
meet the specified characteristics. To fix the structure of castings, relieve internal stresses, annealing and other types of heat treatment are used[10], which provide phase transformations and allow the structure to return to its initial state before subsequent heat treatment operations, for example, quenching.

The control of high temperatures of reaction products due to technological nuances is significantly complicated, that’s why it is required while constructing the dependencies not to focus on the temperature parameters of the reaction products, but to use other values and features indirectly related to the temperature.

Thus, the aim of the work is to determine the influence of production modes, as well as the effect of subsequent heat treatment operations on the structure and physical and mechanical properties of the experimental samples.

To achieve the aim of the study, the following tasks have been carried out:
- to specify the influence patterns of the amount of fillers introduced into the termite composition on the tensile strength and the tensile elongation of experimental samples;
- to specify the influence patterns of heat treatment on the tensile strength and the tensile elongation of experimental samples;
- to make a comparative analysis of the structures of the samples of the experimental alloys before and after heat treatment.

The exothermic reactions have been carried out in refractory crucibles made of EG15 grade graphite scrap used for steel melting in electric arc furnaces in accordance with TU 14-139-177-2003 Technical Specifications «Graphite electrodes of diameter from 75 to 555 mm and nipples for them. Technical specifications». The density of the refractory material is 1700 kg/m³. The working space volume of the crucible is 0.000572 m³, the wall thickness is 0.01 m. The weight of the crucible is 0.71 kg. The volume of the working space corresponds to the charge of compound of 1 kg with a minimum bulk density (without compaction) to obtain a sample of the required size. After the compound charge, the crucible has been covered with a lid having a hole for the gases output (diameter is 20 mm). The inner diameter of the crucible is equal to the height of its working space and is 0.09 m. A one-time-use insert with a hole of 0.007 m in diameter has been installed in the bottom of the crucible to stabilize the melt casting speed. The metal drainage hole is closed with EG15 graphite cone plug. After passing the reaction and dwelling the melt in the crucible for 10 seconds (to ensure the separation of metal and slag), the plug is knocked out, the mould is filled with metal. The mould for obtaining the samples is a deaf-bottomed cylinder, with an internal diameter of 0.03 m, the wall thickness of 0.03 m and height of 0.15 m. Before starting the experiments the refractory equipment has been heated up to 150 °C and has been coated with parting paint of the following composition: marshallit – 20 %, liquid glass – 5 %, water – 74 %, boric acid – 1 %.

Iron-aluminium thermite compound consisted of components, the fraction of which is 0.2 – 1.5 mm, and its chemical composition is the following: reducer – Al = 98.627 %; Cu = 0.018 %; Si = 0.855 %; Mn = 0.019 %; Fe = 0.462 %; Cr = 0.016 %; Ni = 0.004 %; iron scale – Fe = 71,500 %; O2= 22.639 %; Si = 2.960 %; Mn = 1.188 %; Al = 0.697 %; Cu = 0.444 %; Ni = 0.188 %; Cr = 0.173 %; C = 0.150 %; S = 0.030 %; P = 0.030 %. FMn-78(A) ferromanganese of fraction up to 0.04 mm, which corresponds to the requirements of GOST 4755-91 «Ferromanganese. Technical requirements and terms of delivery», with the chemical composition: Mn = 78.050%; C = 6.990%; Si = 0.790%; S = 0.008%; P = 0.189%. Steel alloy grit (St3sp steel grade according to GOST 380-2005) of fraction of 1-3 mm with the chemical composition: C = 0.180%; Mn = 0.520%; Si = 0.210%; S = 0.021%; P = 0.028; Ni = 0.010%; Cr = 0.110%; Cu = 0.220%. The compositions of the used thermite mixtures, the starting materials and the chemical composition of the resulting alloys are shown in table 1.

Preparation of thermite mixtures has been carried out by blending in a mixer for 10 minutes; drying at 150 °C for 1 hour; re-blending for 10 minutes, during which homogenization of the mixture is achieved and partial crushing of the components lead to the cleaning of the surface of the reducing agent particles from the oxide film and the ensuring the intensive interaction between the reacting particles.
The chemical composition of the samples has been determined with the help of Q4 TASMAN 170 BRUKER optical emission spectrometer (the USA). To specify the metal structure of the metal castings, microscope AXIO VERT A1 made by Carl Zeiss (Germany) has been used. To obtain the photos of the microstructure, integrated camera AxioCam ERC5s has been used. The physical and mechanical characteristics have been specified by performing a standardized tensile test in accordance with GOST 1497-84 with the help of Shimadzu AGXplus-250kN universal testing machine (Japan). The fracture diffraction pattern of the samples after tensile tests have been made with help of ZEISS EVO LS-10 Scanning Electron Microscope with zooming x1000 (the UK).

Homogenizing annealing has been performed by heating the samples in SNOL-12/1300 electric laboratory furnace of muffle type (Lithuania). The mode of underannealing for all samples has been the following: heating at the rate of 10 °C/min for 76 minutes to a temperature of 760 °C, dwelling at this temperature for 720 minutes, cooling at the speed of 0.8 °C/min for 592 minutes to the ambient temperature. The mode of homogenizing annealing is shown in Figure 1.

According to the conducted studies, the tensile strength of test samples with an increase in the content of additives in the thermite mixtures from 0.2% to 1.6% decreases in the range from 389 MPa to 335 MPa. It is connected to a decrease in the calorific value of the thermite mixture due to the introduction of fillers, which affect the heat reserve of the resulting alloy, as well as a low yield of iron-carbon alloy. The decrease in tensile strength occurs due to the high cooling rate of the samples, in the form that ensures the formation of high internal stresses in them, contributing to the destruction of the samples. Then an increase in the tensile strength takes is observed, the peak of which reaches at 509 MPa, with the filler content of 4.3% in mixtures, which indicates a favorable set of conditions for obtaining samples, such as: the alloy pouring temperature, the initial mould temperature, the alloy chemical

| Table 1. The compositions of the used thermite mixtures the chemical composition of the resulting alloys |
| --- | --- | --- | --- | --- | --- |
| № | Components | Content of components in exothermic mixtures, % | Mixture 1 | Mixture 2 | Mixture 3 | Mixture 4 | Mixture 5 |
| --- | --- | --- | --- | --- | --- | --- | --- |
| 1. | Reducer | Thermite | 22 | 22 | 22 | 22 | 22 |
| 2. | Scale | 78 | 78 | 78 | 78 | 78 |
| Total, % | 100 | 100 | 100 | 100 | 100 |

Fillers introduced over 100% of thermite per 1 kg, gr

| 3. | FMn-78(A) ferromanganese | 2 | 2 | 2 | 2 | 2 |
| 4. | St3sp steel alloy grit | 0 | 15 | 30 | 45 | 60 |
| Total, gr./% | 2.02 | 17.16 | 32.3 | 47.43 | 62.56 |

Chemical composition of the resulting alloys, %

| 1. | C | 1.93 | 1.87 | 1.83 | 1.83 | 1.32 |
| 2. | Mn | 0.25 | 0.29 | 0.29 | 0.28 | 0.28 |
| 3. | Si | 0.25 | 0.28 | 0.26 | 0.24 | 0.24 |
| 4. | S | 0.015 | 0.017 | 0.016 | 0.016 | 0.017 |
| 5. | P | 0.017 | 0.027 | 0.026 | 0.027 | 0.027 |
| 6. | Cr | 0.050 | 0.050 | 0.050 | 0.050 | 0.050 |
| 7. | Ni | 0.100 | 0.100 | 0.100 | 0.110 | 0.110 |
| 8. | Cu | 0.150 | 0.160 | 0.160 | 0.160 | 0.160 |
| 9. | Al | 0.085 | 0.260 | 0.220 | 0.320 | 0.440 |
| 10. | Fe | 97.153 | 96.946 | 97.048 | 96.967 | 97.356 |
| Total, % | 100 | 100 | 100 | 100 | 100 |
composition, the amount of the alloy poured (the thermite metal yield is 53.24% at this point) and the cooling rate of the cast blanks. After the peak point, a significant decrease in the tensile strength up to 219 MPa is observed, associated with the general decrease in the yield of the metal phase, as well as the low calorific value of the exothermic mixture. The use of underannealing according to the aforementioned mode makes it possible to remove large internal stresses by correcting the cast structure of the cast blanks and eliminating segregation of individual elements, which results in the tensile strength increase of the obtained samples for the majority of the mixtures used. In general, with an increase in the filler content in thermite mixtures, a linear dependence of the decrease in the tensile strength from 562 MPa to 402 MPa is observed. With the filler content of 4.3%, there is a slight decrease in the tensile strength associated with the elimination of quenching structures. Figure 2 shows the dependence of the content of fillers in the thermite mixtures on the tensile strength of experimental samples and the yield of the metal phase.

**Figure 1.** The mode of underannealing

**Figure 2.** Change in the tensile strength of the samples from the experimental alloys and the yield of the metal phase depending on the amount of added additives: 
a – cast samples (without heat treatment); b – the samples after underannealing; c – the yield of the metal phase (along additional axis).
The relative elongation of the samples has a similar dependence with the consistent pattern in the tensile strength on the amount of fillers introduced into the mixture with its own values. While the tension test of the experimental samples with an increase in the content of additives in the thermite mixtures from 0.2% to 1.6%, the relative elongation decreases in the range from 1.69% to 1.3%. Then an increase of this parameter up to 3.29% is observed with the content of additives in mixtures of 4.3%. After that an intensive decrease in the tensile elongation up to 0.43% is observed. The nature of the change in elongation is explained by similar causes and conditions as for the tensile strength. Homogenizing annealing makes it possible to relieve internal stresses by correcting the structure and eliminating the segregation of individual elements, which leads to a general increase in the relative elongation. In the range from 0.2% to 4.3%, the elongation decreases from 4.3% to 2.93%. Then an intensive growth up to 4.27% occurs when the filler content in the thermite mixtures is up to 5.6%, caused by a change in the type of structure components. Figure 3 shows the change in the parameters of elongation of the samples during the tensile test and the yield of the metal phase depending on the amount of the fillers introduced into the thermite mixture.

The experiment has proved that the alloy resulted at the fillers’ content of 4.3% in the thermite mixture practically does not change its properties during homogenizing annealing. So, the properties of the initial components correspond to those formed, which, according to preliminary estimates, allows to use the alloy after receiving the cast blanks under the high temperatures without changing its properties.

![Figure 3](image-url)

**Figure 3.** The change in the deformation of the experimental samples during the tensile test and the yield of the metal phase depending on the amount of the additives introduced:
- a – cast samples (without heat treatment);
- b – the samples after homogenizing annealing;
- c – the yield of the metal phase (along additional axis).

The structure of the resulted samples from the thermite mixtures with the content of the fillers from 0.2 % to 4.3 % which provide the content of carbon in the alloys from 1.83% to 1.93% before heat treatment is with the development of Widmanstätt with the areas of structurally free cementite. Figure 4a shows the structures of the resulted samples produced from thermite mixtures 2 and 4, which ensure in the range of added fillers the minimum and maximum physical and mechanical properties. The samples produced from the mixture with the content of fillers of 5.6% have the chemical composition which corresponds to Y13 grade tool alloy in accordance with GOST 1435-74. Its structure, shown on Fig.4e, is Widmanstätt-like with the localized areas of plate pearlite. The correspondence in chemical composition to the tool steels has specified the choice of annealing mode. For these types of steel, to obtain the granular pearlite, the heat should not exceed much the critical point of $A_{C1}$, so that the plate pearlite does not form which makes the machining of the resulting tool blanks rather complicated. Upon heating to such temperature, only pearlite is converted to austenite, but cementite remains and the
structure of cementite and austenite is formed. Upon subsequent slow cooling, austenite forms the pearlite structure with a granular form of cementite.

**Figure 4.** The structure of the samples produced from the mixtures (x1000): a – mixture 2 before heat treatment; b – mixture 2 after heat treatment; c – mixture 4 before heat treatment; d - mixture 4 after heat treatment; e - mixture 5 before heat treatment; f - mixture 5 after heat treatment.
After annealing, the structure of the experimental samples with the carbon content of more than 1.3% consists of the granular pearlite with the grain size of 9-10 according to GOST 8233-56. As an example, figures 4 b, d, f show the structure of samples produced from thermite mixtures 2, 4, 5. The steel with the granular pearlite structure has lower hardness and improved cutting ability. This makes it possible to make tools from the alloys under study with its subsequent heat treatment to achieve the required properties. The structure consisting of the granular pearlite is suitable for quenching, because the tendency to increase the austenitic grain is significantly reduced and the optimum quenching temperature decreases. This increases the viscosity and strength of the products, reduces the risk of destruction of the products during the operation.

Figure 5 shows the diagram of the tensile tests of the samples produced from thermite mixture 4, which are characterized by a slight change in their properties before and after heat treatment. In general, all experimental samples are characterized by hardening during the plastic flow. According to the tensile test diagrams, it can be concluded that all samples have brittle fracture.

![Figure 5](image)

**Figure 5.** The tensile diagram of the samples produced from thermite mixture 4: a – before heat treatment; b – after heat treatment

Due to the complexity of visual determination of the fracture nature, the fracture areas of the samples have been studied using the electron scanning microscope. The results confirm the presence of brittle transcrystalline fracture. Figure 6 shows, as an example, the fractographs of the fractures of the samples produced from thermite mixture 4 before and after heat treatment.

![Figure 6](image)

**Figure 6.** The fractographs of the fractures of the samples produced from thermite mixture 4 (x1200): a – before heat treatment; b – after heat treatment
According to the conducted studies, the consistent patterns of the influence of the added fillers’ amount into the thermite mixtures on the tensile strength and elongation during the tensile test of the experimental samples have been determined. It has been revealed that a 4.3%-filler-content thermite mixture provides the obtaining of the samples with the maximum values of the abovementioned parameters. The use of underannealing allows to relieve internal stresses in all test samples and significantly increase their tensile strength and elongation. The samples produced from a 4.3%-filler-content thermite mixture practically do not change their properties after heat treatment. Annealing of the experimental samples has made it possible to obtain the structure with the granular pearlite.

Thus, aluminothermy allows to obtain alloys with different chemical composition and properties, including those that meet, and in some cases, exceed the requirements of normative documentation for branded alloys, by introducing various fillers into the composition of the thermite mixtures, providing a high yield of the metal phase and optimal temperature of reaction products. Underannealing of the experimental samples eliminates structural heterogeneity. It also ensures the required properties of the experimental materials before manufacturing products from them, including the products for critical purposes, with the subsequent heat treatment, if it is required, to achieve the required operational characteristics.

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