DEVELOPMENT OF TECHNOLOGY FOR OBTAINING THIN-WALLED DETAILS FROM GRAY CAST IRON IN SAND-CLAY MOULDS

Jamshidbek Khasanov[1], Nozimjon Kholmirzaev[2], Nosir Saidmakhamadov[2], Begijon Tojiboev[1], Ergashev Dilshodbek[1], Khusanboy Makhammadjanov[1], Abdujalol Bektemirov[1], Firyuza Arabbaeva[1], Akramjon Otakuziev[1]
[1]Andijan Machine – Building Institute, 170119 Andijan, Uzbekistan
[2]Tashkent State Technical University, 100095 Tashkent, Uzbekistan
Email: khasanov9339@gmail.com

Abstract - In this article, the technology of casting thin-walled details into sand-clay molds has been developed based on the analysis of existing problems in casting detail manufacturing enterprises. In order to increase the liquid fluidity and hardness properties of G24 gray cast iron alloy, the technology of adding modifiers to the liquid alloy in the furnace and outside the furnace was developed. In addition, the composition of the sand-clay mold material and the technology of the processes of pouring the liquefied gray cast iron alloy into the mold were developed. Also, the technologies of using models made of modern ABS (acrylonitrile butadiene styrene) material have been improved in obtaining casting details of thin-walled parts in a sand-clay mold. Microstructural images of gray cast iron alloy samples cast on the basis of the used technologies were obtained and interpreted. As a result of the introduction of the developed technologies, it was possible to obtain high-quality thin-walled details. Based on the developed technologies and the modifiers included in the liquid alloy, the service life of cast thin casting has increased by 1.3 times.

Keywords: Gray cast iron, Thin-walled details, Sand-clay moulds**,** Brittleness, Perlite, Ferrite, Graphite.

1. Introduction

One of the important tasks in the world today is to obtain high-quality, inexpensive thin-walled cast products based on improving the strength, quality, and mechanical and operational properties of parts used in the engineering and production industry obtained by the casting method. Also, in order to reduce energy and fuel consumption, the need for lightweight products with high strength is increasing.

By using gray cast iron alloys or by reducing its thickness while maintaining its strength, casting parts obtained in the automotive industry reduce the cost per vehicle by almost 15% compared to parts made from steel or aluminum alloys. As a result of the increased demand for thin-walled cast products in the world, many techniques and technologies have been developed, which require the production of high-quality, cheap and competitive parts. For reference, gray cast iron accounted for the largest market share of 37% in the global steel and cast-iron manufacturing market in 2021 [1].

The demand for cast iron alloys in the automotive industry is growing over time due to their low cost and ease of mass production. The USA, China, Germany, India, Australia, Great Britain, Turkey and Brazil are leading in the production of cast iron alloys. The member states of the European Foundry Association achieved production of about 10.7 million tons of cast iron and steel alloys in 2021, an increase of 17.6% compared to the same period last year, and the share of gray iron alloys in the total volume of production was 49.3%. which in turn is explained by the need and high demand for cast iron alloys [2].

It has been studied by the world's leading scientists that it is possible to obtain cheap, durable details by modifying its composition and improving casting technologies in obtaining thin-walled high construction details from gray cast iron alloys.

Mining, metallurgical and engineering details are cast from gray cast iron by adding modifiers to it, improving its corrosion resistance, hardness, fluidity, and other important properties while controlling the cooling rate [3].

The production of cast iron requires less fuel and energy than steel, because the melting point of cast iron is lower than the melting point of steel, and cast iron has high hardness and strength and has low penetration after cooling. According to the phase diagram of iron-carbon alloy, the alloys are in the liquid phase between 1147 ^{o}C and 1400 ^{o}C, which is much lower compared to steels. Because of this, they are easily liquefied and can be recycled in bulk. Also, due to the fact that cast iron is a very fragile material, it is preferable to use the casting method to obtain products of various shapes from them.

Cast iron consists of carbon, silicon, manganese, phosphorus and sulfur elements. High-quality, alloyed and refractory cast iron contains titanium, nickel, boron, vanadium, copper, chromium, molybdenum and other alloying elements. Alloying elements affect the structure and amount of graphite released from the cast iron after it is introduced into the furnace during the liquefaction of cast iron [4-10].

2. Materials and Methods

The object of the study is gray cast iron alloys – grade G24 (GOST 1412 – 85) and lift gate details used in metallurgical enterprises.

The technology of production of the details of the lifting roof used in metallurgical enterprises in sand-clay molds is the subject of research.

In the research work, the chemical composition of the samples was determined using an emission spectroscopy device, fast metallurgical microscopes and scanning electron microscopes were used to analyze the microstructure of the alloy, the analysis of the volume distribution map of the elements in it, and the methods of determining the hardness of the samples.

The lifting roof detail is used in the cooling line at metallurgical enterprises. These parts are high construction, thin-walled casting parts and are mainly cast using the pressure mold casting method. As the main reason for this, it is possible to point out the difficulties in making its model and developing the composition of the alloy. At the moment, one of the problems arising at the factory of "Uzmetkombinat" JSC is difficulties in ensuring the continuity of the production process due to logistical deficiencies caused by the pandemic, the long time it takes to bring these parts from countries such as Belarus and China. Due to the urgency of developing the technology of obtaining these details in the conditions of the enterprise "Uzmetkombinat" JSC in sand-clay molds, a number of technologies were developed during the scientific research. Also, by developing the technology of processing gray cast iron alloys used in liquefaction in the furnace and outside the furnace, it was ensured to increase its fluidity, hardness, and corrosion resistance properties.

For the casting of gray cast iron thin-walled lifting roof thin-walled details, the DSP-0.5 electric arc furnace with three-phase current, with vertically installed coal graphite electrodes, widely used in the industry, of the "Casting - Mechanics" shop of the “Uzmetkombinat” JSC enterprise was selected. Before loading solid materials, it was checked whether the oven was suitable for work, whether there were any cracks or cracks in the lining part. 450 kg of secondary gray cast iron slag was used for the furnace, and ferromanganese FeMn17 GOST 4755-91, ferrosilicon FeSi75 GOST 1415-93, and ferromolybdenum (FeMo70) and copper phosphite CuP_2 GOST 4515 based on GOST 4759-91 were used as modifiers. The number of elements in the samples of the G24 brand GOST 1412-85 gray cast iron GOST 1412-85, which is used in the casting of lifting roof details in the “Uzmetkombinat” enterprise Casting-mechanics shop, and the proposed new composition, are listed in table 1 below.

Table 1. The chemical composition of the proposed casting of the lifting roof detail

Samples	The mass amount of elements %								
	C	Mn	Si	Cr	P	S	Ni	Cu	Mo
Lifting roof N – 1	3,30	0,69	2,14	0,11	0,074	0,064	0,06	0,10	0,3
N – 2	3,35	0,69	2,15	0,11	0,074	0,064	0,06	0,20	0,3
N – 3	3,32	0,65	2,20	0,11	0,074	0,064	0,06	0,50	0,3
N – 4	3,33	0,62	2,3	0,11	0,074	0,064	0,06	0,70	0,3
N – 5	3,35	0,66	2,28	0,11	0,074	0,064	0,08	0,80	0,3

A DSP-0.5 electric arc furnace was selected for casting test samples in the "Casting Mechanics" workshop of "Uzmetkombinat" JSC. Samples were cast into casting molds with G24 (GOST 1412-85) gray cast iron and ferrosilicon FSi75 (GOST 1415-93), ferromanganese FMn88, FMn90 (GOST 4755-91), copper phosphide CuP_2-9, CuP_2-10 (GOST-4515) were used.

a)

b)

Figure 1: A detail of the lifting roof used by the enterprise "Uzmetkombinat" JSC.
a) Rear view of the lifting roof detail b) Front view of the lifting roof detail

Figure 1a shows the rear and figure 1b shows the detail of the lifting roof above. It can be seen from the figure that this detail is thin-walled, complex-shaped, high construction, and there are sharp changes in the thickness of the casting walls, as well as sharp corners in the transition parts from one surface to another.

This increase was achieved by using new innovative methods of modeling, taking into account the time, raw materials, and energy consumption of casting a window detail using a wooden model. SP-1037 and SP-1033 were drawn using Solidworks software based on the drawings, and combustible material was used as a model. Below is a three-dimensional view of the part of the lifting roof in the Solidworks program in figure 2.

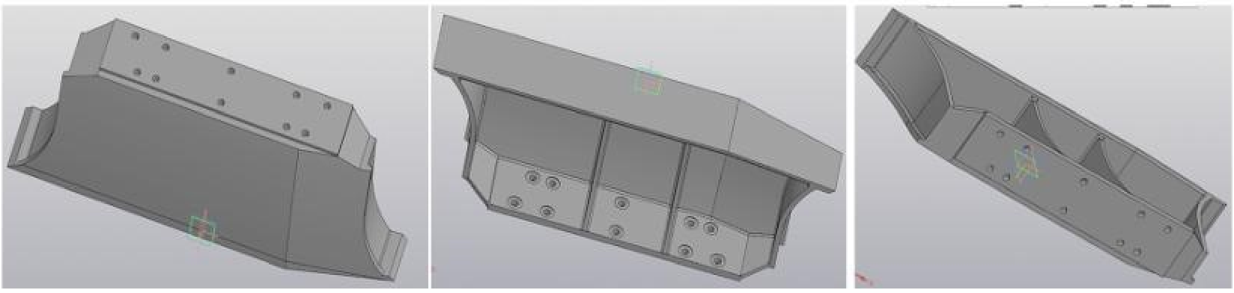
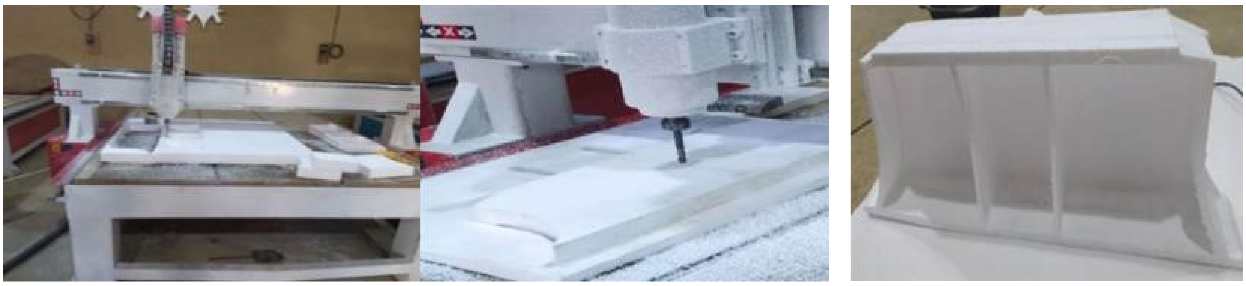


Figure 2: Three views of the 3D model of the lifting roof detail drawn in the Compass program based on the SP-1037 drawing

With the help of the mentioned drawings, the models were made of polystyrene material, which is flammable and consists of a mixture of 5% hydrocarbon monomer styrene and 95% air. The density of this selected polymer material is 11-32 kg/m^3, strength limit is 30-40 MPa, liquefaction temperature is 150-200 ^{o}C. Based on this material, with the help of the drawings provided by "Uzmetkombinat" JSC, combustible models were prepared on the CNC ROUTER machine, and its sequence is shown in Figure 3 below.



a) b) c)

Figure 3: Models of lifting roof detail made of polystyrene material using a CNC ROUTER machine
a) making from polystyrene on the CNC ROUTER device b) semi-finished model c) finished model

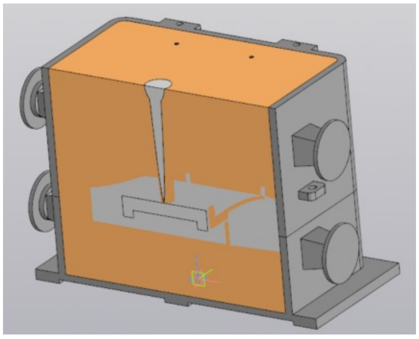
Above figure 3a shows the initial view of the preparation of a thin-walled detail on a CNC ROUTER machine from polystyrene material, and figure b shows the semi-finished state of polystyrene material, and figure c shows the front view of the finished model. On the basis of ready-made models, G24 gray cast iron alloy was cast using a vacuum mold at the foundry-mechanics section of JSC "Uzmetkombinat".

For the vacuum mold, 80-84% quartz sand, 5-6% bentonite clay, 6-7% water were mixed in a begun machine for 15-20 minutes. During the loading of first large and then small solid materials into the induction furnace, it was ensured that the composition of the secondary alloys does not contain water and moisture. Two retainers attached to the walls of the model and a retainer placed on top of them also served as a slag holder. Composition: 8-11% aluminum oxide fireclay, 4-5% electrocorundum, 2.9-4.4% zirconium, 1.5-2.5% fire clay, 1.5-2.9% kaolin, liquid glass 4.5-5% and anti-scald with water mm paint, dried at room temperature, the models with taped channels and supplies are given in figure 4.

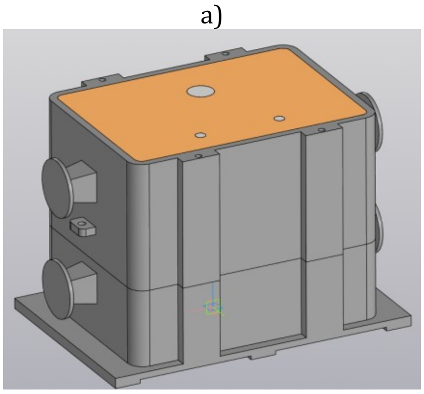
a) b) c)

Figure 4: Models prepared for casting in a vacuum mold based on a drawing a) SP-1037 is a model of a raised roof detail based on the drawing b) SP-1033 is a model of a raised window detail based on the drawing c) models of lifting roof details based on drawings SP-1037 and SP-1033

In order to increase castability and mechanical properties, modifiers were added to cast iron in order to create additional crystallization centers of graphite. In order to increase the fluidity and hardness of the raised roof part being cast, modifiers ferromolybdenum (FeMo70) were loaded in the furnace and copper phosphite (CuP_2) in the furnace. According to GOST 4515-93, copper phosphite CuP_2 is known to contain up to 10% phosphorus, and phosphorus is a harmful element of cast iron and increases hardness and corrosion resistance. 45 kg of secondary cast iron was used for one part of the raised shingle, and taking into account the addition of 0.225 kg of copper phosphite to this concrete material, the amount of phosphorus in it was 0.05%, even if it was calculated at a maximum of 10%. That is, it was ensured that the amount of phosphorus does not exceed the requirements of GOST 1412-85 for the liquefied gray cast iron alloy (Fig 5).



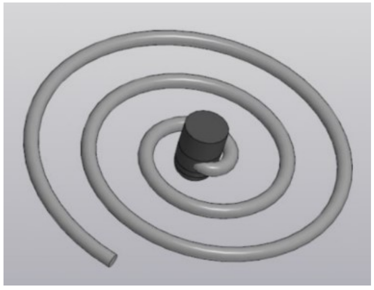
a)



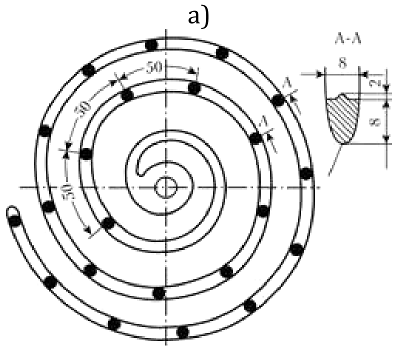
b)

Figure 5: A figure *of the placement of the mold of the lifting roof detail a) a cropped image of the placement of the models in the mold b) flasks layout of models*

Liquid flow test analyses. Due to the ability of metals and alloys to fill the mold in a liquid state, the ability to return the dimensional accuracy of the casting is called fluidity. The fluidity of cast iron alloys is determined by casting spiral plates and measuring the filled part of the spiral (Fig 6).



a)



b)

Figure 6: Spiral sample for fluidity determination a) spiral sample 3D view b) spiral sample dimensions

When the amount of carbon (C), silicon (Si) and phosphorus (P) increases up to a certain limit, the fluidity property of cast iron improves, but when the mass fraction of sulfur exceeds 0.15%, it reduces the fluidity of cast iron. Phosphorus (P) does not significantly affect the graphitization process and improves the fluidity of cast iron. In gray cast iron, phosphorus forms a ternary eutectic, which liquefies relatively easily (at 950^{o}C). This eutectic liquid iron consists of high-phosphorus austenite, carbide (Fe_3C) and phosphide (Fe_3P) during solidification. The reason for the improved fluidity properties of phosphorous cast irons in the liquid state is this triple eutectic, which is easily fluidized. The presence of iron phosphide sites in cast iron increases the hardness and corrosion resistance properties of cast iron.

The liquid flow rate of gray cast iron according to the thickness of the cast walls according to the spiral sample should be calculated as follows - table 2 [11-17].

Table 2. Dependence of the length of thin-walled details on thickness

Wall thickness, mm	3 – 6	6 – 15	16 – 25	Above 25
Fluidity length, mm	500– 700	400 – 500	300 – 400	200 – 300

3. Results and Discussion

- ***Liquid flow test results***

Using the given information, experiments on increasing the fluidity of gray cast iron were carried out in the laboratory of the "Casting Technologies" department of Tashkent State Technical University named after Islam Karimov. For liquefaction, 2 kg of BF-TB2 brand induction furnace was selected, and the solid materials were prepared according to table 1, and the composition of the mold material was prepared according to table 3 and laboratory work was carried out.

a) b) c)

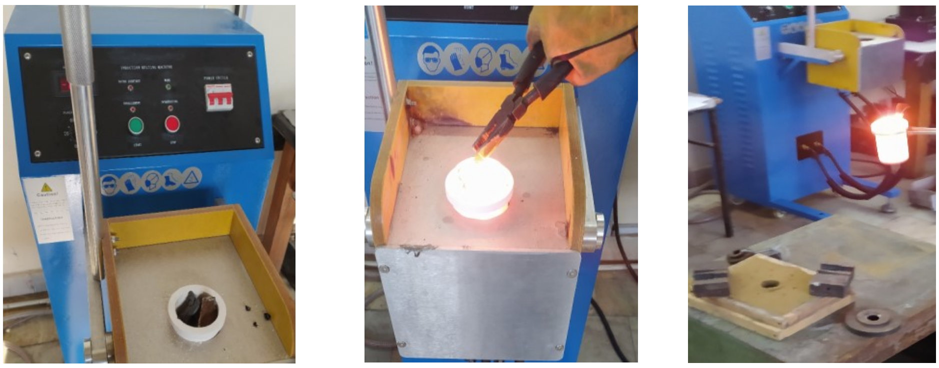
Figure 7: A mold made using a spiral model to determine the ductility of modified gray cast iron a) model ready for rammering with sand b) the inner part of the mold based on the prepared spiral pattern c) mold ready for casting.

The sand used in the preparation of the mold material was first sieved, quartz sand and bentonite clay were added in the amount specified in the table and mixed, then it was molded into a wooden block and the sequence of this process is shown in fig 7.

Table 3. Table of composition of used mold material

Used sand, %	70 – 80
Quartz sand, %	5 – 10
Kaolin clay, %	6– 8
Water, %	3 – 7

Kaolinite binder used as mold clay listed in table 3 is obtained from Al_2O_3, $2SiO_2$, $2H_2O$ minerals, its density is according to the 2...2.5 scale, its density is 2.58 - 2.60 g/cm^3, and the melting temperature is 1750 - 1790°C. and kaolin clay becomes hygroscopic when heated to 100 – 140 °C, and at 350 – 580 °C clay loses moisture and turns into metakaolinite (Al_2O_3 * $2SiO_2$), in which the process of losing the binding properties of clay is called “liamotization of clay” and metacaolinite at 900 – 1050 °C $3Al_2O_3$ $2SiO_2$ (mullite) is formed between 1200 and 1280 °C when it decomposes into amorphous components Al_2O_3 and SiO_2 [18-21].



a) b) c)

Figure 8: The process of liquefaction of gray cast iron in the BF-TB2 induction furnace
a) The process of loading charges into the furnace crucible b) the process of adding a modifier to the alloy being liquefied c) the process of casting a liquid alloy into a spiral mold

The process of liquefaction of gray cast iron in the BF-TB2 induction furnace was 11-13 minutes and it was cleaned of slag before pouring into the mold. The rate and temperature of pouring the modifier into the liquefied gray cast iron mold was the same for each sample (Fig 8).

a) b) c)

Figure 9: Processes of de-molding from the mold and measuring the length of samples cast with copper phosphide as a modifier in gray cast iron a) separating the cast samples from the mold b) the process of measuring various samples c) the process of measuring the length of a cast sample without the addition of a modifier.

When calculating the lengths of samples cast without modifiers in gray cast iron with 0.00% CuP_2 amount, it was 230 mm (Fig. 9). The amount of modifier included in the amount of 0.6-0.9% increases the fluidity by a certain amount, but due to the fact that its brittleness increases due to the phosphorus content of copper phosphide, the amount of 0.5% was determined as optimal. Fig 10 also shows some samples at 3 different temperatures and Table 4 shows the lengths of the cast samples.

a) 0.00 % CuP_2 b) 0.2 % CuP_2 c) 0.4 % CuP_2 d) 0.5 % CuP_2

Figure 10: Proportion of lengths to the amount of copper phosphide as a modifier for gray cast iron.

During the experiments, it became clear that with the increase in the amount of suitable phosphide added to the gray cast iron as a modifier, the fluidity also increases proportionally to a certain level. The thickness of the spiral sample is 7 mm, which is increased by 11 - 14% based on the technology and composition developed for this thickness of details. The change graph of the obtained laboratory results is given in the following figure 11 and the obtained results in table 4 [22-25].

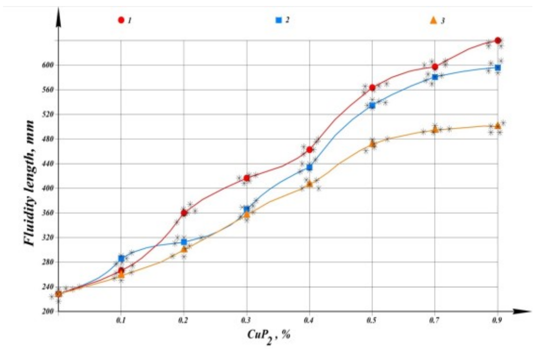


Figure 11: Copper phosphide and temperature dependence graph of fluidity length (1.1450 °C, 2.1430 °C, 3. 1400°C).

Table 4. Dependence of fluidity of copper phosphide and temperature

Amount of copper phosphide %	1400 °C	1430 °C	1450 °C
	Fluidity of samples (mm)		
0.1	252	268	285
0.2	294	312	360
0.3	353	367	410
0.5	470	545	560
0.7	496	570	600

Molybdenum was selected as a modifier for G24 gray cast iron and its effect on mechanical properties was determined during the research. With the help of copper phosphide, the hardness and fluidity properties of gray cast iron increased, and in order to improve its mechanical properties, molybdenum was put into the furnace up to 0.1-0.6%. The amount of copper phosphide 0.5% in the obtained samples was determined as the optimal amount, because the fluidity of the liquid alloy in this amount, together with the level of brittleness, did not lead to the observation of defects during detail processing. For this reason, based on GOST 4759-91, ferromolybdenum (FeMo70) was introduced in the furnace at a temperature of 1430-1440 °C. Molybdenum is an element that contributes to the formation of carbides and increases the strength and hardness properties of gray cast iron due to the transformation of austenite from fine pearlite to bainite. Molybdenum-carbon introduced as a modifier slows down the process of free graphite, and increases its amount without affecting the detail processing properties and increases corrosion resistance.

Above, in Table 4, the optimal amount of copper phosphide, 0.5 percent FeMo70, was put into the furnace and after waiting for 1-3 minutes, it was taken out. The hardness and fluidity properties of the samples obtained from cast details were determined. During the experiments, as the amount of ferromolybdenum added to the gray cast iron increased, its hardness property increased proportionally, but due to the fact that the fluidity property decreased sharply when adding more than 0.3 percent, this amount was determined as the optimal amount for casting the raised shingle detail. In figure 12, with increasing molybdenum content, its length decreases accordingly: 524 mm at 0.05%, 502 mm at 0.1%, 490 mm at 0.2%, 476 mm at 0.3%, 426 mm at 0.4%, 387 mm at 0.5%, 0.6 % 369 mm was determined. Due to the negative effect of molybdenum on the release of free graphite in gray cast iron, it was known that it reduced its fluidity.

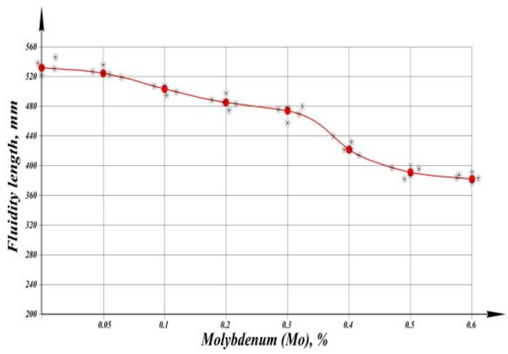


Figure 12: The graph of the dependence of the fluidity length of gray cast iron on the amount of molybdenum added to it as a modifier.

- ***The Results of Testing the Brittleness Properties of Research Samples***

In the laboratory of Karabuk University, "Iron and Steel" Scientific Research Institute of Turkey, the samples casted at a temperature of 1430 °C based on the composition of N - 2, N - 3, N - 4, N - 5 listed in Table 1 were prepared by ZWICK/ROELL Z600 device. The graphic images obtained by checking the compressive strength are presented in figure 13. In the course of research, it is known that the fragility of the gray cast iron alloy increases due to the presence of phosphorus in the copper phosphide. Compression test the cross-sectional area of the specimen continuously increases while the length of the specimen is continuously reduced due to the compressive load. The materials used in these experiments are usually brittle materials [26-29].

The graph taken on the ZWICK/ROELL Z600 device shows the most brittle state in line 1 when the amount of copper phosphide is 08 percent, line 2 is 0.7 percent copper phosphide, line 3 is 0.5 percent copper phosphide, and line 4 is 0.2 percent copper (Fig. 13). the result of compressive strength properties of samples with phosphide is given. From this study, it was found that as the amount of copper phosphide increases, its brittleness also increases. Although the graph gives the highest result when the amount of copper phosphide is 0.2 percent, the fluidity of the sample is much lower than the remaining amounts.

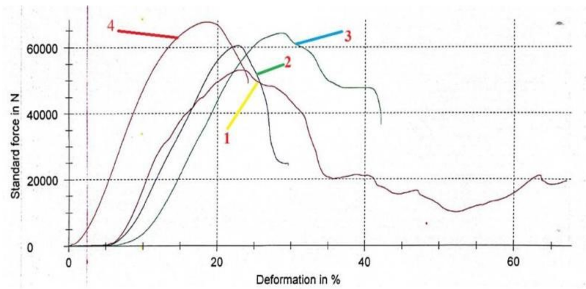


Figure 13: Graph of dependence of copper phosphide and ferromolybdenum added as modifiers to gray cast iron samples on its brittleness property.

- ***Research Results of Compressive Strength Properties of Samples***

Microstructures, hardness and compressive strength properties of the samples taken in the laboratory of the "Foundry Technologies" department of Tashkent State Technical University were studied. When determining the compressive strength property on the ZWICK/ROELL Z600 device, the length and diameter of the samples were prepared to be 10 mm, the test speed was 1 mm/min and the standard force was obtained by compressing the upper and lower parts of the sample (Fig 14).

a) b) c)

Figure 14: Determining the compressive strength properties of gray cast iron samples a) ZWICK/ROELL Z600 laboratory equipment b) a sample prepared for testing the property of brittleness c).

- ***Research Results at a Manufacturing Enterprise***

Ferromanganese FeMn17 in the amount of 0.56 kg and ferrosilicon FeSi75 in the amount of 1.7 kg were loaded into the furnace 10 minutes before the casting of the liquid alloy.

The temperature of liquid gray cast iron alloy was checked using a thermocouple Positherm device and poured into a crucible at a temperature of 1447 ^{o}C, and SiO_2 quartz sand was loaded for slag separation and the separated slag was removed from the crucible, these processes are shown in figure 15.

a) View of electric arc furnace b) The process of heating the bucket b) The process of casting a liquid alloy into a bucket

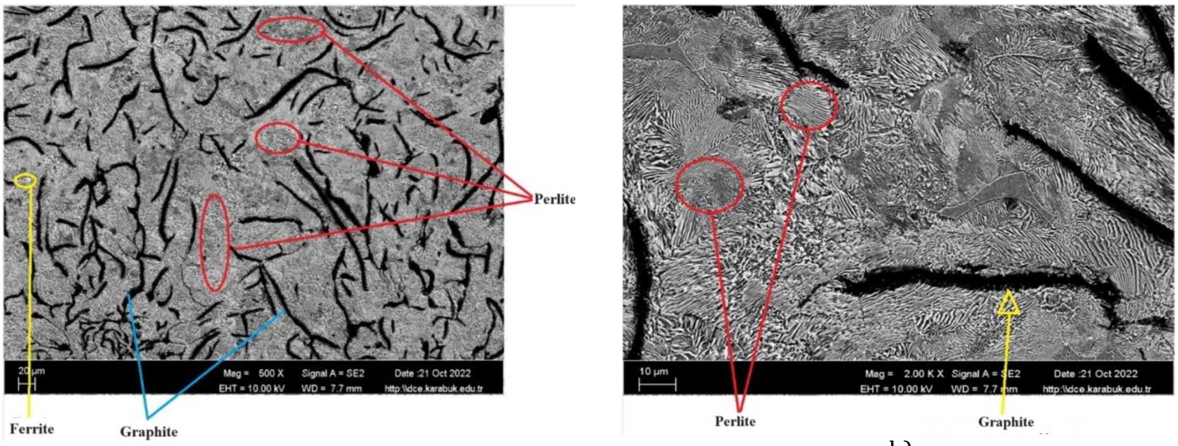
Figure 15: Casting process of liquefied gray cast iron alloy in an electric arc furnace.

On the basis of the above-mentioned technology, together with the possibility of obtaining thin-walled lifting roof details and using them without mechanical processing of their surfaces, the production processes of the enterprise "Uzmetkombinat" JSC enabled the quick delivery of lifting roof details (Fig. 16).

Figure 16: Detail of a thin-walled high-rise construction raised roof cast in gray cast iron in sand-clay moulds.

- ***Microstructural Analysis of Research Samples***

The microstructures and volume distribution of elements were examined by Carl Zeiss Ultra Plus Field Emission scanning electron microscope in the laboratory of Iron and Steel Institute of Karabuk University. The samples were studied by 2-parts of each at x100, x500, x1000, x1500, x2000 magnification. In this case, the images of microstructures in SEM taken at WD 7.6 – 7.7 mm using the SE2 detector at 10.00 kV are presented in figure 17.



a) b)

Figure 17: Microstructures of copper phosphide 0.5% and molybdenum 0.3% in Carl Zeiss Ultra Plus Field Emission scanning electron microscope in the laboratory of "Iron and Steel" Institute of Karabuk University a) image magnified x500 times b) image magnified x2000.

Separation of graphite from carbon is usually considered an important process in the production of details by liquefying cast iron, and is especially necessary in the production of thin-walled products. It was observed that the ductility, strength and hardness of gray cast iron increased. When copper phosphide (CuP_2) is added to 0.8% or more, it was found in the course of research that, although its fluidity and hardness increased, its brittle property was high. In figure 17, the volume distribution of the liquidized samples according to the content in Table 1 was checked by magnifying x5000 times in the Carl Zeiss Ultra Plus Field Emission scanning electron microscope of the Karabuk University "Iron and Stell" Institute laboratory. In the sample studied in figure 18, the elements are iron (Fe) red, carbon (C) green, silicon (Si) purple, manganese (Mn) blue, chromium (Cr) black, nickel (Ni), phosphorus (P) brown, sulfur (S) is shown separately in light green colors.

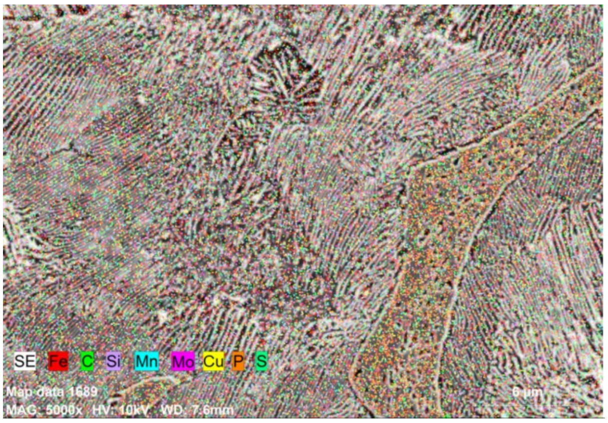


Figure 28: Volume distribution of elements in gray cast iron samples taken by Carl Zeiss Ultra Plus Field Emission scanning electron microscope in the laboratory of the Iron and Steel Institute of Karabuk University.

4. Conclusions

“The following main conclusions were presented on the work "Development of technology for obtaining thin-walled details in sand-clay molds from gray cast iron":

1. The technology of out-of-furnace processing of liquid alloy has been developed for obtaining thin-walled castings from gray cast iron. This makes it possible to increase the fluidity of the liquid alloy by 9-11%.
2. The technology of in-furnace processing of liquid alloy has been developed for obtaining thin-walled castings from gray cast iron. This allows to increase the hardness of the cast product by 10-12%.
3. Model preparation technology based on 3D technology has been developed for making thin-walled castings from gray cast iron. This resource allows saving 13-15%.
4. In the gray cast iron liquefaction furnace, the casting technology has been developed, which provides increased efficiency after modification with the help of CuP2 and Mo elements. This allows for savings in modifiers.
5. During the cooling process of the casting, a scheme for placement of the lifting roof detail in the casting mold, which ensures uniform distribution of corrosion resistance on the strengthening surface, has been developed. This serves to select an effective mold material.
6. The technology of increasing the fluidity of gray cast iron has been developed. This allows you to get thin-walled details with a complex shape.

References

[1] https://www.sphericalinsights.com/reports/iron-steel-casting-market
[2] https://www.caef.eu/statistics/

[3] Khasanov, J., Turakhodjaev, N., Abdukarimov, A., & Mirkamalov, S. (2022). Microstructural Analysis of Details Obtained by Liquefying Gray Cast Iron in a Sand – Clay Mold. Central Asian Journal of Theoretical and Applied Science, 3(12), 107-112. https://doi.org/10.17605/OSF.IO/BS4W2

[4] International Journal of Cast Metals Research Relationship between matrix-microstructure and mechanical properties of copper alloyed thin wall austempered gray cast iron (TWAGI) Tanmoy Sarkar & Goutam Sutradhar (2017): Relationship between matrixmicrostructure and mechanical properties of copper alloyed thin wall austempered gray cast iron (TWAGI), International Journal of Cast Metals Research, DOI: 10.1080/13640461.2017.1351705 17 Jul 2017.

[5] Nosir, S. ., Nodir, T. ., Jamshidbek, K. ., Nilufar, Z. ., & Anvar, T. . (2022). Improvement of the Technology of Pouring Thin – Walled Gray Cast Iron into a Sand – Clay Mold. *European Multidisciplinary Journal of Modern Science*, *9*, 90–96. Retrieved from https://emjms.academicjournal.io/index.php/emjms/article/view/747

[6] Saidmakhamadov Nosir, Turakhodjaev Nodir, Abdullaev Kamol, Khasanov Jamshidbek, & Tadjiev Nuritdin. (2022). Improvement of Technology of Liquefaction of Gray Cast Iron Alloy. *Global Scientific Review*, *6*, 19–28. Retrieved from https://scienticreview.com/index.php/gsr/article/view/40

[7] Khasanov, J., Turakhodjaev, N., Makhmudov, F., Turakhujaeva, S., Ermanov, O., & Ibragimov, A. (2023). Improvements in Obtaining Thin-Walled Casting Details Through Liquid Glass Mixtures. *Central Asian Journal of Theoretical and Applied Science*, *4*(4), 51-54. https://doi.org/10.17605/OSF.IO/6T843

[8] E. Heidari, S. M. A. Boutorabi, and M. T. Ablation casting of thin-wall ductile iron. Honaramooz School of Metallurgy and Materials Engineering, Iran University of Science and Technology, Tehran, Iran J. Campbell School of Metallurgy and Materials Engineering, The University of Birmingham, Edgbaston B152TT, UK Copyright 2021 American Foundry Society, 37-43 pages. May 2020. https://doi.org/10.1007/s40962-021-00579-7.

[9] Agus Yulianto, Rudy Soenoko, Wahyono Suprapto, As'ad Sonief, Agung Setyo Darmawan, Muhammad Debi Setiawan.; Microstructure and Hardness of Gray Cast Iron as a Product of Solidification in Permanent Mold. Materials Science Forum (Volume 991) https://doi.org/10.4028/www.scientific.net/MSF.991.37

[10] J. O. Agunsoye, S. A. Bello, S. B. Hassan, R. G. Adeyemo, J. M. The Effect of Copper Addition on the Mechanical and Wear Properties of Grey Cast Iron. Odii Journal of Minerals and Materials Characterization and Engineering, 2014.

[11] Nodir, T., Nosir, S., Shokhista, S., Furkat, O., Nozimjon, K., & Valida, B. (2021). Development of 280x29nl alloy liquefaction technology to increase the hardness and corrosion resistance of cast products. International Journal of Mechatronics and Applied Mechanics, 1(10), 154–159. https://doi.org/10.17683/IJOMAM/ISSUE10/V1.19

[12] Kidao, "Application of copper in Automotive Iron Castings", Copper in Cast Iron, 1970, pp 13-18.

[13] http://w3.bilecik.edu.tr/wp-content/uploads/sites/119/2016/12/Basma Deneyi.pdf

[14] Kholmirzaev, N., Turakhodjaev, N., Saidmakhamadov, N., Khasanov, J., Saidkhodjaeva, S., & Sadikova, N. (2023). Development of Technology of Making Shafts from Steel Alloy 35XGCL. Lecture Notes in Networks and Systems, 762 LNNS. https://doi.org/10.1007/978-3-031-40628-7_18

[15] Kholmirzaev, N., Turakhodjaev, N., Saidmakhamadov, N., Khasanov, J., Bektemirov, A., & Sadikova, N. (2024). Effects of titanium (Ti) contents on the wear resistance of low-alloy steel alloys. In E3S Web of Conferences (Vol. 525, p. 03003). EDP Sciences.

[16] Xiao, Z., Lv, Z., Zhou, X. *et al.* Numerical Simulation and Optimization of Investment Casting for Complex Thin-walled Castings. *Inter Metalcast* **18**, 159–179 (2024). https://doi.org/10.1007/s40962-023-00990-2

[17] Łukasz Rakoczy, Rafał Cygan, Analysis of temperature distribution in shell mould during thin-wall superalloy casting and its effect on the resultant microstructure, Archives of Civil and Mechanical Engineering, Volume 18, Issue 4, 2018, Pages 1441-1450, ISSN 1644-9665, https://doi.org/10.1016/j.acme.2018.05.008.

[18] Krutiš V, Novosad P, Záděra A, Kaňa V. Requirements for Hybrid Technology Enabling the Production of High-Precision Thin-Wall Castings. Materials. 2022; 15(11):3805. https://doi.org/10.3390/ma15113805

[19] Bingxu Wang, Yuming Pan, Yu Liu, Gary C. Barber, Feng Qiu, Ming Hu, Wear behavior of composite strengthened gray cast iron by austempering and laser hardening treatment, Journal of Materials Research and Technology, Volume 9, Issue 2, 2020, Pages 2037-2043, ISSN 2238-7854, https://doi.org/10.1016/j.jmrt.2019.12.036.

[20] Ibrahim, M. (2023). An overview on Thin Wall Cast Iron Castings and its Applications in Automotive Industry. International Journal of Materials Technology and Innovation, 3(1), 57-69. doi: https://doi.org/10.21608/ijmti.2022.153909.1056

[21] Y.W. Dong, X.L. Li, Qi Zhao, Jun Yang, Ming Dao, Modeling of shrinkage during investment casting of thin-walled hollow turbine blades, Journal of Materials Processing Technology, Volume 244, 2017, Pages 190-203, ISSN 0924-0136, https://doi.org/10.1016/j.jmatprotec.2017.01.005.

[22] Lu, Y., Lü, K., Li, Y. *et al.* Effect of Wall Thickness on Properties of Multilayer Composite Plaster Mold for Investment Casting. *Inter Metalcast* (2024). https://doi.org/10.1007/s40962-024-01350-4.

[23] V. Lopes, H. Puga, I.V. Gomes, N. Peixinho, J.C. Teixeira, J. Barbosa, Magnesium stents manufacturing: Experimental application of a novel hybrid thin-walled investment casting approach, Journal of Materials Processing Technology, Volume 299, 2022, 117339, ISSN 0924-0136, https://doi.org/10.1016/j.jmatprotec.2021.117339.

[24] Nosir, S., & Bokhodir, K. (2023). Development of Liquefaction Technology 280X29NL to Increase the Strength and Brittleness of Castings. In Lecture Notes in Networks and Systems: Vol. 534 LNNS. https://doi.org/10.1007/978-3-031-15944-2_10.

[25] Baode Sun, Jun Wang, Da Shu Precision Forming Technology of Large Superalloy Castings for Aircraft Engines DOI: https://doi.org/10.1007/978-981-33-6220-8

[26] Ren, J., Chen, X., Li, Yx. *et al.* Properties of fiber reinforced plaster molds for investment casting. *China Foundry* **17**, 332–340 (2020). https://doi.org/10.1007/s41230-020-0056-9.

[27] Mardonov, U., Meliboyev, Y., & Shaozimova, U. S. (2023). Effect of Static Magnetic and Pulsated Electromagnetic Fields On the Dynamic and Kinematic Viscosity of Metal Cutting Fluids. International Journal of Integrated Engineering, 15(1), pp: 203-212. doi: https://doi.org/10.30880/ijie.2023.15.01.018

[28] Lu, Y., Liu, X., Li, Y. *et al.* Effect of Ball Milling Time on Strengths of Hybrid Fiber-reinforced Plaster Molds for Investment Casting. *Inter Metalcast* **15**, 864–873 (2021). https://doi.org/10.1007/s40962-020-00522-2.

[29] Lynch, P., Hasbrouck, C.R., Wilck, J., Kay, M. and Manogharan, G. (2020), "Challenges and opportunities to integrate the oldest and newest manufacturing processes: metal casting and additive manufacturing", Rapid Prototyping Journal, Vol. 26 No. 6, pp. 1145-1154. https://doi.org/10.1108/RPJ-10-2019-0277.