ABSTRACT

Ustymenko A.I.. Technology of production of cast iron castings with gradient structure and properties. – Qualification scientific work on the rights of manuscript.

Dissertation for the degree of Doctor of Philosophy in the field 13 Mechanical Engineering, specializing in 136 Metallurgy. – National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”, Kyiv, 2025.

The dissertation is dedicated to the development and research of a technology for producing heat-resistant cast iron castings with a gradient structure and properties, designed to withstand intense cyclic thermomechanical loads. Various technological methods have been developed to achieve a gradient change in structure and properties by altering the morphology of graphite inclusions in castings made from heat-resistant cast irons. This study is relevant for improving the operational properties of equipment used in the glass packaging industry, particularly the molding set, which is exposed to high thermal stress. Therefore, the practical value of this research serves as the foundation for the study and practical application of the developed set of technological methods.

The content of the work consists of four chapters in which the main results of the dissertation are presented and substantiated.

The introduction describes the relevance of the dissertation research, sets the goal and objectives, and formulates the scientific novelty and practical value.

The first section highlights global environmental issues related to the destructive impact of plastic packaging materials on the environment and current trends in replacing them with alternative materials of natural origin, such as glass. Specific problems of global glass packaging manufacturers and trends in the industry as a whole are described. The problems of manufacturers of equipment, namely moulding sets (glass moulds), for its production are revealed. Based on the literature review, the features of the glass packaging production process that constitute the basic requirements for the operational properties of molds are presented. The common materials used by mold manufacturers worldwide are analyzed, and the competitiveness of domestic production is assessed. Modern methods for

enhancing the performance properties of materials are discussed, which enable the evaluation of the characteristics and effectiveness of technological methods for future use in producing castings from heat-resistant cast irons. Consequently, the study formulates the aim and objectives.

The second section describes the starting materials and technological process of smelting heat-resistant cast irons, materials for out-of-furnace treatment of cast irons, and the specifics of its implementation. Technological variants of castings production, methods for studying phase transformations and heat resistance of materials, microstructure, mechanical properties, and thermal conductivity of cast irons are presented.

Chapter 3 describes the studies conducted to select the chemical composition of heat-resistant siliceous cast irons 310SM and 350SMHAN based on the analysis of the influence of chemical elements on the formation of heat resistance properties of materials. According to the results of the analysis, the main elements were determined as follows: % wt: C = 3,0-3,2; Si = 3,1-3,5 for 310SM cast iron; C = 3,0-3,6; Si = 1,8-2,6 for 350SMHAN cast iron. Si, Mo, Cr, Al, Ni were selected as the main alloying elements.

The temperatures of the onset of phase transformations in the experimental cast irons 310SM and 350SMHAN were determined by differential thermal analysis. The results obtained were compared with the characteristics of homogeneous samples of cast iron from a mould set for the manufacture of glass containers. For comparison, the mould (next – the original sample) was used, which, according to visual inspection, had no critical defects and was rejected due to local glass ingress into the ventilation ducts during the process setup. It was found that the temperature of the onset of phase transformation of the experimental cast irons 310SM and 350SMKhan exceeded the temperature of the onset of phase transformation of the cast iron sample from the original sample by 31,9 °C and 17,7 °C, respectively.

The heat resistance of 310SM and 350SMHAN cast irons at a temperature of 1000±20 °C, specifically scale resistance, growth resistance, and heat resistance, was determined by comparing them with the cast iron of the spent glass mold. It was found that after 50 hours of holding, the change in the specific gravity of 310SM and 350SMHAN cast irons is smaller compared to the indicators of the original sample. In percentage terms, the scale resistance of 310SM and 350SMHAN cast irons is 4 % and 2 % better than the scale resistance of the original sample.

According to the results of the growth resistance study, it was demonstrated that the growth of 310SM and 350SMHAN cast iron samples increases linearly with an increase in the number of heating-cooling cycles (25±3 °C↔1000±20 °C). Accordingly, after 60 cycles of growth resistance tests, it was determined that the changes in the geometric dimensions of 310SM cast iron are relatively the same as in the original sample, and for 350SMHAN cast iron they are half as much. In terms of heat resistance, after 60 heating-cooling cycles, 310SM and 350SMHAN cast irons are at the level of the original sample.

Chapter 4 presents the results of applying technological options for the manufacture of castings with gradient changes in structural components along their cross-section from 310SM and 350SMHAN cast irons. Experimentally conducted studies were reflected in the results of metallographic studies, determining mechanical and thermal properties, which confirm the presence of a gradient structure along the cross section of the castings.

The first technological option for manufacturing casting from 310SM and 350SMHAN cast is to surface treat the melt in the casting mould with a silicon-barium inoculant of SB5 grade with fractions of 0,315 mm, 0,4 mm, and 0,63 mm. The results of a metallographic study of the castings' cross-section showed that the shape of the graphite inclusions is lamellar and the distribution of inclusions is uniform. The average size of graphite inclusions for the 310SM alloy varies from 290 μm to 700 μm in cross-section, while for the 350SMHAN alloy, the size of graphite inclusions is approximately 1,5 times smaller than for 310SM, depending on the zone. For cast iron 310SM, a ferrite-pearlite matrix is present in the cross-section of all samples. The microhardness of the ferrite component ranges from 180 HV to 120 HV, and the pearlite component ranges from 347 HV to 230 HV. The 350SMHAN samples have a pearlite-ferrite metal matrix with a small ferrite content in the form of rims around graphite inclusions. The microhardness of the dominant pearlite is in the range of 365 HV to 300 HV in the cross-section of all samples.

The second technological variant of casting production involves surface treatment of 310SM and 350SMHAN melt with SB5 silicobarium inoculant with a fraction of 0.315 mm in combination with the use of 10 mm, 20 mm and 30 mm thick chillers in the lower cavity of the casting mould. The technological variant produced a lamellar shape of graphite inclusions with a change in their distribution from finely branched to uniform. It was found that the size of graphite inclusions in castings from 310SM and 350SMHAN cast irons decreased by about 2,5 times compared to the previous surface treatment, from 80 μm to 475 μm. The metallographic study of castings produced according to this variant revealed that 310SM castings are characterized by a ferrite-pearlite matrix, with the microhardness of the ferrite component varying from 218 HV to 162 HV, and the pearlite component from 350 HV to 253 HV. The 350SMHAN samples are characterized by a pearlite-ferrite metal matrix with a low ferrite content, the microhardness of the dominant pearlite ranging from 337 HV to 260 HV in the cross-section of all samples.

To obtain a ferrite metal matrix, a technological variant was used, which involves ladle treatment of 310SM and 350SMHAN cast irons with an SB5 inoculant and pouring the melt onto chillers with thicknesses of 10 mm, 20 mm, and 30 mm. It has been established that this option allows for a gradient change in the cross-section of lamellar graphite in both alloys. This change involves transitioning from finely interdendritic to rosette and then to uniform lamellar graphite distribution. It has been determined that the castings of this variant are characterized by a decrease in the size of graphite inclusions depending on the studied zone compared to the previous technological variants. Specifically, for castings made from 310SM cast iron, the size of graphite inclusions varies from 84 μm to 357 μm, and for 350SMHAN, it ranges from 65 μm to 227 μm. It has been established that for 310SM cast iron castings, there is complete ferritization of the metal matrix, with microhardness values ranging from 184 HV to 126 HV in the zonal section. Meanwhile, samples from 350SMHAN cast iron exhibit a pearlite metal matrix with carbide phases. The microhardness of pearlite varies zonally from 380 HV to 296 HV in the cross-section of all samples.

To achieve a gradient morphology of structural components, the combined processing of 310SM and 350SMHAN cast irons was conducted. This involved ladle treatment of the melt with SB5 inoculant and in-mold modification in the reaction chamber with VL63(M) modifier, followed by melt casting on 10 mm, 20 mm, and 30 mm thick chillers.

This technological variant ensures that all 350SMHAN castings have a lamellar graphite distribution ranging from finely branched interdendritic to rosette and uniform distribution, which is similar to the previous variant. The dispersion of graphite inclusions increased by up to 1,5 times compared to ladle treatment alone. For 310SM cast iron castings produced using 10 mm and 20 mm thick chillers, the distribution of changes in the morphology of graphite inclusions is similar to that of 350SMHAN.

The results of the study revealed that a specific gradient change in graphite inclusions along the cross-section is present in a casting made of 310SM cast iron, which was produced using a 30 mm chiller. Studies of the casting show that the surface in contact with the chiller contains a layer of spheroidal graphite inclusions with a diameter of 2 μm to 17 μm, and the degree of spheroidization ranges from 70 % to 80 %. The thickness of the cast iron layer with spheroidal graphite inclusions is about 6 mm. It has been determined that spheroidal graphite is replaced by vermicular graphite, with a thickness of about 15 mm. After that, there is a transition to lamellar graphite with inclusion sizes up to 245 μm. According to the results of studies on 310SM alloy castings, it was determined that they are characterized by a ferrite metal matrix, while 350SMHAN castings are characterized by the formation of both ferrite and pearlite components. The microhardness of the ferrite component in castings from both cast irons showed high values at 210 HV, which decrease along the cross-section of the casting to 145 HV. The microhardness of the pearlite component of the matrix of castings from 350SMHAN cast iron varies along the cross-section of the castings from 340 HV to 225 HV.

After studying the thermal conductivity of castings produced by ladle treatment of 310SM and 350SMHAN cast irons with SB5 inoculant, using melt casting on a 30 mm thick chiller and combined treatment, which involves ladle treatment with SB5 inoculant and in-mold modification in the reaction chamber with the VL63(M) modifier on a 30 mm thick chiller casting, it was observed that a gradient change in structural components occurred not only in terms of changes in the morphology of the structure but also in terms of thermal conductivity. The study revealed that the thermal conductivity coefficients of 310SM cast iron samples are up to 26 % higher than those of 350SMHAN cast iron and original sample cast iron.

It has been determined that the most promising technological option is the use of combined processing of 310SM cast iron. This process involves ladle treatment of the melt with the SB5 inoculant and in-mold modification in the reaction chamber of the casting system with the VL63(M) modifier. The castings are poured on a 30 mm thick chiller, which ensures the production of castings with a gradient in the morphology of structural components along their cross-section. This gradient ranges from a layer of cast iron with spheroidal graphite to a layer with lamellar graphite through an intermediate layer of cast iron with a vermicular graphite form. This process results in a change in both mechanical and thermal properties along the cross-section of the castings. Castings with a gradient structure and properties can be used to manufacture parts with increased durability under cyclic thermal and mechanical loads. The technological option for manufacturing castings by combined processing should be selected based on the requirements for a particular product.

Key words: ecology, structure, solubility, microhardness, spheroidal graphite, moulding materials, iron oxides, phase analysis, high-strength cast iron, modification, crystallisation, surface condition, mould, thermal conductivity, casting