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Innovation technology for the production of massive slag ladles at the Krakodlew S.A. Foundry. Presentation of design works on research and development

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Abstract

This article is a description of the progress of research and development in the area of massive large-scale castings - slag ladles implemented in cooperation with the Faculty of Foundry Engineering of UST in Krakow. Slag ladles are the one of the major castings that has been developed by the Krakodlew (massive castings foundry) for many years. Quality requirements are constantly increasing in relation to the slag ladles. Slag ladles are an integral tool in the logistics of enterprises in the metallurgical industry in the process of well-organized slag management and other by-products and input materials. The need to increase the volume of slag ladles is still growing. Metallurgical production is expected to be achieved in Poland by 2022 at the level of 9.4 million Mg/year for the baseline scenario - 2016 - 9 million Mg/year. This article describes the research work carried out to date in the field of technology for the production of massive slag ladles of ductile cast iron and cast steel.

Keywords: Slag ladle, Ductile cast iron, Cast steel, Large castings, Massive castings

1. Introduction

The technological challenge posed by the use of slag ladles is the generation of structural defects in thick-walled castings. Massive slag ladles [1] produced according to the specific needs of customers have different shape and size. On the market [2,3,4], there are mainly ladles made of grey or ductile cast iron as well as carbon and low alloy cast steel. Cast steel ladles have high strength, impact strength and low tendency to crack. The main reason of their wear are cracks which are occurred during filling operation, and high- temperature based deformation.

A controlled combination of the share of perlite and ferrite [5,6] in the metal matrix in the required range of wall thicknesses of massive slag ladles is necessary. The factor affecting the thermal fatigue resistance of ductile cast iron is the proportion of spheroidal graphite, their number and shape, which requires the creation of a controlled spheroidization procedure and a graphitizing modification procedure, which will increase the number of ball graft embryo pads. The purpose of reconstruction in industrial conditions is predictability in terms of mass repeatability, uniform structure and surface.

2. Work Methodology and Materials for Research

The research methodology describes the research carried out in industrial conditions (laboratory industrial experiment) for cast steel and cast iron.

Tests were carried out in the area of cast steel issues and the conditions for melting low-carbon cast steel intended for the casting of slag ladles with capacities above 2 m^3. It was made to conduct laboratory (induction furnace) and industrial melts in an electric arc furnace (30 Mg capacity). Selection analysis of charge materials (including deoxidizers and modifiers) was performed, and the order and place of introducing V and Nb micro-additives, carbides and nitrides forming elements into the metal bath to determine the fine-grained microstructure of the casting. Testing melts showed a best grain refinement effect after introduction FeV modifier. In large-scale laboratory melts, the oxidation process was carried out using iron ore. As deoxidation agent a mixture of aluminium and SiCa30 was used.. Due to the fact that the walls and upper part of the ladle are exposed to frictional forces, Cr, Mo and Ni were added with maximum content 0.3, 0.15 and 0.3%. An experimental cast was made in small-scale laboratory conditions for a wall thickness of 90 mm (equivalent to the wall thickness of the slag ladle).

The spheroidizing and graphitizing modification procedure was performed in a slim ladle with a capacity of 40 Mg using a flexible PE duct with a diameter of ϕ 16. Several chemical compositions were selected (for wall thickness of castings in the range of 100-250 mm). One of the proposals is presented in Table 1. Test castings were made and analysis of the ductile cast iron microstructures obtained in the ladle cast to the strength samples No. 1, 2 and 3 (bottom, middle and top) was carried out.

As part of the research on moulding sand technology, tests were carried out using moulding materials - furan resin binder, matrix - a mixture of regenerate and fresh sand. Moulding and assembly took place within 16 hours.

Table 1.
Proposal for the chemical composition of ductile cast iron (mass%)

Mark/ Elements	C	Si	Mn	P max	S max	Cu
A (GJS-400-18)	3.7	1.9	0.3-0.4	0.03	0.01	1.0

2.1. Simulations of Foundry Process and Defects

As part of the research, simulations using ProCast and MAGMA programs were also carried out. The computer simulation was performed using the finite element method (FEM). The simulations took into account the type of moulding sand used for the mould (moulding sand made of quartz sand cured with furan resin). In the beginning, the location and size of heating nodes in the slag ladle castings were analysed, as well as the estimation of solidification time and power demand for individual nodes. On this basis, the appropriate location, the minimum necessary volume of the headings supply part and the required operating time was selected. Making a casting with high properties requires designing such a system of supplying metal to the mould cavity and feeding the casting during solidification and cooling to obtain a casting free of shrinkage defects. These defects occur mainly in heat distribution canters, where the walls are connected. Elimination of shrinkage defects during solidification requires compensation of metal loss (due to shrinkage) by providing an additional portion of liquid metal, e.g. by using a sprue in the right place. Figure 4 and Figure 5 below show selected frames from the simulation to illustrate the formation and distribution of porosity (and their share) at critical locations of slag ladle castings of varying capacities.

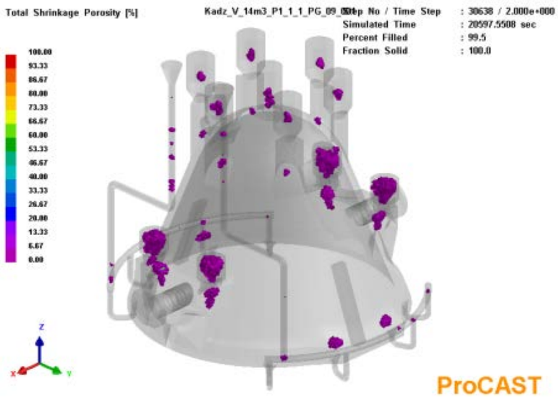


Fig. 1. Simulations for a steel ladle made using the ProCast program with examples of porosity distribution in the casting

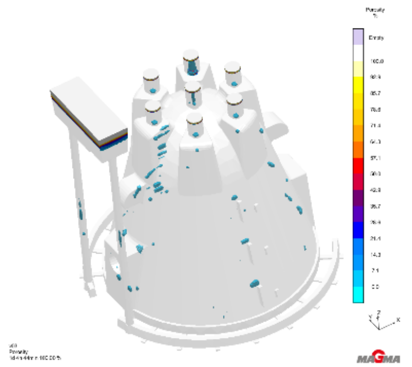
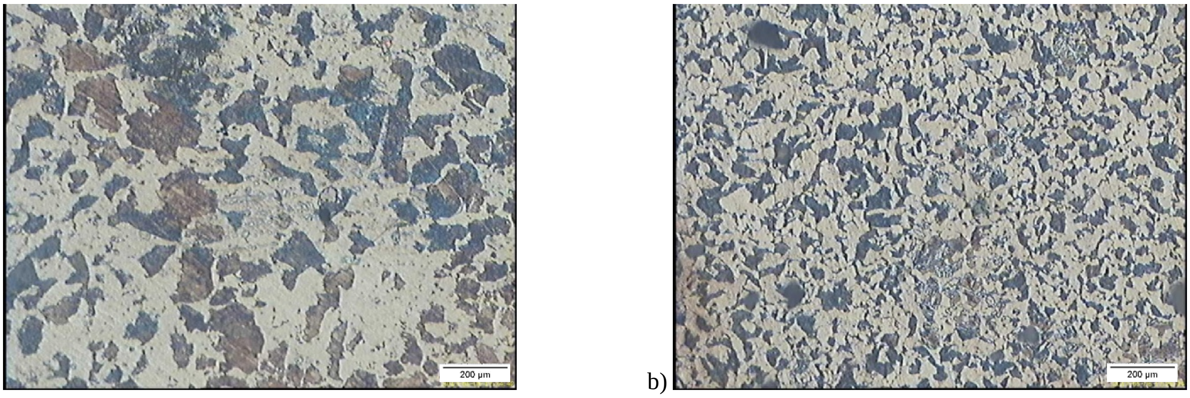


Fig. 2. Simulations for a steel ladle made using the MAGMA program with examples of porosity distribution in the casting

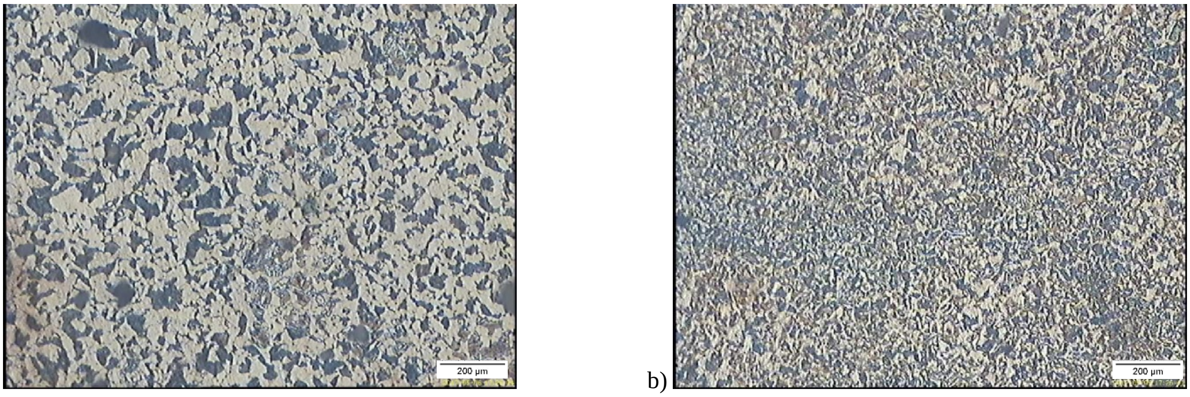
2.2. Cast Steel Research

In the area of cast steel research issues, the microstructure of a new cast steel grade has been investigated. The exemplary microstructure obtained using light microscope is presented in Fig. 1 and Fig. 2.



a) b)

Fig. 3. The microstructure of cast steel without V in the initial state a) and after normalization, b) marker 200 µm



a) b)

Fig. 4. The microstructure of cast steel with a micro-additive of 0.1% V: a) in the initial state, b) after normalization; marker 200 µm

In the cast steel after the introduction of 0.07 - 0.1% V, an improvement grain refinement in as-cast and after normalization treatment is observed. In addition the dendritic structure was partially eliminated and the machining conditions were improved. The results of oxygen and nitrogen measurements content in randomly selected melts before and after the argon stirring of liquid cast steel are presented in Table 2 and Table 3.

Table 2.
Oxygen content in the metal bath (average of three measurements)

Melting number	in the furnace (ppm)	before argon stirring (ppm)	after argon stirring (ppm)
1	140	117	83
2	156	103	85
3	158	97	74

Table 3.
Nitrogen content in the metal bath (average of three measurements)

melting number	in the furnace (ppm)	before argon stirring (ppm)	after argon stirring (ppm)
1	123	122	113
2	105	99	88
3	120	111	123

The obtained results indicate how unstable the process of melting of steel for castings and the argon stirring process in industrial conditions can be. Therefore, it is important to train people directly responsible for the technology implementation phase in the field of proper secondary metallurgy processing of liquid cast steel. It is also possible to modify non-metallic inclusions in liquid steel under industrial conditions of Krakodlew S.A. The solution is to use a 6 strand cored wire feeder (for cast iron) using a powdered, modifying $CaO-SiO_2-Al$ based mixture in a steel flexible tube. The tube should be filled with a core from PE Flexible Conductor device for spheroidization and iron modification. Such modification of inclusions in the case of liquid cast steel must, however, be preceded by previous sludge deoxidation of the liquid metal during tapping into the ladle with possible modification of the liquid metal by introducing iron titanium.

Table 4 shows how the introduction of the complex CaSiAl modifier affected the mechanical properties of cast steel (rendered in laboratory conditions), the designation D (unalloyed) and F (low alloyed cast steel). However, one must take into account that high values of UTS and YP will be accompanied by reduced plastic properties represented by El.

Table 4.
The results of the mechanical tests of the test cast steel subjected to additional modification

Designation	UTS [MPa]	YS [MPa]	El. [%]
Ac. to norm	min. 480	min.260	min.25
D_01	803.3	486.7	16.3
D_31	717.2	426.7	17.7
F_01	879.1	524.4	16.2
F_31	895.3	491.5	15.1

2.3. Ductile Cast Iron Research

In the area of cast iron research issues, it can be stated that the correct shape of the type VI regular graphite beads separation was obtained at a level of 85%, and irregular type V graphite (evaluation of graphite particles in cast iron according to ISO 945). In the microstructure, a small number of nodules per unit area (mm^2) of 31 grains is observed, but experience shows that the reason for this is the low cooling speed of the massive casting (in the first case - the first casting microstructure of the casting weighing 29.15 tons (Mg) obtained a number of balls at 55 / mm^2). There is a low undercooling ΔT and hence a low graphite seed count, despite the graphite modifying procedure. The ferritic microstructure of ductile cast iron was obtained, and the number of graphite ball precipitations and the almost ferritic metal matrix is suitable for the values of the parameters of mechanical properties. All three tested samples had sufficient required values of mechanical properties, and even this ductile cast iron can be classified as castings with a wall thickness in the range of 30 - 60 mm, because three adherence samples obtained the following property values (values rounded to one): minimal tensile strength URS = 349 ÷ 357 MPa, conventional yield strength YS = 235 ÷ 241 MPa and elongation El = 24 ÷ 25%.

Moulding sand and regenerate met the assumed requirements. The mass life after leaving the mixing chamber of the aggregate for fresh sand was approx. 30 min., for pure, regenerate approx. 10 min. longer. It was assumed that due to the change in resin, the viability of the mass decreased. In order to extend the setting time, further tests of the moulding sand composition will be carried out. During the summer, the mass is made of binder 1.0%, hardener 40%. In summary, it can be concluded that the foundry mass results are satisfactory. The mass strength in various sand dosing configurations after 240 min. remained above FS > 90N / cm^2. The acidity reaction is approx. 7 pH. It can be seen that the type of matrix used significantly affects the mass parameters, which can be seen from the results obtained. The mass showed no tendency to slag or abrasion. It was significantly soaked in binder, which was reflected in its weaker fluidity. It follows that the ratio of resin to the sand matrix used may be too high, which may have a negative effect on the quality of the ladle casting. The result of this can be the gas gassing or the formation of non-metallic inclusions such as slag as a result of the reaction of the mould with liquid metal entering the mould cavity. After 1440 min., the moulding mass obtained quite high strength properties reaching approx. 240 N / cm^2. It was considered whether they occurred as a result of the high density of the mass, or as a result of the number of components contained to make the mass. It was found that due to the increased viscosity of the moulding sand, the main factor was too much binder in the mass equal to 1.1%. The inspection of the casting did not show such a defect as slag. The cast had a healthy surface. Certainly, this could be evidence of a properly selected infusion system and proper venting of the mould by puncturing. Defects arose only on the vault of the ladle in the upper part. They arose as a result of slag precipitation during pouring liquid metal into the mould or pouring the mould into an empty tank.

3. Conclusions

3.1. Cast Steel Research

As part of secondary metallurgy processes, it is important to deoxidize, introduce complex modifiers (e.g. CaSiAl fed in the PE flexible hose) or carry out argon treatment in the ladle during melting of the tested cast steel. Table 4 shows how the introduction of the complex CaSiAl modifier affected the mechanical properties of cast steel (rendered in laboratory conditions), the designation D (unalloyed) and F (low alloyed cast steel). However, one must take into account that high values of UTS and YP will be accompanied by reduced plastic properties represented by El..

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The results of the mechanical tests of the test cast steel subjected to additional modification

Designation	UTS [MPa]	YS [MPa]	El. [%]
Ac. to norm	min. 480	min.260	min.25
D_01	803.3	486.7	16.3
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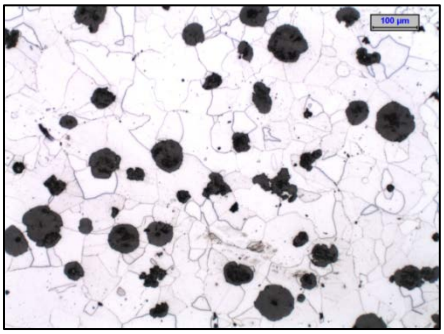
F_01	879.1	524.4	16.2
F_31	895.3	491.5	15.1

The properties of cast steel castings are also affected, though to a lesser extent, by the wall thickness of the casting. The tests were carried out on walls 15, 30, 50 and 80 mm thick, such as occur in castings of slag ladles.

3.2. Ductile Cast Iron Research

The microstructure of cast iron from the ingot poured into the cast iron ladle is shown in Figure 7, and the results of strength tests are given in Table 5.

a) 

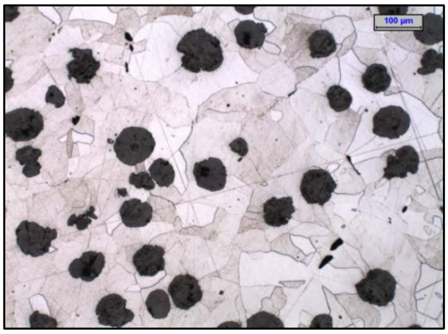
b) 

Fig. 5. The microstructure of the strength ingot adhered to the surface of the slag ladle: a) slag ladle with a capacity of 3.6 m^3, b) slag ladle with a capacity of 11 m^3

Table 5.
The results of mechanical tests of ductile cast iron in the samples of the subject cinder ladles

Designation	Slag ladle ca.	UTS [MPa]	YS [MPa]	El. [%]	Place of excision
ODST40/2S	V=3,6 m^3	410	390	21.5	bottom
		401	275	22	top
		412	298	18	center
67D/2S	V=11 m^3	415	265	18.5	bottom
		400	280	22.2	top
		390	254	19.5	bottom

All tested samples had sufficient required values of mechanical properties, and ductile cast iron can be classified as castings with a wall thickness in the range of 30 - 60 mm, because in three samples added the following property values (values rounded to one):

a) slag ladle with a capacity of 3.6 m^3

min. tensile strength UTS= 401-412 MPa, conventional yield strength YS = 275-390 MPa and elongation El.= 18-22 %,

b) slag ladle with a capacity of 11 m^3

min. tensile strength UTS= 390-415 MPa, conventional yield strength YS = 254-280 MPa and elongation El.= 20-22 %.

The research works carried out so far on the SLAG LADLE TECH technology being developed allow confirming the preliminary research assumptions and it will be possible to give properties to foundry alloys from which massive slag ladle castings are to be made. The implementation of research works is co-financed from the funds of the Intelligent Development Operational Program 2014-2020 under the project: "Development of innovative technology for the production of massive slag ladles with increased operation parameters (SLAG LADLE TECH)".

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