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Technological Aspects of Low-Alloyed Cast Steel Massive Casting Manufacturing

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Abstract

In the paper authors have undertaken the attempt of explaining the causes of cracks net occurrence on a massive 3-ton cast steel casting with complex geometry. Material used for casting manufacturing was the low-alloyed cast steel with increased wear resistance modified with vanadium and titanium. The studies included the primary and secondary crystallization analysis with use of TDA and the qualitative and quantitative analysis of non-metallic inclusions.

Keywords: Low-alloyed cast steel, Crystallization, Modification, Non-metallic inclusions, TDA method

1. Introduction

Low-alloyed cast steels with increased wear resistance belong to the group of materials often used for heavy-duty machinery elements, such as: mining combines, loaders, mills etc [1-5]. The representative material of the entire group mentioned above, is the L20HGSNM cast steel according to PN-88/H-83160 standard [6], characterised by the highest mechanical properties (Rm > 1300MPa and Re> 1100 MPa) among all cast steel grades included in Polish Standards. In some cases of application such mechanical characteristics are insufficient and need to be improved. This premise initiated the studies undertaken in Department of Foundry of Silesian University of Technology on elaboration of new low-alloyed cast steel with high mechanical and operational properties. Laboratory studies enabled obtainment of cast steel with tensile strength higher than 1450MPa. Encouraging results influenced the decision of massive casting manufacturing, using the elaborated cast steel, in one of the Polish foundries.

In the work selected results were presented, which were registered during the massive casting manufacturing. Analysis of results was aimed on describing the causes of cracking observed on some surfaces of the casting.

2. Cast steel, technology of melting and casting

Analysed low-alloyed cast steel with increased wear resistance, modified with vanadium and titanium was used for massive casting manufacturing with complex geometry with mass of 3 tons.

The alloy was prepared in an electric-arc furnace with basic lining with full process of oxygen refining. Liquid metal was deoxidised with use of Al and Ti according to elastic wire method and modified with ferrovanadium and ferrotitanium. After modification the liquid melt was purified by argon bubbling. The mould was poured with cast steel at temperature of 1640°C with bottom-tap ladle through two tap holes at the same time.

In Table 1 the chemical composition of obtained low-alloyed cast steel (marked with K) was presented.

Table 1.
Chemical composition of (K) low-alloyed cast steel in %wt.

C	Mn	Si	P	S	Cr
0,23	0,85	0,58	0,013	0,006	0,81
Ni	**Mo**	**Al**	**Cu**	**V**	**Ti**
1,13	0,31	0,032	0,09	0,06	0,04

The mould was prepared with use of furan resin. Due to complex geometry and diverse wall thickness of the casting, a large number of risers and feeders was applied. The casting mass together with the entire gating and feeding system was about 8 tons.

After pouring the casting cooled down in the mould about five days. Then it was knocked out and the gating system together with feeders was cut off using the gas burner. The raw casting was machined. After machining the casting was visually inspected; during the inspection the shrinkage cavities and porosity were discovered in regions close to side feeders. These flaws were eliminated with welding techniques according to PN-EN ISO 11970:2009 standard. Next the casting was subjected to penetrant inspection. Extensive net of cracks was revealed in regions of top risers. In regions of casting with no feeders such net of cracks did not occur. Depth of cracks was in range of 5-8mm. In Fig. 1 casting surface with cracks was shown.

Fig. 1. Net of cracks on test casting surface

The region of cracks was removed with use of machining. Crucial regions of the test casting was also subjected to ultrasonic inspection, which did not show any other flaws. After elimination of discovered defects and inspection the test casting was transferred to heat treatment.

Although the shrinkage defects were hard to avoid (and easy to predict) for such geometry of the cast steel casting, the cracks net was a bit of surprise, especially when considered the earlier experiences with similar cast steel grades in the foundry, which did not revealed such cracking tendencies. The aspect of crackin was further explored using different methods.

3. Analysis of primary and secondary crystallization

During the test casting manufacturing the Thermal and Derivative Analysis (TDA) was employed to analyse the crystallization process of the prepared low-alloyed cast steel [8-11]. Testers construction as well as the moulding materials applied enabled diversification of cooling rate for specimen castings. For applied testers two different cooling rate were obtained: for ATD-C tester - 100 K/min and ATD-Is - 50 K/min. Temperature registration during the analysis was conducted with use of TDA stand, shown schematically in Fig. 2.

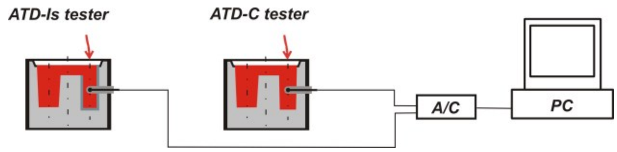
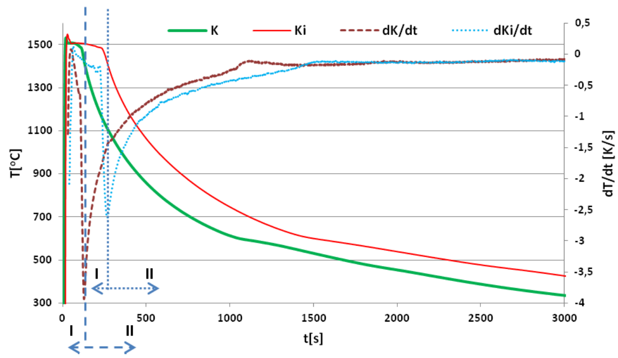


Fig. 2. Scheme of TDA stand

In Fig. 3 the TDA curves in function of time were presented for low-alloyed cast steel, in range of primary and secondary crystallization, for both testers used during the analysis.

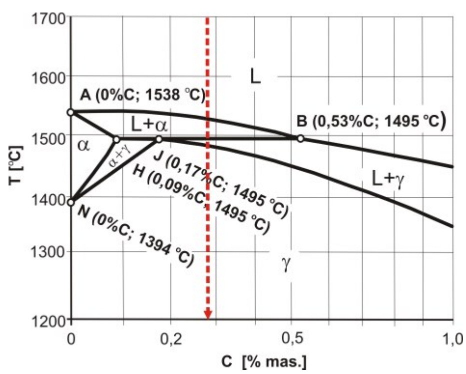


I – primary crystallization II – secondary crystallization

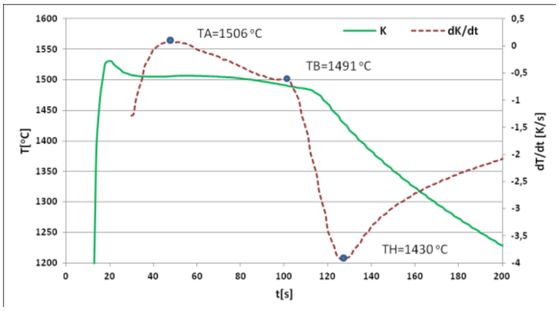
Fig. 3. TDA curves registered with use of ATD-C and ATD-Is testers for low-alloyed cast steel during primary and secondary crystallization

Based on Fe-C binary equilibrium system and TDA curves the path of primary crystallization was established; during the primary crystallization the peritectic transformation takes place (Fig. 4).

a)



primary crystallization path **L → L+α (δ) → L+γ → γ** b)



c)

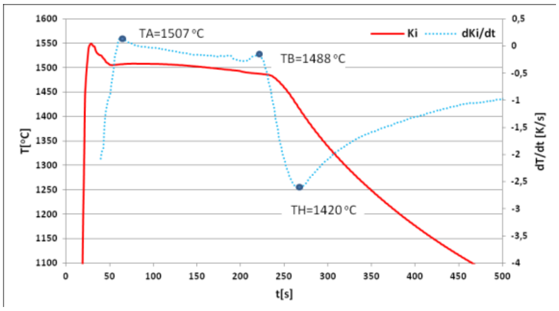
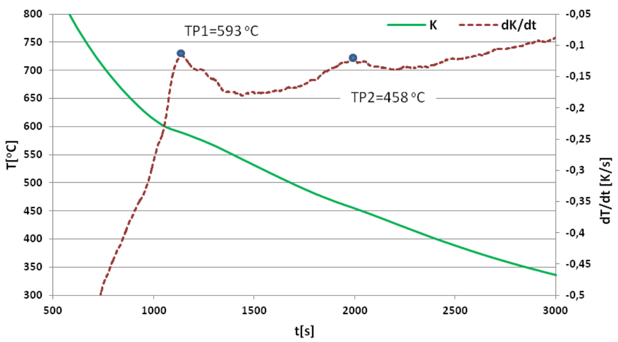


Fig. 4. Analysis of primary crystallization of (K) low-alloyed cast steel (a – path of crystallization in stable conditions, according to Fe-C binary system, b – TDA curves for higher cooling rate of sample casting, c – TDA curves for lower cooling rate of sample casting

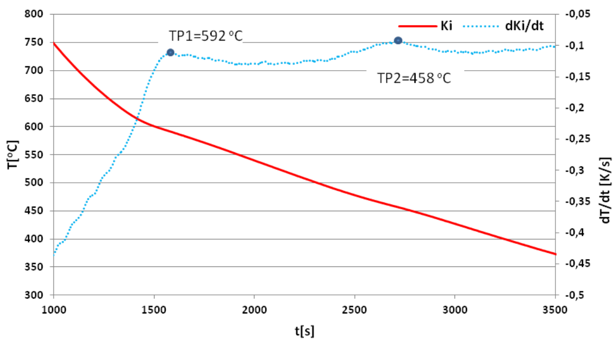
In Fig. 4a the probable path of primary crystallization for analysed cast steel was shown, in fragment of Fe-C binary system. The characteristic temperature points were defined, based on TDA curves registered during the experimental studies (Fig 4b and 4c) at different cooling rates. The crystallization starts in TA, registered in maximum thermal effect of the α (δ) phase crystallization. Next temperature point which is registered is marked as TB and indicates the peritectic transformation temperature. The primary crystallization of studied cast steel ends in temperature TH. Conducted studies showed that changes in cooling rate influenced the characteristic temperature points position.

Phase transformations during the secondary crystallization are also indicated in TDA curves diagrams. In Fig. 5 the considered TDA curves together with as-cast structure were presented. Registered characteristic temperature points indicated that during the crystallization the baintic transformation takes place. The microstructure of low-alloyed cast steel consists of bainite and ferrite (Widmanstatten structure) together with non-metallic inclusions (Fig. 5c and Fig. 5d).

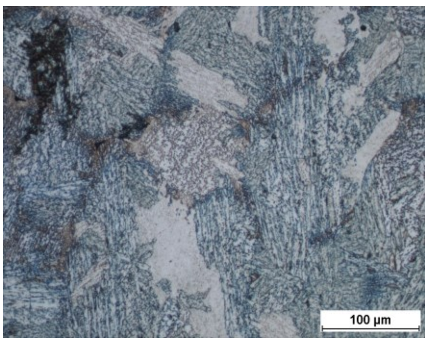
a)



b)



c)



d)

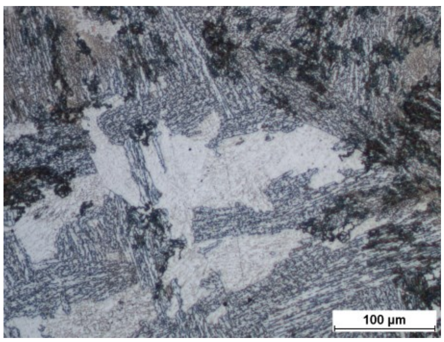


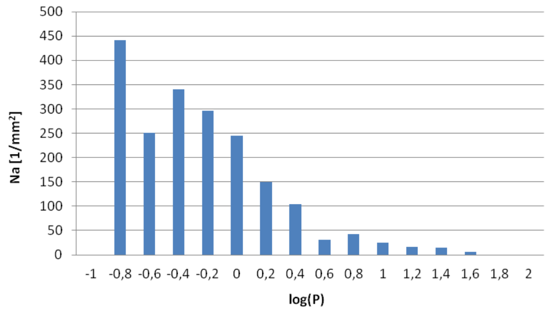
Fig. 5. Analysis of secondary crystallization for (K) low-alloyed cast steel (a –TDA curves at higher cooling rate, b –TDA curves at lower cooling rate, c – as-cast microstructure of sample casting observed for higher cooling rate, d – as-cast microstructure of sample casting observed for lower cooling rate)

4. Analysis of non-metallic inclusions

To describe the stereological parameters on non-metallic inclusions, the metallographic specimens were prepared from TDA sample castings. Quantitative analysis was performed on non-etched specimens and 400x magnification, for ten measuring fields using the NIS ELEMENTS BR 3.10 software. The measuring system consists of two applications; first one (NIS ELEMETS F) is used for image capture and the second one (NIS ELEMETS BR 3.10) is used for image analysis (inclusion counting, area, capacity, shape ratio etc.). In Figs. 6 and 7 histograms of non-metallic inclusions distributions of its quantity and fraction were shown, for sample casting ATD-C (Fig. 6) and ATD-Is (Fig. 7), respectively. For analysed cast steel, at higher cooling rate, the non-metallic inclusions fraction was 0,21% and their quantity for 1mm^2 is 1960. For lower cooling rate the parameters were: 0,24% and 1540, respectively.

a)

b)



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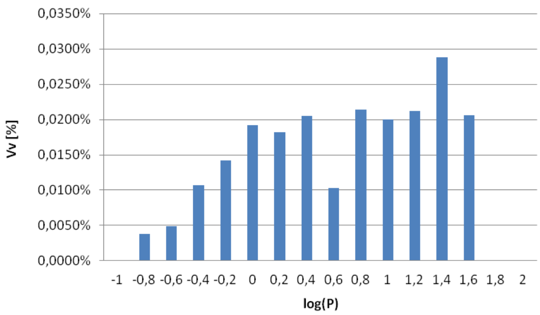
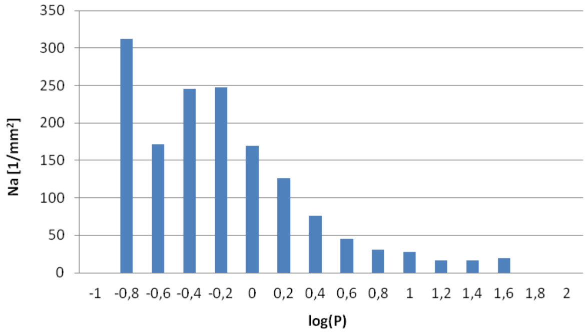


Fig. 6. Non-metallic inclusions in sample casting ATD-C (higher cooling rate); a- example image of inclusions, b-distribution of inclusion size according to size class, c- distribution of volumetric fraction according to size class

a)

b)



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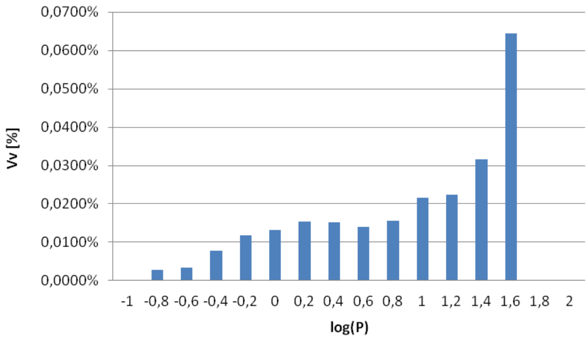


Fig. 7. Non-metallic inclusions in sample casting ATD-Is (lower cooling rate); a- example image of inclusions, b-distribution of inclusion size according to size class, c- distribution of volumetric fraction according to size class

Qualitative analysis of non-metallic inclusions consisted of scanning microscopy of fracture and inclusions identification with use of roentgen microanalysis. In Fig. 8 the fracture of as-cast sample after KCV Charpy impact testing was shown. Specimens was taken from sample casting designated to mechanical testing. On specimens fracture porosity and different inclusions were observed eg. the manganese sulphides and titanium carbides.

a) b) c) d)

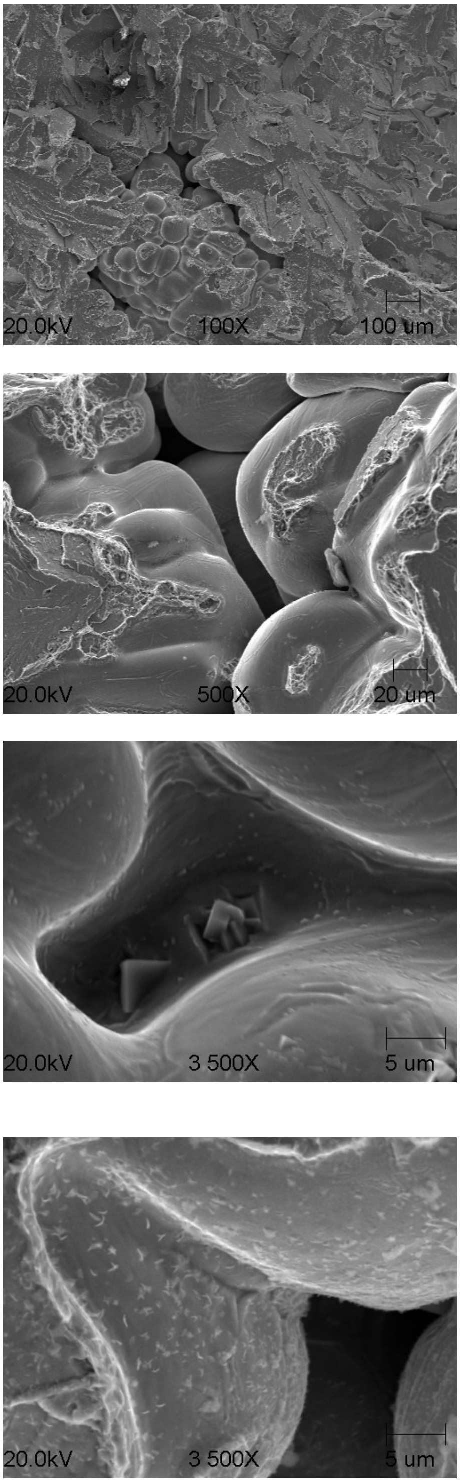


Fig. 8. Specimen fracture for low-alloyed cast steel investigated; (a- microporosity, b- hollow interdendritic spaces, c, d- titanium carbon inclusions on dendrites surface)

a) b) c)

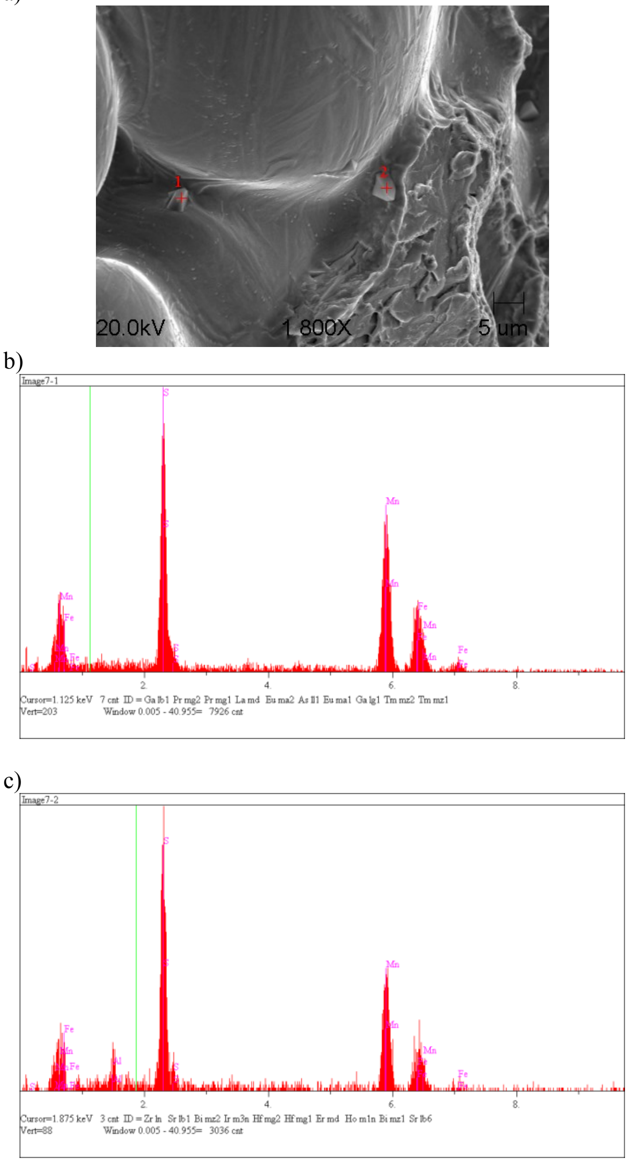
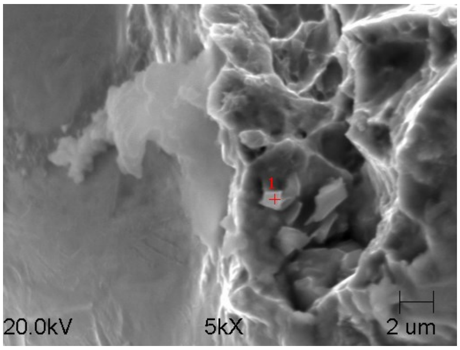


Fig. 9. Sulphide inclusions on low-alloyed cast steel fracture (a – inclusions 1 and 2 in interdendritic spaces, b and c – microanalysis of inclusions chemical composition

a)



b)

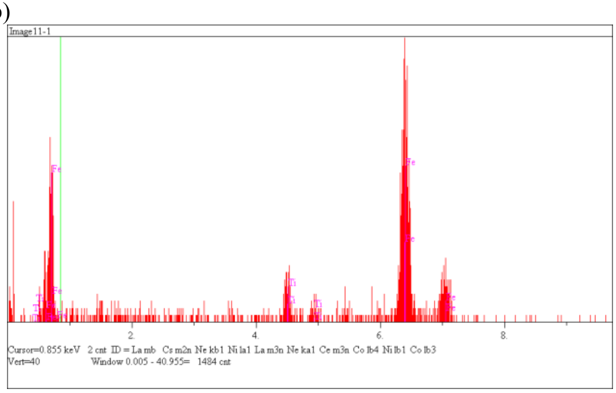


Fig. 10. Probable inclusion of titanium carbide on low-alloyed cast steel fracture (a – inclusion 1, b – microanalysis of the inclusion)

5. Summary

Occurrence of cracks net on upper surface of the test casting, located under risers would indicate that the causes of such state need to be searched for in final stage of the primary crystallization or during the gating and feeding system removal. The foundry stated that, the removal process was performed according to standards applied to L20HGSNM and similar cast steel massive castings and that such flaws did not occur in the past. The size and geometry of applied risers and feeders were verified using the MAGMA software. Sufficient range of feeding system action was in that way theoretically confirmed. Nevertheless, small shrinkage cavities and porosity were indicated in regions near to side feeders, what can indicate, that the designed chemical composition of low-alloyed cast steel with increased wear resistance needs different feeding model to be applied. In case of top risers its size was in agreement with the theory. Thus, the remaining solution of the problem is the low quality of the liquid metal, represented by high quantity of non-metallic inclusions, exceeding 0,2%. During the primary crystallization the inclusions locate themselves at grain boundaries. Different sulphides occur, not necessary manganese sulphides and complex oxides, containing Fe, Mn and Si. In case of studied cast steel some titanium carbides and carbide-nitrides can be treated as impurities, regarding the fact that this element was used as a deoxidant and modifier. All indicated phases can occur in the final stage of the primary crystallization, in regions under the top risers, which solidifies the last. The phases are pushed out by the moving front of solidifying dendrites towards the top risers. Difference in cooling rate of different casting regions causes stress exceeding the material strength at elevated temperature, resulting in deterioration of bounding between structural components and finally in cracking occurrence.

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