

ARCHIVES
of
FOUNDRY ENGINEERING



DOI: 10.2478/afe-2013-0066

ISSN (2299-2944)

Volume 13

Issue 3/2013

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

88 – 91

Fracture Mechanisms in Steel Castings

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Received 24.05.2013; accepted in revised form 29.05.2013

Abstract

The investigations were inspired with the problem of cracking of steel castings during the production process. A single mechanism of decohesion – the intergranular one – occurs in the case of hot cracking, while a variety of structural factors is decisive for hot cracking initiation, depending on chemical composition of the cast steel. The low-carbon and low-alloyed steel castings crack due to the presence of the type II sulphides, the cause of cracking of the high-carbon tool cast steels is the net of secondary cementite and/or ledeburite precipitated along the boundaries of solidified grains. Also the brittle phosphor and carbide eutectics precipitated in the final stage solidification are responsible for cracking of castings made of Hadfield steel. The examination of mechanical properties at 1050°C revealed low or very low strength of high-carbon cast steels.

Keywords: Cast steel, Hot cracking, Solidification, Segregation

1. Introduction

The basic problem which is to be faced by metallurgists and mould designers with regard to the small-batch and piece production is the natural fluctuation of chemical composition or deviations in the production process resulting in the emergence of defects which often disable the functional properties of a product. The problem is even broadened by the multitude of chemical compositions of cast steel and a diversity of phenomena taking place during the solidification and the cooling of a casting. Defects which influence the effectiveness of production and its costs to the greatest degree are cracks, often discovered only in the finished castings and resulting in their final rejection [1, 2]. The simulation programs significantly aid the process of mould designing and make it shorter, they also can take into account the phenomena concurrent to the solidification, they cannot, however, be a substitute for the practical experience of foundry engineer.

The cracking of steel castings occurs both at high temperature (hot cracking, often initiated already in the final stage of solidification) and during the working life of a casting, the latter being strongly influenced by the obtained structure

of a casting. Some of structural components originated during the solidification process and later are inherited by the secondary structures achieved by heat treatment. These components include e.g. the type II sulphides and eutectics, mostly carbide ones, increasing the range of high-temperature brittleness. The crack susceptibility in hypereutectic tool cast steels is additionally increased by the presence of ledeburite and secondary cementite, which are – on the other hand – the desirable components of microstructure achieved by careful selection of chemical composition, for example in wear-resistant cast steel. The secondary cementite distributed selectively in the net-like form along the boundaries of solidification grains cannot be eliminated by the applied heat treatment. The morphology of ledeburite undergoes no change during the heat treatment of castings.

2. Results of investigation and their discussion

The experimental part presents the results of authors' own work, most often related to the prepared expert opinions on castings cracked in the course of production process. As far as the low-alloyed steel castings are concerned, the most frequent cause of cracking is the presence of the type II sulphides distributed along grain boundaries and coexisting shrinkage microporosity. The results presented in Fig. 1 are obtained from the non alloyed steel castings of the following chemical composition [mass %]: 0.17-0.25 C, 1.2-1.6 Mn, 0.20-0.50 Si, 0.04 max S and P, 0.30 max Cr and Ni. Microfractographs shown in Figs. 1b and 1c were taken from the impact test specimen made of the material presented in Fig. 1a.

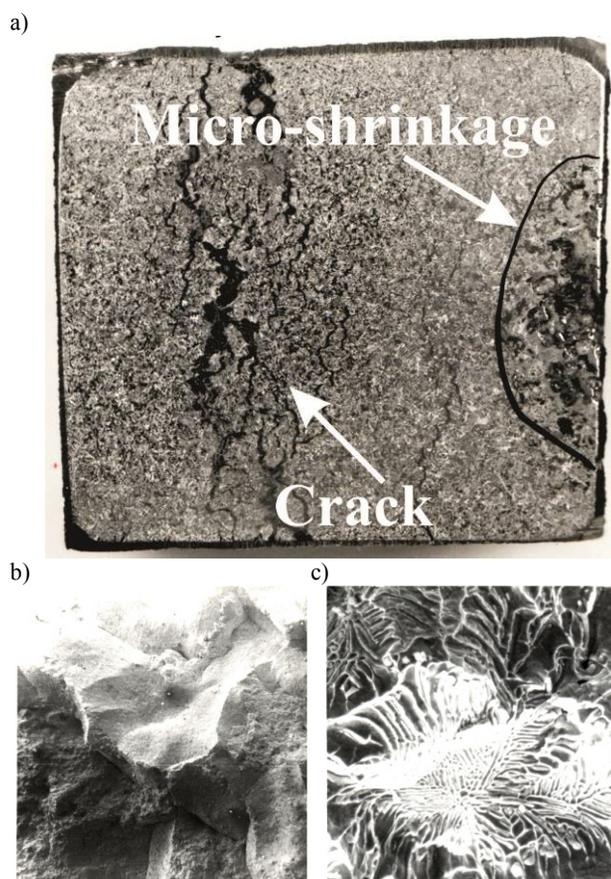


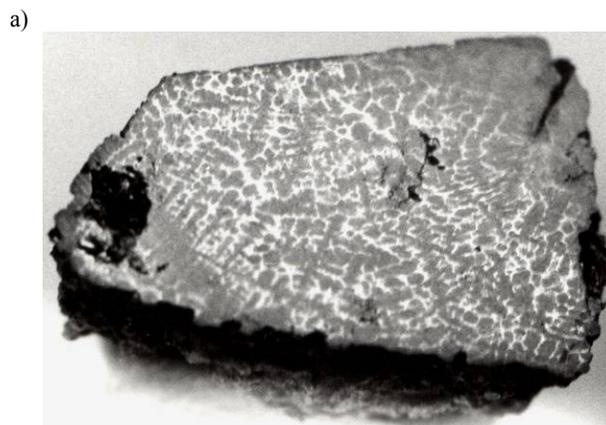
Fig. 1. Non-alloyed cast steel; a) oxidized surface of hot cracks and the shrinkage porosity, magn. 3 \times ; b) the type II sulphides revealed at the surfaces of the intergranular fracture, magn. 250 \times ; c) the type II sulphides, magn. 600 \times

The emergence of the type II sulphides – selectively distributed in cast steel structure – depends on both the quantity of metallic aluminium in the melt and the solidification rate. The high solidification rates promote the generation of the type II sulphides, therefore the content of metallic aluminium (Almet) in

thin-walled castings should exceed 0.04%. This content in massive, slow cooling castings should be limited to the range 0.02-0.04%, because higher aluminium content can result in the precipitation of Fe-AlN eutectics, promoting the occurrence of rock candy fracture, which disqualify castings. Also the increased manganese content in steel is advantageous, because the increased quantity of this element in sulphides rises the temperature of their precipitation from the residual liquid phase, and as a result the quantity of sulphides precipitating along grain boundaries is reduced.

The selective distribution of the type II sulphides is also decisive for the intergranular fracture mechanism in fine-grain cast steel obtained after heat treatment. The lowered plastic properties (impact strength, elongation, necking) of such a material, often lower than the minimum required for acceptance, result from the fact that the deformation regions are confined to the micro-regions close to the solidification grain boundaries with precipitated type II sulphides. The fractures of acceptance test specimens often reveal the secondary transverse cracking along the boundaries of coarse solidification grains.

Cracks in the high-carbon low-alloyed hypereutectic cast steels used e.g. for production of tools for metallurgy industry are most frequently revealed only during the final mechanical working of the heat-treated castings [3-6]. The material for examination comes from the cracked steel mill rolls of several tons weight, made of either L180HMF or L200HNM cast steel. After breaking them down, there were disclosed vast, strongly oxidized fractures indicating cracking at high temperature during the solidification and/or the subsequent cooling of the castings. The sample material taken from the regions adjacent to hot cracks occurring in the L200HNM mill roll revealed the dendritic structure with macro- and micropores pointing out to the too high pouring temperature or the inappropriate feeding (Fig. 2a). Multiple microcracks were revealed while examining microstructures, both in the secondary cementite net of the L180HMF cast steel and in the ledeburite net of L200HNM cast steel, as shown in Fig. 2 b, c. The fractures of samples taken of the regions adjacent to hot cracks were of cleavage character and propagated along the secondary cementite or ledeburitic cementite precipitates. The strongly deformed and cracked cementite plates shown in Fig. 3 are the evidence of high shrinkage stresses occurring in the cooling casting.



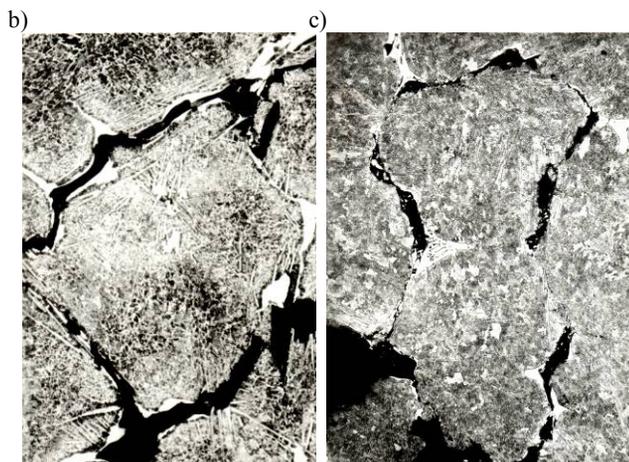


Fig. 2. Shrinkage macro- and micropores in the cracked mill roll of L180HMF cast steel; a) cracks along the boundaries of solidification grains, magn. 5 \times ; b) cracks in the secondary cementite net, magn. 100 \times ; c) cracks in the ledeburite net, magn. 60 \times ; etched with Nital

The structure of low-alloyed hypereutectic mill rolls heat-treated at the temperature below the A_{cm} temperature were pearlitic with precipitated carbides of various morphology and distribution. The strongly deformed and cracked cementite plates shown in Fig. 3 are the evidence of high shrinkage stresses occurring in the cooling casting.

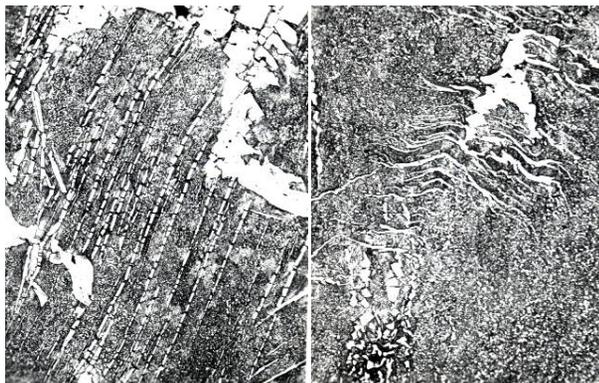


Fig. 3. Deformed and cracked secondary cementite plates in the casting made of L180HMF cast steel, magn. 60 \times , etched with Nital

Table 1.

Results of mechanical properties researches (mean values for three samples)

Cast steels	Test Temp. °C	Rm MPa	Re MPa	A %	Z %
L180HMF	20	781.1	-	-	-
	1050	20.7	-	13.1	28.2
L200HNM	20	420.7	-	-	-
	1050	5.2	-	5.4	3.15

The results of static tensile test performed both at the ambient temperature and at the temperature of 1050°C (at which there occurred austenite accompanied by trace quantities of secondary cementite in the L180HMF cast steel, but the ledeburite net in L200HNM cast steel remained unchanged) gathered in Table 1 indicate that:

- at the ambient temperature both cast steels exhibit brittle fracture mode, without the visible macro-deformation, and the presence of ledeburite decreases the material strength almost by half;
- at the temperature of 1050°C the strength is low or even very low. The austenite present in the L180HMF cast steel exhibit good plasticity, whereas the presence of ledeburite in the L200HNM cast steel makes the material brittle at this temperature as well.

The investigations show that the seemingly small differences in carbon content (1.75% in L180HMF and 1.95% in L200 HNM) significantly influence the susceptibility to hot cracking. The presence of ledeburite considerably broadens the range of high-temperature brittleness, extending it in practice up to the final stage of casting solidification. The lower carbon content narrows this range, and the brittleness begins when the secondary cementite begins to precipitate and to form a net at austenite grain boundaries. The only way to protect the massive castings from cracking is the maximum reduction of internal stresses, which depend on the moulding technology.

The high-manganese Hadfield cast steel is an example of the material exhibiting high susceptibility to hot cracking [7, 8]. A variety of factors can influence the intergranular strength, but the ones of the most significant influence are the additions exhibiting a high susceptibility to segregation, which decrease the temperature of the end of solidification. The high content of carbon, manganese, and silicon in Hadfield steel strongly decreases the already low partition coefficient of phosphorus k , which for the Fe-C alloys is about 0.17. The residual liquid phase enriched in phosphorus and carbon solidifies at grain boundaries in the shape of phosphorus and carbide eutectics, lowering the temperature of the solidification end to about 900°C. Results of investigations presented in Fig. 3 point out that these phases precipitate in the net-like form along grain boundaries and on the dendrites of shrinkage micro-pores which arise during the solidification of the residual liquid phase and become then the hot crack initiators.

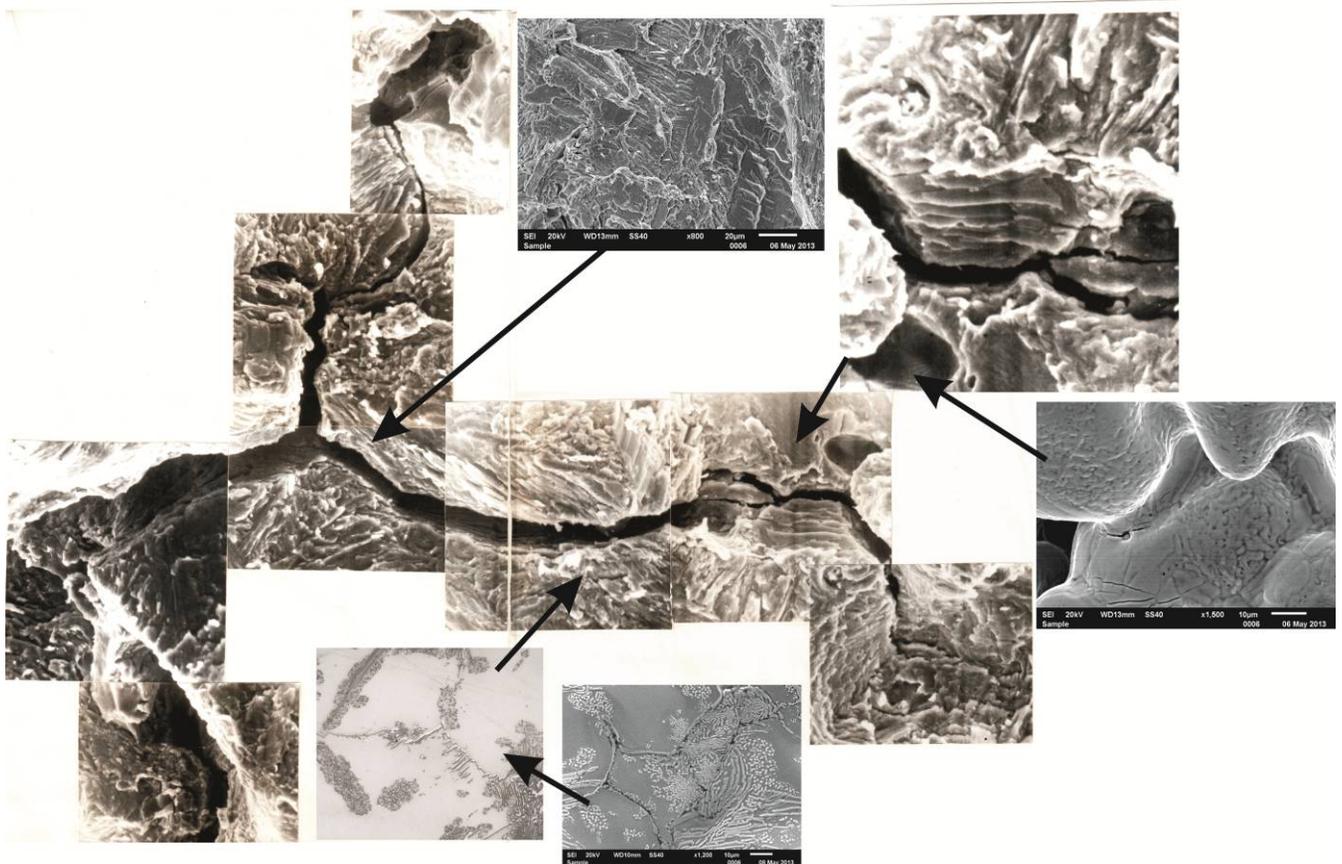


Fig. 4. Hot crack initiated by shrinkage spreading on the boundaries of large grains of solidification and details of eutectics. Scanning microscope

3. Conclusion

The presented results of investigations indicate that – despite the variety of structural factors contributing to the hot cracking of steel castings – there is a single cracking mechanism, the intergranular one. The negative influence of brittle phases is intensified by the microporosity arising in the final stage of solidification. This is related to the precipitation of brittle phases or their mixtures along the boundaries of the solidification grains, which decrease the intergranular strength of the material.

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