ARCHIVES of FOUNDRY ENGINEERING

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

ISSN (1897-3310)
Volume 9
Issue 4/2009

17 – 22

4/4

Cracks in high-manganese cast steel

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Received 30.06.2009; accepted in revised form 07.07.2009

Abstract

The reasons which account for the formation of in service cracks in castings made from Hadfield steel were discussed. To explain the source of existence of the nuclei of brittle fractures, the properties of cast steel were examined within the range of solidification temperatures, remembering that feeding of this material is specially difficult, causing microporosity in hot spots. This creates conditions promoting the formation of microcracks which tend to propagate during service conditions involving high dynamic stresses, and explains why the cracks are mainly characterized by a brittle nature. The reason for crack formation in service are micro-porosities formed during casting solidification.

Keywords: Hadfield cast steel; Hot cracking, Solidification brittleness

1. Introduction

In the past few years, numerous new grades of cast steel have been introduced to combine a high abrasion resistance with good plastic properties. In spite of this, the high-manganese cast steel (Hadfield steel) remains the grade used most often for service in conditions of high dynamic loads. It is therefore widely used in cement plants for lining of mills, for rammers operating in coal crushers, in power generating plants, for railway points, or for track links in heavy excavators. Table 1 gives examples of the mechanical properties of this cast steel [1,2].

Table 1.
Mechanical properties of the high- manganese cast steel.

UTS, MPa	Re, MPa	A5, %	Reduction of Area %
900	300	40	50

It is interesting to note the combination of high values of elongation and impact resistance, ensuring that castings will not suffer the brittle failure in heavy-duty performance. In spite of the fact that some grades of the low- and medium-alloyed cast steel offer much better abrasion resistance, users are generally willing to order castings made from Hadfield steel. Considering the mechanical properties, it is difficult to imagine that a casting made from Hadfield steel could suffer failure in service. However, cases like this do happen, specially in heavy-section elements and result in enormous losses of material and long downtimes. The reason for such failures is usually attributed to insufficient ductility, resulting from an inadequate heat treatment. But in reality the causes of failure are much more complex. It can only be supposed that the phenomenon of crack formation and failure results from propagation of the crack nuclei formed in casting during the process of its manufacture. This article discusses the types of these nuclei and a probable process of their formation.

2. Microcrack formation during casting solidification

The high-manganese cast steel is characterized by a strong tendency towards crack formation within the range of solidification temperatures.

curves near the end of solidification shows that the solidus point falls to about 1270 °C.

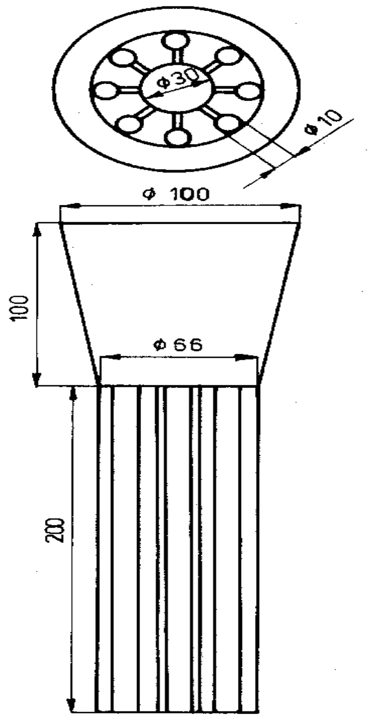

Fig. 1. Test sample for high manganese steel

These cracks are revealed after dressing of the castings, sometimes after heat treatment. To explain the reasons which account for their formation, the authors studied the cast steel behavior at a temperature close to the solidus. The metal was melted in an electric arc furnace from a new charge with complete oxidation. The test bars of a configuration shown in Figure 1 were cast in resin-bonded sand moulds
The configuration was designed in a way such as to ensure en efficient feeding of the test bar, reducing at the same time to minimum the operation of machining.

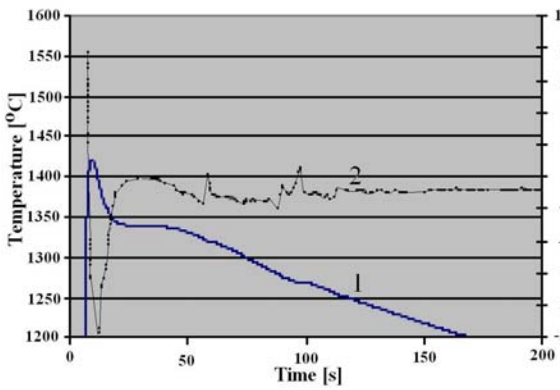

Fig. 2. Cooling Curve of high manganese steel. 1 – temperature, 2- derivative of temperature.

A thermal analysis was carried out monitoring both the temperature and dT/dτ, during the solidification and cooling. The

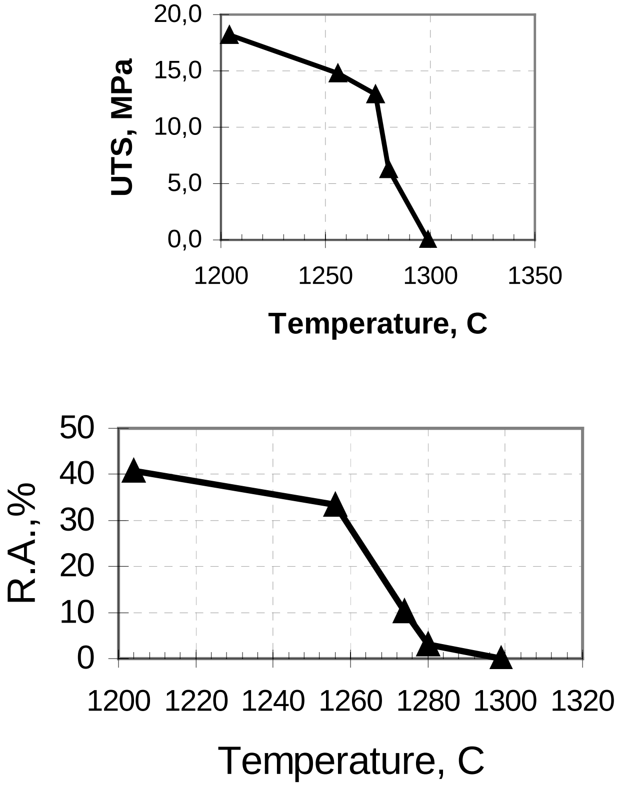

Fig. 3. The reduction of the area (a) and the ultimate tensile strenght (b) of the high manganese steel samples

It is presented in the figure 2.
The mechanical tests were conducted on a computer-operated testing machine with an attachment for high-temperature testing, made by the Faculty of Foundry Engineering, Technical University- VSB in Ostrava. With temperature decreasing below the solidus point, recorded on the cooling curve, a rapid increase in the reduction of area up to 35 – 40 % is observed. The rise in UTS with fall of temperature is nearly linear from the solidus temperature (figure 3b). The metal preserves its high ductility down to about 1160 °C, then the reduction of area drops to below 15% at 1010 °C, which is corresponding to a range of this cast steel heat treatment. One can speak about the appearance of a secondary range of brittleness.
To determine the reasons for the secondary range of brittleness at a temperature below the solidus point, the failed samples were subjected to scanning and metallographic examinations. The results are shown in Figures 4 – 9. The fractographic analysis was made on the selected samples representing low, medium and high reduction of area, obtained during the tensile test at different temperatures.

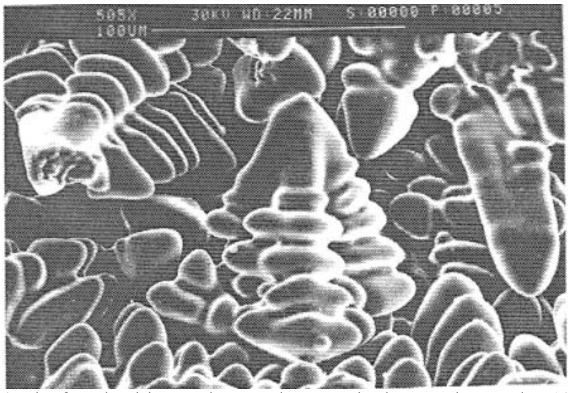

Fig. 4. The free dendrites at the sample center in the sample tested at 1275^{o}C

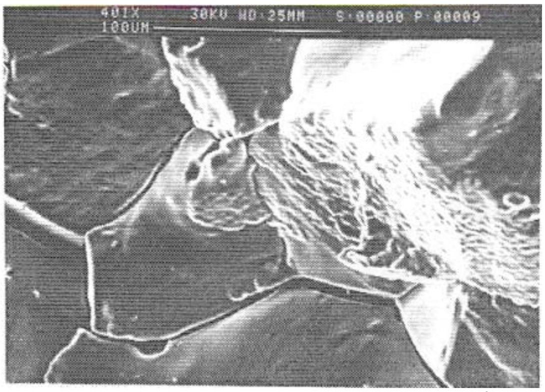

Fig. 5. Intergranular, brittle fracture formed at 1275 ^{o}C

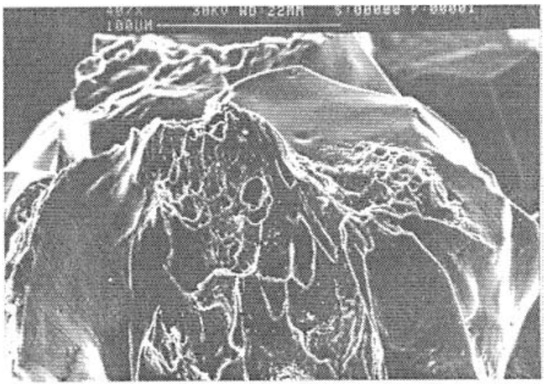

Fig. 6. Plastic deformation in the sample failed at 1230 ^{o}C

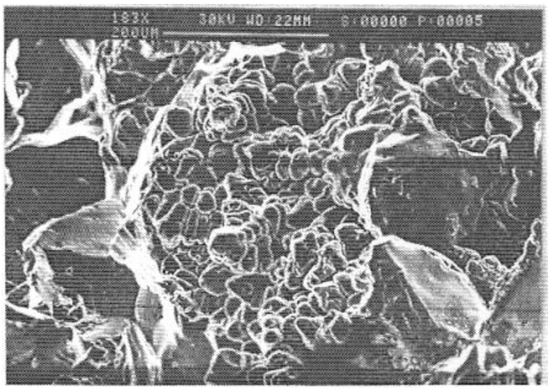

Fig. 7. The axial zone of sample with the porosities

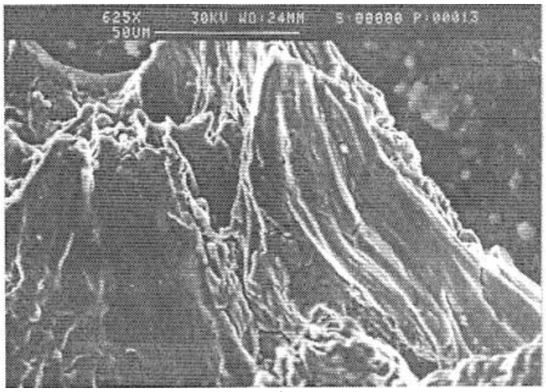

Fig. 8. Sample tested at 1131 ^{o}C. High plastic deformation

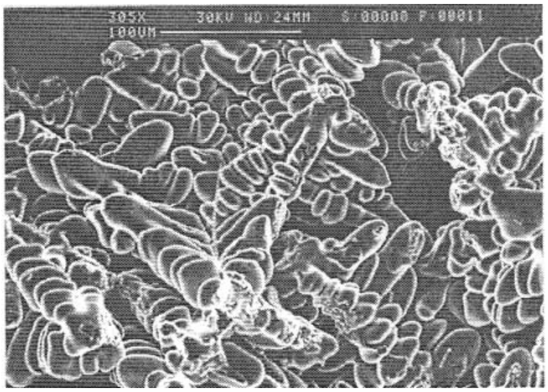

Fig. 9. The free dendrites in axial zone (porosities)

The sample failed at a temperature of 1275^{o}C suffered brittle fracture with a reduction of area equal to 0%. The fracture was of a typically intercrystalline nature (Fig. 4). In the central part of the sample one can see shrinkage porosity defects formed during solidification of the cast test bar. The process of hot cracking proceeds along the smooth grain boundaries. The tensile test at a temperature of 1230^{o}C gives reduction of area equal to 30%. Figure 6 shows the fracture with clearly visible flow lines on the side surface; the fracture is of a partly ductile nature. At this testing temperature, cracks also appear along the grain boundaries (Fig. 7). In central part of the test bar there is a shrinkage porosity which considerably reduces the value of the reduction of area.

At the testing temperature of 1131^{o}C the fracture is usually of a ductile nature (Fig. 8). Yet, the presence of a shrinkage porosity in central part of the sample is the reason why the reduction of area in this place on the fracture is 22% only. Within the region of porosity, the crack is propagating along the dendrite boundaries without any deformation. The deformation at a temperature of 1028^{o}C results in heavy yielding as a consequence, the material suffers deformation even within an area of a severe porosity (Fig. 10). The reduction of area is small and amounts to

14%. The propagation of intercrystalline cracks near the sample edges, and so beyond the porosity-affected region, has been observed. This cracking behavior indicates the presence of the secondary hot brittleness range below the solidus point. The low ductility at a temperature much below the solidus point is the result of the microporosity. The temperature of the secondary brittleness range corresponds to the temperature of a heat treatment applied to Hadfield steel.

The porosity appeared in all the test bars in both zones during the test, i.e. in the space affected by deformation and the no deformed zone. During solidification the conditions were created under which a complete feeding of the test bars should have occurred. In reality the microporosity was always observed. during microscopic examination. It results from the formation of large dendrites of austenite, which make impossible the filling of the shrinkage micro voids during solidification. The manganese steel never attains the superplasticity state characteristic for plain carbon steel below the solidus [3] The micropores are acting either as nuclei of the cracks, or they promote propagation of the crack nuclei formed previously. The effect is low ductility, particularly at a temperature that happens to be applied in heat treatment of this cast steel grade. Then the cracks can easily form not only during solidification but also during heat treatment. The numerous nuclei of the brittle fracture can propagate also in the exploited castings.

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3. Influence of the heat treatment on the brittle crick formation.

On the surfaces of fracture of heavy high manganese cast steel the inclusions of carbides $(Fe,Mn)_3C$ are frequently observed [1], suggesting the insufficient heat treatment - too low temperature or insufficient time of operation. Authors decided to verify this thesis. The kinetic of the solution of carbides in very heavy castings was studied. The cylindrical 100 mm dia samples of Hadield steel were cast in insulated mould. Insulation has increase the physical solidification modulus about 45 – 50 % and the solidification time was 2.25 time longer then in silica
sand mould. The samples were heat treated 2, 5, 7 or 10 hours at 1050 ^oC. After water quenching the sample were cuted. The structure of steel was examined for the determination of the quantity of carbides. The results are presented in the Table 2. In Figs. 10-14 the structure of the steel is presented. Before the heat treatment over the 10 % of carbides can be observed. The solution is very quick, especially during first two hours. After this time in the structure one can observe a very limited quantity of small inclusions. They cannot acts as the nucleus of fracture, during exploiting of casting. In foundry practice the castings of the wall thickness over 60 mm is treated about 5 hours. Then, the carbides quantity would be less than 0.8% and their dimensions less than 30 μm

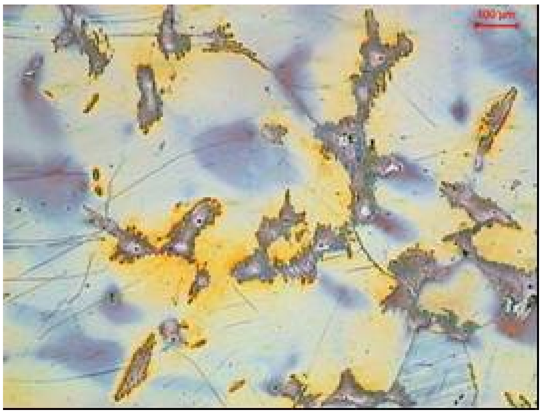
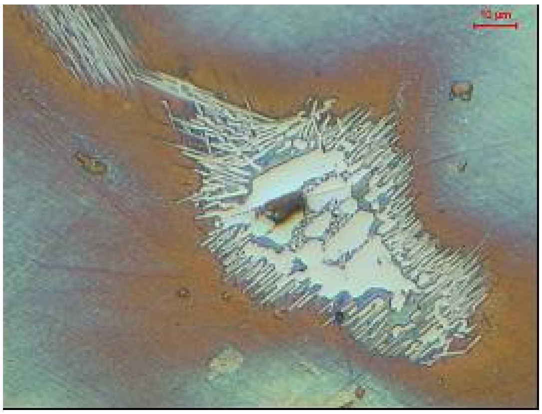

Fig. 10. Cast high manganese steel, before the heat treatment

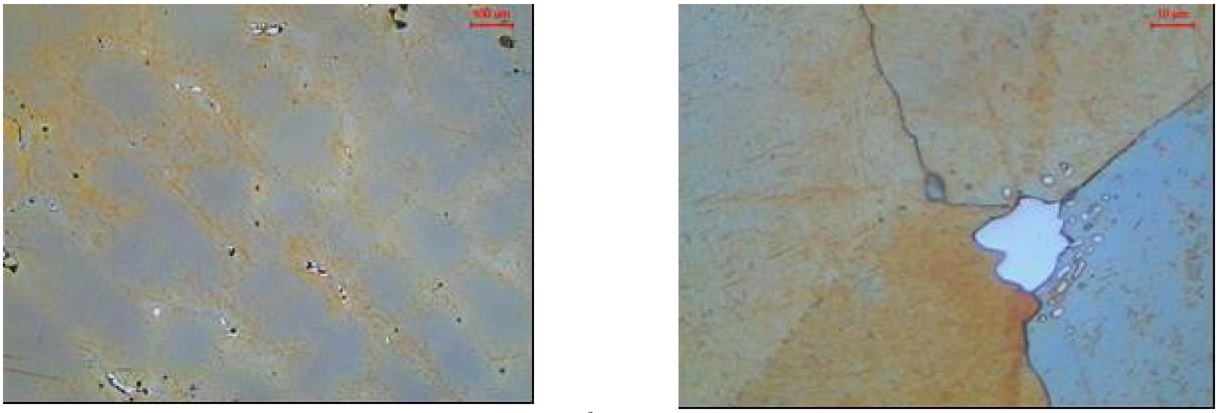

Fig. 11. Carbides in high manganese steel after 3h at 1050 ^{o}C and water quenched. Solidification modulus of casting 9 cm

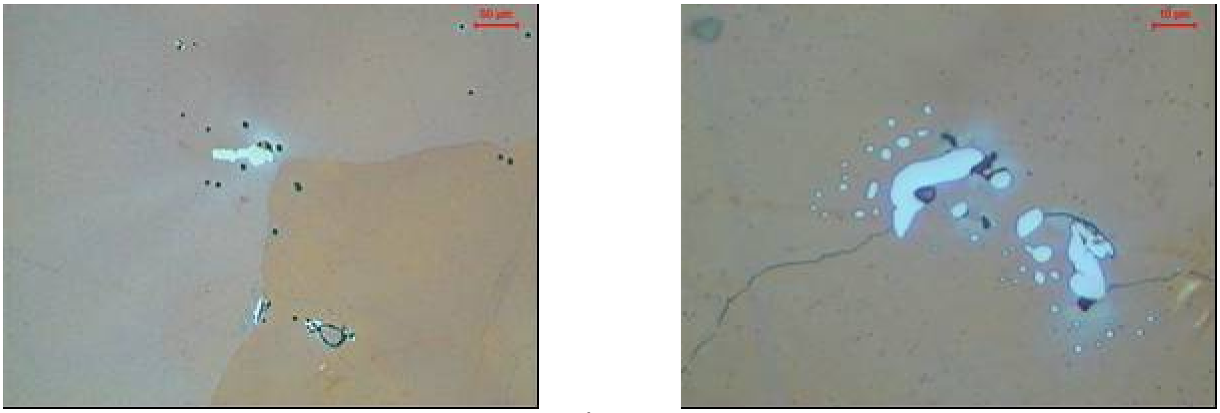

Fig. 12. Carbides in high manganese steel after 5h at 1050 ^{o}C and water quenched. Solidification modulus of casting 9 cm

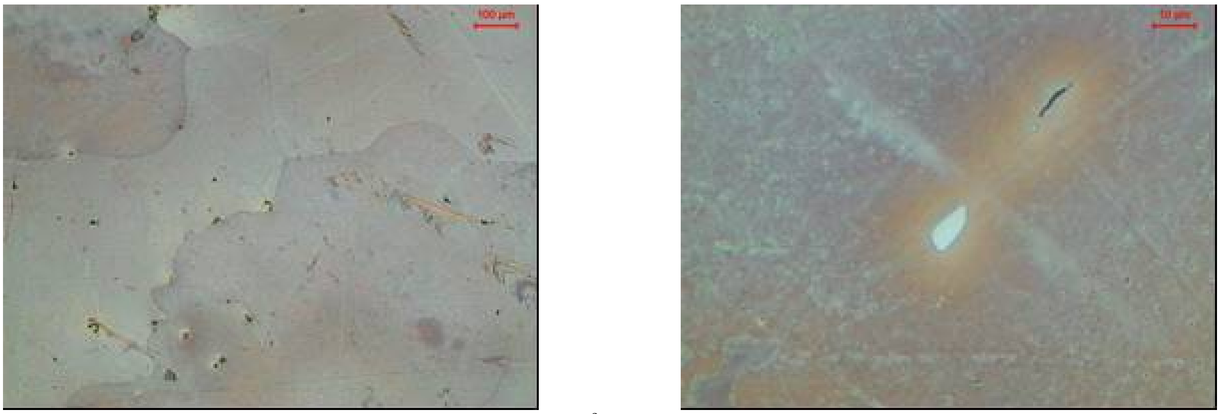

Fig 13. Carbides in high manganese steel after 10h at 1050 ^{o}C and water quenched. Solidification modulus of casting 9 cm

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If the carbides appears in the surface of fracture, formed during casting exploitation it can be supposed that the quenching was no effective. Very low thermal conductivity of the Hadfield steel and the thickness of the wall results the very low decrease of the temperature during water quenching. Secondary carbides can form as a nucleus of brittle fracture.

Table 2.
Volume of carbides in the cast high manganese steel.

Solidification modulus of the sample [cm]	Time (h)	Average volume of carbides, %	Standard Deflexion
9	0	13.98	2.01
	3	1.94	0.39
	5	0.77	0.44
	7	0.35	0.15
	10	0.22	0.18
5	0	12.07	0.94
	3	1.51	0.68
	5	0.89	0.34
	7	0.45	0.26
	10	0.26	0.15

4. Conclusions

The solidification of high-manganese cast steel is characterized by the formation of large dendrites of austenite. Their growth makes the flow of interdendrite liquid difficult and hence impairs the proper feeding of the casting. Even if the conditions are created for a directional solidification of samples, in each case the presence of the free-growing dendrites, enclosing the regions of porosity, can be traced on the sample fracture. An immediate result is the occurrence of a secondary range of brittleness, observed in this cast steel below the temperature of the end of solidification. The mechanism of crack formation , observed during mechanical testing, within this range is similar to that proposed by Rappaz,[7] where the microporosities formed during solidification act as nuclei of brittle fractures. They are prone to propagation under the effect of stresses. Yet, because the work required for cracks to be formed is much greater than in the case of common hot cracking, formed in presence of liquid, severe local plastic deformation occurs. In the case of castings, the process usually ceases at the preliminary stage of propagation, and therefore the formed microcracks are usually undetectable and propagate only later under the effect of high dynamic loads. during casting service.

Acknowledgements

This study has been done under Research Project of the Committee of Scientific Research No. 7 TO8B 004 21. The authors wish to extend their thanks to the Committe for kind assistance and support.

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