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Effect of SiZr Modification on the Microstructure and Properties of High Manganese Cast Steel

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Abstract

The paper presents the results of research on GX120Mn13 modification performed with the SiZr38 inoculant. The microstructure of Hadfield cast steel in as-cast condition was studied through optical microscopy before and after inoculant introduction into the liquid steel. After heat treatment, mechanical properties and wear resistance tests were conducted to analyse the influence of the inoculant. The wear rate was determined according to the Standard Test Method for Determination of Slurry Abrasivity (ASTM G-75). The results show that average grain diameter, area of eqiuaxed grains crystallization and secondary dendrite arm spacing were lower after inoculation. After inoculation, the ultimate tensile strength and proof strength were higher by 8% and 4% respectively, in comparison to the initial state. The results of abrasion wear tests show that the introduction of 0.02 wt. % of zirconium significantly improved wear resistance, which was 34% better in comparison to steel without zirconium.

Keywords: Hadfield cast steel, Grain refinement, Microstructure, Wear resistance

1. Introduction

The high manganese cast steel known as Hadfield's steel, due to its properties, is a common material for railroad crossings, elements of crushers and other equipment operating in wear conditions especially under heavy loads. Cast steels of this type are hardened via strain hardening which leads to the formation of microstructure defects such as: twins, stacking faults, the formation of ε and α' martensite, as well as formation of nanostructures [1, 2]. These effects are visible after explosion surface treatment, cold-working and also in castings worked in heavy load conditions.

In foundry practice, the wear resistance of Hadfield's steel can be improved after modification of the chemical composition and grain refinement of as-cast microstructure. The elements that have a significant impact on the mechanical properties of cast steel with a high manganese content are: chromium, vanadium, titanium, molybdenum, niobium, carbon and nitrogen. When these elements are in a solid solution there is a change in lattice parameter and an increase in yield strength [3]. In addition, they decrease the diffusion of carbon at high temperatures, especially with castings working with heavy loads, and heating up their surface. Carbide-forming elements, however, have a high affinity for carbon and form carbides in the microstructure.

According to Chen [4], the addition of chromium and nitrogen has a positive influence on tensile strength and inhibits grain coarsening during annealing, even if the temperature of the solid solution treatment exceeds 1200°C.

Table 1.
Chemical composition of cast steel (mass %)

Mark/ Elements	C	Si	Mn	P max	S max	Cr	Ni	Al	Zr	Fe
Initial state	1.0	0.98	12.5	0.039	0.002	0.45	0.83	0.006	-	balance
Modified SiZr38	0.97	1.06	12.4	0.042	0.001	0.45	0.84	0.013	0.02	balance

Table 2.
Results of mechanical properties, and microstructure examinations

No	Condition	0.2% YS, MPa	TS, MPa	Elongation, %	SDAS in columnar grains zone	Av. Grain diameter in eqiuaxed grains zone
1.	Initial state	324 (13.2)	640 (48.6)	58 (14.8)	69μm (5.4)	450 μm (276.7)
2.	Modified SiZr38	352 (9.7)	667 (67)	75 (16.6)	63μm (7.5)	314 μm (335.7)

Std. deviation are given in the brackets

On the other hand, the introduction of Cr and Ni, has a negative effect on impact toughness, as reported by Pribulova [5]. Hadfield cast steel with a composition above 0.1% Cr and 0.05% Ni cannot be used in railroad crossings due to the risk of cracking [5].

The second method to increase mechanical properties and wear resistance of high-Mn cast steels is grain refinement modification. Modifying agents are introduced into the molten alloys and promote fine-grain crystallization. Their introduction leads to the creation of crystallization nuclei, inhibition of the crystal growth rate and modification of the shape of non-metallic inclusions. Generally, inoculation leads to an increase in mechanical properties and a decrease in the segregation of alloying elements. This issue has been reported in the literature for many years, [6-14].

In Hadfield cast steel melting, the most commonly used inoculation elements are Ti, Zr, Ce and La [5,7-10]. The introduction of a modifier such as Mg [11], Fe-Al-Si-Ca [12], and particles of carbonitrides and nanoparticles of oxides of refractory metals (i.e. TiO_2, ZrO_2) and others are reported by some researchers [8,13].

The introduction of modifiers like Zr, Ti to the cast steel after modification by SiCa30 does not affect the impact toughness of high Mn cast steel [5]. Introduction of about 0.08 to 0.22 wt. % of magnesium into the high-Mn liquid steel leads to grain refining and decrease of cementite as well as wear rate in the as-cast conditions [11]. The addition of cerium inoculant to the high manganese (30Mn-9Al-1C) cast steel radically affects grain refinement. At 0.1 wt. % addition of cerium authors reported an increase of tensile properties and decrease of impact toughness as well as it resulting in a large number of non-metallic inclusions [14].

The development of high-strength, high Mn cast steels with long service life for railway and mining industry application is important for manufacturers of equipment for this purpose. The goal of this study is to determine the effect of the SiZr inoculant application on grain refinement, wear-resistance and the mechanical properties of Hadfield cast steel.

2. Experimental part

The Hadfield cast steel was melted and modified in a laboratory induction furnace with a capacity of 30 kg. Final deoxidation was carried out in the ladle with SiCa30 and Al, followed by the introduction of the inoculant. The SiZr38 ferroalloy in the amount 0.010 kg was used as the inoculator. The time from the introduction of SiZr38 to the start of pouring into the mould was about 10 seconds. The pouring temperature of the unmodified sample was 1475°C, while the pouring temperature of the modified sample with SiZr, was 5 degrees higher. The chemical composition was examined using a spark emission spectrometer and is given in Table 1.

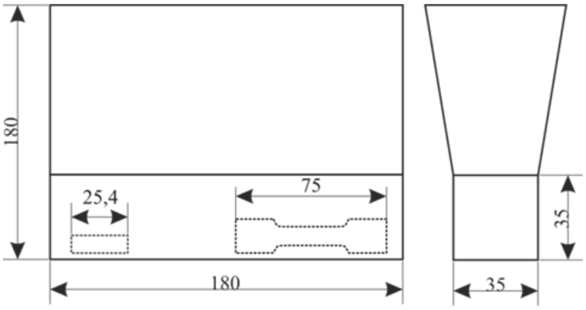

Fig. 1. Schema of test ingots, with indicated specimen for tensile and wear tests

The prepared steel was poured into a mould which created V–shaped ingots each weighing 10 kg. The ingots dimensions is given in Fig. 1. After cutting the bottom side of the ingots (35x35x180 mm) they were annealed at 1100°C for 1 hour per inch and then chilled in water. The tensile specimens were cut from this cuboid via wire electrical discharge machining. Flat tensile specimens (dog-bone), according to standard EN-ISO 6892-1:2009, were used for tensile properties testing. Their gauge length was 30 mm, the cross-section in the reduced section was 3x10 mm and the slimness ratio was 5.65. The wear test was carried out using the Miller machine tester (according to ASTM G-75) in 4 cycles of 4 hr each. Each of the specimens was loaded with a weight of 2 kg. The wear specimen wearing surface area was 25.4x12.7 mm.

Microstructure samples were collected from cylindrical ingots with a diameter of 50 mm and height of 70 mm, casted together with the V-shape ingots. The microstructure was analysed at a distance of 20 mm from the bottom surface of the ingot before and after inoculation. The average grain diameter and secondary dendrite arm spacing were determined on 64 randomly chosen areas of the microstructure. These parameters were measured by applying the linear intercept method (Heyn method). Two perpendicular straight lines were used to average the result, especially in the columnar crystal zone. Pictures for measurement were captured in a distance below 1, 5, 10 and 15 mm from the quenching surface of the cylindrical sample.

3. Results

The results of the mechanical tests are given in Table 2 and Fig. 2. It is shown that the introduction SiZr38 into the Hadfield cast steel leads to an increase of ultimate tensile strength (UTS) and yield strength (0.2%YS). While UTS and YS increase slightly (+8.6% YS, +4.2% UTS), the elongation (El) shows a significant increase (+29% El).

In the case of SiZr38 modification, there are three types of impact on the microstructure: the first is an increased equiaxed crystal area, the second is the refining of grains and the third is the decrease of secondary dendrite arm spacing (SDAS).

Fig. 3 shows the area of equiaxed crystals before and after SiZr38 introduction, marked by pink line. It is clearly shown that after modification the area of equiaxed crystallization is bigger. Measurements of this area show that in its initial state, the equiaxed grains zone is approximately 32.4% of total the specimen area, as well as 50.2% in the specimen after SiZr modification.

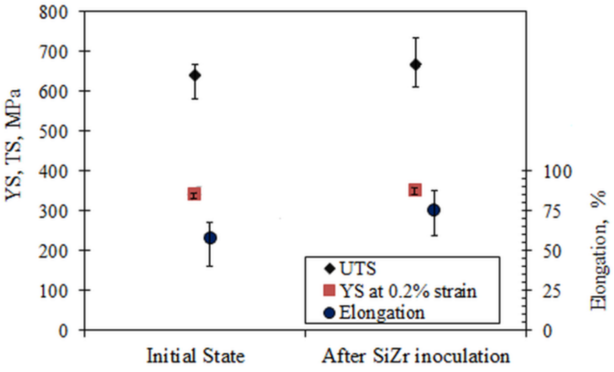

Fig. 2. Mechanical testing results

Similarly, after modification, the average grain diameter is decreased in comparison to the initial state (Table 3). In the frozen crystal zone (distance below 1 mm from the wall surface), the average grain diameter decreases from 332 µm in the initial state to 291 µm after inoculation with SiZr38.

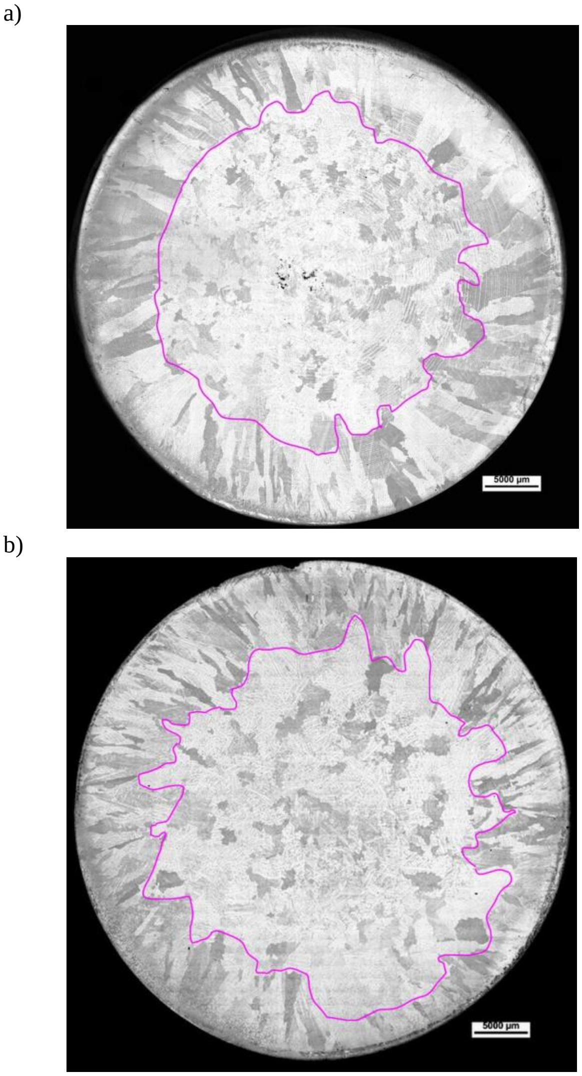

Fig. 3. Macrostructure of examined steel, (a) in initial state, (b) after SiZr inoculation

Table 3.
Average grain diameter of examined cast steel

Distance from the surface, mm	Initial state, µm	Std. dev.	Modified, µm	Std. dev.
Bellow 1	332	193.3	291	170.5
5	581	378.0	467	213.0
10	596	512.7	655	405.8
15	450	276.7	314	335.7

In the columnar crystal zone (5 mm from the wall surface), the average diameter was 581 µm and 467 µm after modification. In the equiaxed crystallization zone (15 mm from the wall surface), the average grain diameters were 450 µm and 314 µm respectively.

Measurements of secondary dendrite arm spacing also show the positive effect of SiZr38 inoculation. This parameter was determined in the columnar crystal zone, due to the simplicity and reliability of distance measurements. In this zone, secondary dendrite arms are clearly visible and measurements of the distance between them are accurate and stable. As it is shown in Table 2, SDAS changed from 69 µm in the initial state to 63 µm after inoculation.

The Hadfield cast steel wear rate was determined according to the Standard Test Method for Determination of Slurry Abrasivity (ASTM G-75). The wear test shows that inoculation with SiZr exerts a significant influence on abrasion resistance in a SiC slurry (Table 4).

Table 4.
Weight and cumulative mass loss during wear tests

Time, hr	Initial state, g	Modified, g
0	26.974 0.0	27.010 0.0
4	26.725 0.249	26.843 0.167
8	26.508 0.466	26.700 0.310
12	26.301 0.673	26.560 0.450
16	26.123 0.851	26.445 0.565

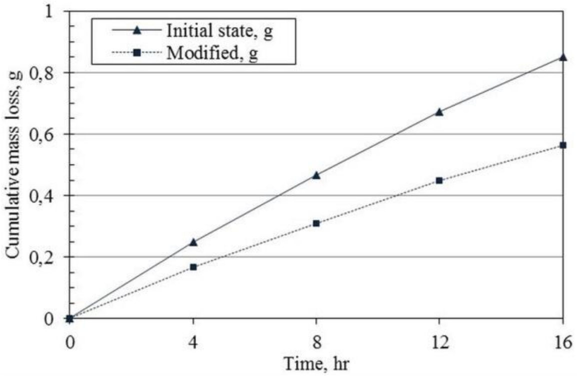

Fig. 4. Cumulative mass loss of tested specimens

Analysis of mass loss shows that the sample wear rate is approximately a logarithmic curve (Fig 4). After 16 hr of the test, mass loss for the specimen in the initial state was 0.851 g whereas it was 0.565 g for the specimen after inoculation. The analysis of the friction surface showed that the dominant wear mechanism was abrasive wear.

An influence of modification of Hadfield cast steel with the silicon-zirconium on the wear resistance is caused by the grain refinement effect. It is well known that the decreasing of grains affects the mechanical properties such as tensile strength and hardness, which is described by the Hall-Petch equation for metal alloys. In the case of austenitic manganese cast steel, grain refinement leads to reducing the possibility of slipping, and dislocation movement. The fine-grained materials have a greater total grain boundary area to impede dislocation motion.

4. Conclusions

Hadfield cast steel in its initial state and after inoculation have been analysed. Obtained results can be summarized as follows:

1. Introduction of SiZr38 inoculant influences the mechanical properties of Hadfield cast steel. The ultimate tensile strength and yield strength increases respectively by 8% and 4% in comparison to the initial state.
2. It is clear that small addition of SiZr 38 in the amount of 0.02 wt.% has a positive effect on grain refinement. The average grain diameter and SDAS decrease after inoculation.
3. It is shown that SiZr38 inoculant greatly influences abrasion wear resistance of Hadfield cast steel. After inoculation, it was almost 34 % better.

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References

[1] Zambrano, O.A., Tressia, G. & Souza, R.M. (2020). Failure analysis of a crossing rail made of Hadfield steel after severe plastic deformation induced by wheel-rail interaction. *Engineering Failure Analysis*. 115, 104621. DOI: doi.org/10.1016/j.engfailanal.2020.104621

[2] Chen, C., Lv, B., Feng, X., Zhang, F. & Beladi, H. (2018). Strain hardening and nanocrystallization behaviors in Hadfield steel subjected to surface severe plastic deformation. *Materials Science and Engineering: A*. 729, 178-184. DOI:10.1016/j.msea.2018.05.059.

[3] Fujikura, M. (1986). Récents développements au Japon d'aciers austénitiques au Mn destinés aux applications amagnétiques. *Matériaux & Techniques*. 74, 341-353. DOI: 10.1051/mattech/198674070341.

[4] Chen, C., Zhang, F.C., Wang, F., Liu, H. & Yu B.D. (2017). Efect of N+Cr alloying on the microstructures and tensile properties of Hadfield steel. *Materials Science & Engineering A*. 679, 95-103. DOI:10.1016/j.msea.2016.09.106.

[5] Pribulová, A., Babic, J. & Baricová, D. (2011) Influence of Hadfield´s steel chemical composition on its mechanical properties. *Chem. Listy*. 105, 430-432.

[6] Kasińska, J. (2020). The Morphology of Impact Fracture Surfaces in Manganese Cast Steel Modified by Rare Earth Elements. *Archives of Foundry Engineering*. 20, 89-94. DOI: 10.24425/afe.2020. 131308.

[7] Guzman, Fernandes, P.E. & Arruda, Santos, L. (2020). Effect of titanium and nitrogen inoculation on the microstructure, mechanical properties and abrasive wear resistance of Hadfield Steels. *REM - International Engineering Journal*. 73(5), 77-83. https://doi.org/10.1590/ 0370-44672019730023.

[8] Vdovin, K.N., Feoktistov, N.A., Gorlenko, D.A. et al. (2019). Modification of High-Manganese Steel Castings with Titanium Carbonitride. *Steel Transl*. 3, 147-151. https://doi.org/10.3103/S0967091219030136.

[9] Gürol, U., Karadeniz, E., Çoban, O., & Kurnaz, S.C. (2021). Casting properties of ASTM A128 Gr. E1 steel modified with Mn-alloying and titanium ladle treatment. *China Foundry*. 18, 199-206. https://doi.org/10.1007/s41230-021-1002-1

[10] Haakonsen, F., Solberg, J.K., Klevan, O. & Van der Eijk, C. (2011). Grain refinement of austenitic manganese steels. In AISTech - Iron and Steel Technology Conference Proceedings, 5-6 May 2011. Volume 2, 763-771, Indianapolis, USA. ISBN: 978-1-935117-19-3

[11] El-Fawkhry, M.K., Fathy, A.M., Eissa, M. & El-Faramway H. (2014). Eliminating heat treatment of hadfield steel in stress abrasion wear applications. *International Journal of Metalcasting*. 8, 29-36. DOI: 10.1007/BF03355569.

[12] Issagulov, A.Z., Akhmetov, A.B., Naboko, Ye.P., Kusainova, G.D. & Kuszhanova, A.A. (2016). The research of modification process of steel Hadfield integrated alloy ferroalumisilicocalcium (Fe-Al-Si-Ca/FASC). *Metalurgija*. 55(3), 333-336.

[13] Zykova, A., Popova, N., Kalashnikov, M. & Kurzina, I. (2017). Fine structure and phase composition of Fe–14Mn–1.2C steel: influence of a modified mixture based on refractory metals. *International Journal of Minerals, Metallurgy and Materials*. 24(5), 523-529. DOI: 10.1007/s12613-017-1433-2.

[14] Bartlett, L.N. & Avila, B.R. (2016). Grain refinement in lightweight advanced high-strength steel castings. *International Journal of Metalcasting*. 10, 401-420, DOI: 10.1007/s40962-016-0048-0.