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INFLUENCE OF INOCULATION METHODS AND THE AMOUNT OF AN ADDED INOCULANT ON THE MECHANICAL PROPERTIES OF DUCTILE IRON

VPLIV METOD MODIFIKACIJE IN KOLIČINE DODANEGA MODIFIKATORJA NA MEHANSKE LASTNOSTI DUKTILNEGA ŽELEZA

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In most cases an addition of inoculants to molten cast iron is advisable and even necessary to produce good-quality castings. The mechanical properties and machinability of cast iron with nodular graphite greatly depend on the formation of graphite and the matrix microstructure and both are significantly influenced by the inoculation treatment. The mechanism of inoculation, the influence of the inoculation method and the amount of added inoculants are presented.

Keywords: ductile iron, inoculation, microstructure, graphite, metallic matrix

V večini primerov je dodatek modifikatorjev staljenemu livnemu železu priporočljiv in celo potreben za izdelavo dobrih ulitkov. Mehanske lastnosti in obdelovalnost litega železa z nodularnim grafitom so močno odvisne od oblike grafita in od mikrostrukture osnove, na oboje pa močno vpliva obdelava z modifikatorji. Predstavljen je mehanizem modifikacije, vpliv metode modifikacije in vpliv količine dodanega modifikatorja.

Ključne besede: duktilno železo, inokulacija, mikrostruktura, grafit, kovinska osnova

1 INTRODUCTION

Inoculants are the materials added to molten cast iron, modifying the microstructure and, thereby, changing the physical and mechanical properties to a degree not explained on the basis of the change in the composition. Inoculation is a phase of the technological process of producing ductile iron that controls and improves the microstructure and mechanical properties of castings. Through inoculation, graphite nucleation and eutectic undercooling of the melt can be controlled, which is crucial for achieving the required service properties of the castings.[1–3]

The inoculant most commonly used in foundries is a ferrosilicon alloy with precisely defined contents of Ca, Ba, Sr, Zr, Al and rare-earth elements. The benefits of inoculations are: an improved machinability, increased strength and ductility, reduced hardness and fracture sensitivity, a more homogenous microstructure, a reduced tendency for solidification shrinkage, etc.

During modularizing, numerous inclusions with a sulfide core and an outer shell containing complex magnesium silicates are formed. Such micro-inclusions do not provide an effective nucleation for graphite because the crystal lattice structure of magnesium silicates does not match sufficiently with the lattice structure of graphite. After the inoculation with a ferrosilicon alloy containing Ca, Ba or Sr, the surfaces of the micro-inclusions are modified and other complex Ca, Sr, or Ba silicate layers are obtained. Such silicates have the same hexagonal crystal lattice as graphite and act as effective nucleation sites for graphite nodules to grow during solidification.[4]

The required rate of adding inoculants to a liquid depends very much on the place and time of their inoculation.

2 EXPERIMENTAL PROCEDURE

In the investigations of the response of ductile-iron test melts to different amounts of added inoculants and different inoculation methods, three types of the inoculation method were applied: the ladle inoculation, the in-stream inoculation and the in-mold inoculation. The partner foundry in this research project was "Cimos TMD Casting" in Zenica.

In the first project step, 15 melts were prepared. Full lists of the chemical compositions, the amounts of added inoculants and the places of the inoculant introduction are included in **Table 1**. High-purity FeSi with additions of Al, Ca, and Sr was used for the inoculation. The test

Table 1: Chemical compositions of the experimental melts, places of the inoculation and added amounts of the inoculants (first step of the project)
Tabela 1: Kemijska sestava eksperimentalnih talin, mesto dodajanja modifikatorja in količina dodanega modifikatorja (prva stopnja projekta)

No.	Chemical composition (%)								Inoculant (%)			Temp.
	C	Si	Mn	P	S	Cr	Cu	Mg	stream	mold	ladle	°C
1	3.52	2.17	0.428	0.016	0.006	0.086	0.314	0.043	0	0	0	1388
2	3.51	2.20	0.433	0.016	0.006	0.090	0.314	0.040	0	0.05	0	1392
3	3.49	2.06	0.401	0.015	0.006	0.089	0.332	0.032	0	0.15	0	1402
4	3.58	2.15	0.403	0.014	0.005	0.076	0.346	0.043	0	0.20	0	1407
5	3.56	2.09	0.482	0.011	0.003	0.111	0.340	0.040	0.05	0.05	0	1395
6	3.44	2.11	0.485	0.012	0.003	0.095	0.356	0.047	0.05	0.10	0	1410
7	3.60	2.14	0.345	0.016	0.006	0.054	0.080	0.053	0.10	0	0	1380
8	3.54	2.10	0.337	0.017	0.009	0.071	0.090	0.055	0.05	0	0	1380
9	3.52	2.15	0.362	0.014	0.007	0.064	0.091	0.045	0.15	0	0	1390
10	3.56	2.11	0.398	0.017	0.008	0.068	0.316	0.047	0.10	0.05	0	1400
11	3.62	2.45	0.353	0.017	0.009	0.049	0.119	0.065	0.20	0	0	1387
12	3.65	2.11	0.392	0.019	0.012	0.054	0.149	0.079	0.15	0.05	0	1405
13	3.62	2.12	0.382	0.019	0.011	0.054	0.144	0.060	0	0.20	0	1390
14	3.61	2.11	0.357	0.018	0.009	0.037	0.187	0.048	0	0	0.05	1398
15	3.64	2.14	0.384	0.016	0.011	0.084	0.212	0.052	0	0	0.20	1402

Table 2: Range of the chemical compositions of the test melts (second step of the project)
Tabela 2: Obseg kemijskih sestav preizkusnih talin (druga stopnja projekta)

Composition	C	Si	Mn	S	P	Mg
w/%	3.4–3.6	2.1–2.3	0.2–0.4	0.003–0.012	0.01–0.02	0.003–0.055

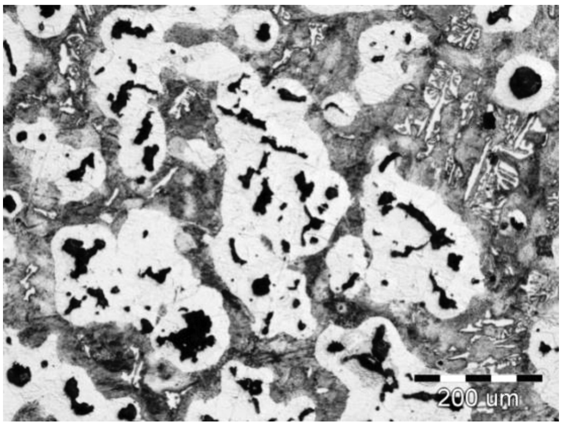

Figure 1: Ladle inoculation, Nital etched
Slika 1: Modifikacija v ponvi, jedkano v nitalu

iron melts were obtained using an induction furnace and casting iron into a green-sand mold. After the casts were cooled down and cleaned, samples for the mechanical-property examination were prepared.[1]

The testing of the mechanical properties was performed according to BAS EN 100002:2002 relating to tensile testing and BAS EN 6507-1/2007 relating to hardness testing of fractured tensile-test bars.

Based on the summary of the results of testing the casting properties, conclusions about the optimum amounts of the added inoculants needed for obtaining the required values of the mechanical properties, were drawn.

Casting procedures involving the exact amounts of the added inoculants required for three different methods

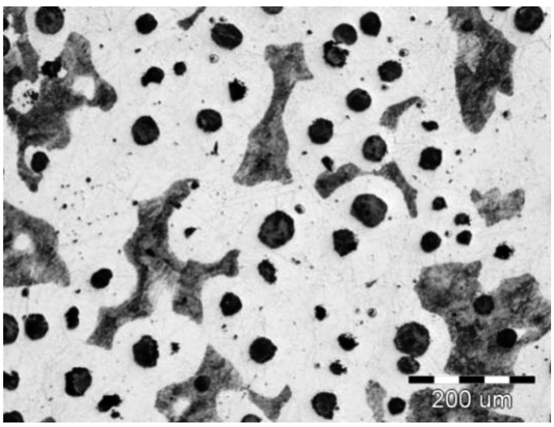

Figure 2: In-stream inoculation, Nital etched
Slika 2: Modifikacija v curek, jedkano v nitalu

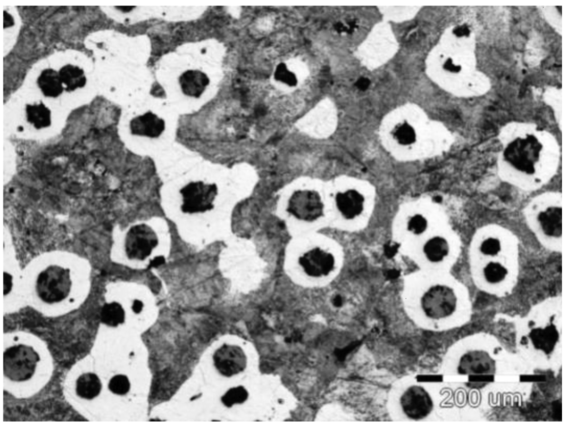

Figure 3: In-mold inoculation, Nital etched
Slika 3: Modifikacija v kokili, jedkano v nitalu

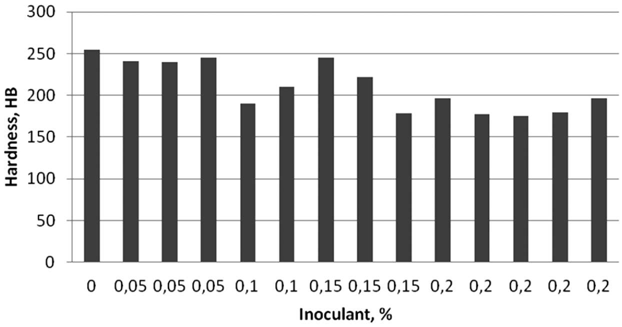

Figure 4: Hardness values of the tested samples (first step of the project)
Slika 4: Trdota preizkusnih vzorcev (prva stopnja projekta)

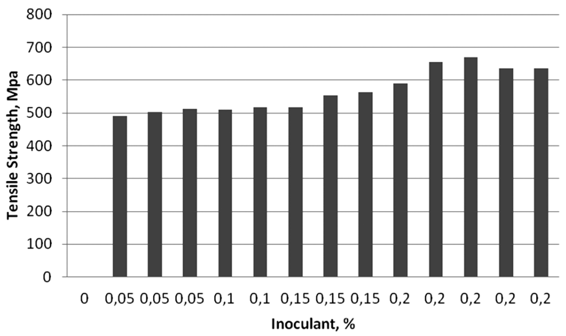

Figure 5: Tensile-strength values of the tested samples (first step of the project)
Slika 5: Natezna trdnost preizkusnih vzorcev (prva stopnja projekta)

Table 3: Average values and standard deviations of the hardness and tensile strength (second step of the project)
Tabela 3: Povprečne vrednosti in standardna deviacija trdote in natezne trdnosti (druga stopnja projekta)

	Hardness (HB)			Tensile strength (MPa)		
Inoculation method	In mold	In stream	Ladle	In mold	In stream	Ladle
Average	212.15	203.8	205.3	564.65	546.3	474.95
St. deviation	7.86	6.88	27.02	29.1	9.41	33.61

of inoculation were conducted in the second step to find the most suitable casting technology in the partner foundry. A total of 60 melts were prepared in the second step of the project and the average melt chemical composition is presented in **Table 2**.

3 RESULTS AND DISCUSSION

Figures 1 to **3** show the microstructures of the samples taken from the melts (castings) inoculated with different methods; the tensile strengths and hardness values are presented in **Figures 4** and **5**.

The required hardness was in the range of 180–220 HB and the tensile strength was in the range of 500–550 MPa. According to the results in **Figures 1** and **2**, the best result was observed with the samples with 0.1 % of the inoculants. In the second project step we used 20

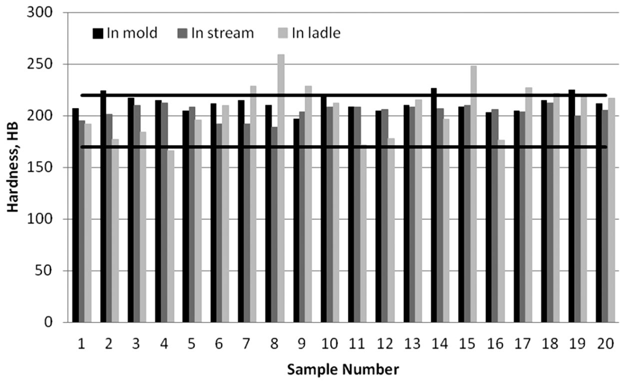

Figure 6: Hardnes values of the tested samples (second step of the project); black horizontal bars – targeted values
Slika 6: Trdota preizkusnih vzorcev (druga stopnja projekta); črne vodoravne črte – ciljne vrednosti

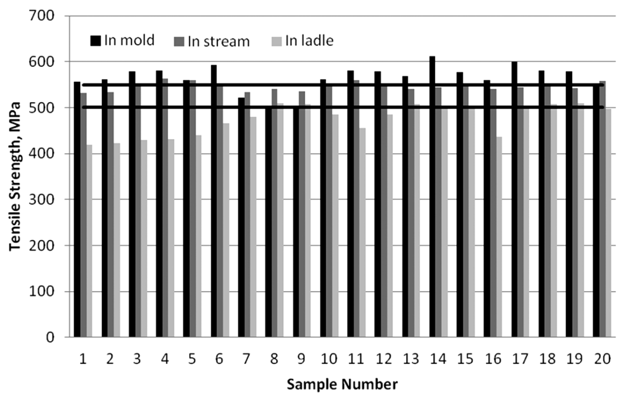

Figure 7: Tensile-strength values of the tested samples (second step of the project); black horizontal bars – targeted values
Slika 7: Natezna trdnost preizkusnih vzorcev (druga stopnja projekta); črne vodoravne črte – ciljne vrednosti

melts for each inoculation method, i.e., 60 melts were treated with 0.1 % of the added inoculants. The mechanical properties are shown in **Figures 6** and **7** and in **Table 3**.

4 CONCLUSIONS

Experimental materials with quite satisfactory characteristics were prepared with vacuum induction melting. The results obtained in the first project step showed that with 0.1 % of the inoculant the targeted hardness and tensile strength for the given ductile iron were achieved.

In the second project step it was found that the in-stream inoculation ensured the best result as almost 100 % of all the samples achieved the targeted values for the hardness and tensile strength and the standard deviation was the smallest.

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