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## MANUFACTURING OF FERRITIC LOW-SILICON AND MOLYBDENUM DUCTILE CAST IRON WITH THE INNOVATIVE 2PE- 9 TECHNIQUE

### OTRZYMYWANIE ŻELIWA FERRYTYCZNEGO ŚREDNIOKRZEMOWO-MOLIBDENOWEGO SFEROIDALNEGO PRZY WYKORZYSTANIU NOWOCZESNEJ TECHNIKI 2PE-9

The use of two cored wire injection methods (2PE- 9) and the unique application of a drum ladle as a treatment, transport and casting one, instead of a vertical treatment ladle are presented. Optimization parameters, like: length of nodulariser wire, treatment and pouring temperature have been shown. The influence of various treatment temperatures on magnesium recovery is demonstrated. The typical microstructure, mechanical properties and cost calculation of the ferritic ductile cast iron (type SiMo – EN-GJS-SiMo40-6 Grade) production according to EN 16124:2011 (E) are presented. Injection of two Ø 9 mm as well wires; cored in FeSi + Mg nodulariser mixture and inoculant master alloy into a drum ladle is a treatment method that can be used for the production of ferritic ductile cast iron (SiMo) melted in a coreless induction furnace.

*Keywords:* Treatment ladle, Cored wire, Si-Mo ductile iron, Nodulariser, Ferritic matrix

W pracy przedstawiono analizę wyników badań otrzymanych podczas produkcji żeliwa sferoidalnego typu SiMo, z zastosowaniem nowej metody sferoidyzacji metalu w kadzi bębnowej (technika 2PE- 9). Zaprezentowano wyniki badań w zakresie optymalizacji parametrów procesu, takich jak: długości przewodu sferoidyzującego, krytycznej zawartości magnezu, temperatury zabiegu i temperatury zalewania. Pokazano wpływ temperatury zabiegu, prędkości przemieszczania przewodu sferoidyzującego (czasu zabiegu sferoidyzowania) i masy ciekłego stopu na uzysk magnezu ze sferoidyzatora. Przedstawiono mikrostrukturę, właściwości mechaniczne i koszt wytwarzania ferrytycznego żeliwa sferoidalnego SiMo; gatunku EN-GJS-SiMo40-6, zgodnie z najnowszą EN 16124:2011 (E). Wprowadzenie dwóch przewodów elastycznych o średnicy Ø 9 mm; jeden wypełniony mieszaniną FeSi + Mg, a drugi modyfikatorem grafityzującym do zabiegowej kadzi bębnowej, jest nową metodą obróbki pozapiecowej produkcji ferrytycznego żeliwa typu SiMo, która może być wykorzystana do produkcji żeliwa sferoidalnego wytapianego w indukcyjnym piecu.

### 1. Introduction

The high-silicon grey cast irons with flake graphite were developed by BCIRA and are commonly called Silal. This type of cast iron is used for the high-temperature application.

Converting the eutectic flake graphite network into the isolated graphite nodules improves growth and oxidation resistance. The higher strength and ductility of the nodular cast iron qualifies it for more demanding application, which means extending the upper limit of elevated temperatures. Silicon decreases the eutectic carbon content, which must be controlled to avoid graphite flotation [1]. Molybdenum is the most efficient element for heat-resistance improvement. Adding molybdenum in to low-silicon ductile cast iron improves thermal fatigue and thermal creep resistance [2]. For most applications, the optimal range of Mo varies between 0.5 and 1.1 wt. %. Higher molybdenum addition tends to generate interdendritic carbides, which persist even through annealing, and

tend to reduce toughness and ductility at room temperature [1]. The composition of the carbide ranging from approximately  $Fe_4Mo_2C$  to  $Fe_3Mo_3C$  [3]. Ferritic nodular graphite cast iron alloyed with silicon and molybdenum is known as Si-Mo cast iron and has nine grades according to EN 16124:2011 standard; with the range of 2.3-5.2 wt. % Si and 0.4-1.1 wt. % Mo. An important stage in the production of high-quality ductile iron was implementation into industrial practice, new fully, mechanised technique of magnesium- and inoculant reagents introducing into molten alloy called cored wire injection method. This technique eliminates time and labour, because the repeated preparation of nodulariser and inoculant individual batches, typical in other methods [4, 5, 6] and magnesium recovery is constant and characteristic for Mg-treatment 2PE – method [7].

The aim of the present study has been determination of microstructure and mechanical properties of the ferritic nodular graphite cast iron (SiMo – ductile cast iron).

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## 2. Experimental procedure

A special technique of Mg- and inoculation treatment was implemented at the Foundry of EGM Automotive GmbH in Germany. It comprised the change of the ladle type and treatment method. Instead of molten alloy treatment with the use of the FeSiMg master alloy placed at the bottom of the vertical treatment ladle, followed by the two-stage emptying from the treatment ladle to pouring ladles, two Ø 9 mm cored wire injection method in the drum ladle was applied. Common use of vertical treatment ladles comes from the assumption that the height of a molten alloy column in the ladle against its diameter must be at least (2:1) [8]. The same drum ladle was not used only for treatment, but also for transport and pouring process. The drum ladle with a standard capacity of about 950 kg liquid metal was next filled with molten alloy and transported to the treatment chamber (Fig. 1).

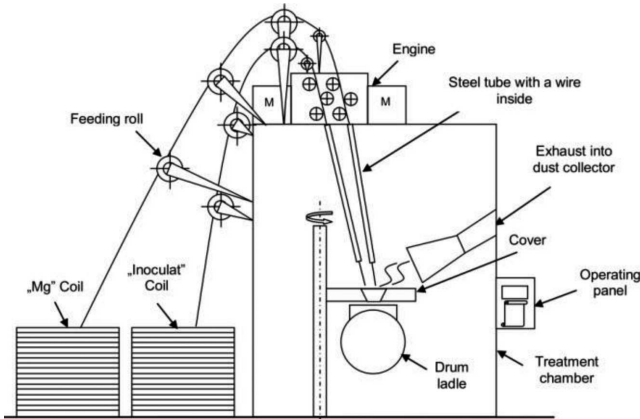


Fig. 1. Schematic view of the two cored wire injection method (2PE- 9) used during experiment

Typical chemical composition of EN GJS-SiMo40-6 Grade cast iron used in the optimized process was (wt. %): 3.1 C (spectrographic analysis), 3.96 Si, 0.52 Mo, 0.17 Ni, 0.05 Cr and 0.1 Mn and decrease of sulphur content after Mg-treatment was equal to 0.004 (No. of 395 molten alloy treatments). The treatment temperature was in the range 1390 to 1412°C and was reduced from about 1460°C, which yielded an optimization of about 60 grades. The mean value of residual magnesium was equal to 0.054 wt. % and during all experiment the value was kept in the range from 0.043 to 0.064 wt. %. A specimen for the microstructure analysis was cast into the last mould for all test. It has been correlated with standard sample. Control of kind of metal matrix and volume fraction and shape graphite was made under the LEICA MEF-4M optical microscope (LM). Carbide analysis was made with use of the JOEL 5500 LV scanning electron microscope (SEM) equipped with an energy-dispersive spectrometer EDS (IXRF firm). Such analysis can only be considered as some approximation due to carbon contamination. However, from the experimental point of view the most valuable information was amount of Mo and Si substituting Fe in carbide.

## 3. Results and analysis

From the analysis it can be concluded that the parameters and their ranges used in this method guarantee the microstructure and mechanical properties of tested ferritic Si-Mo ductile cast iron. Metallographic examinations of all specimens proved that this technique produces SiMo ductile cast iron with graphite type V, VI >80% with regular shape of nodules and their size of 5 and 7 according with EN-ISO 945. About 3% of carbides was present in ferritic matrix (Fig. 2a). The EDS chemical analysis of area contained carbides in SiMo ductile cast iron (Fig. 2b) showed that they contained also Fe, Mo, C and Si. Such carbide is demonstrated in Fig. 2c and its chemical composition in the Table 1 (point 2). The mechanical properties: tensile strength UTS, elongation El, yield strength YS of Si-Mo ductile iron are shown in Table 2.

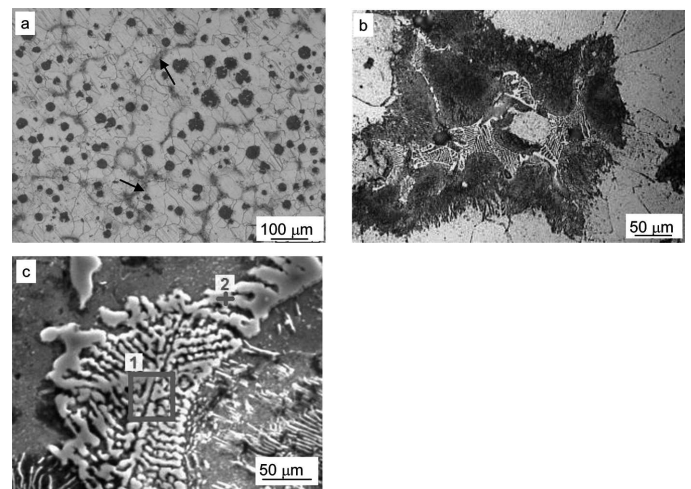


Fig. 2. (a) Light microscope image showing graphite nodules and metal matrix as well as carbide areas (see arrows), (b, c) SEM images of carbide in ferritic SiMo ductile cast iron (EN-GJS-SiMo40-6 Grade)

An increase of magnesium recovery mean values, calculated according to equation (1) [7] was observed during the optimization process.

$$\eta_{Mg} = [(0.76 \cdot \Delta S + Mg_r) \cdot m] / (L \cdot Mg_c), \% \quad (1)$$

where:

0.76 is the coefficient calculated from the ratio of atomic weights, Mg/S;

$\Delta S$  is the difference between sulphur content in molten alloy before and after treatment ( $S_1 - S_2$ ), wt. %;

$Mg_r$  is the residual magnesium content, wt. %;

$m$  is the molten alloy weight in the ladle, kg;

$L$  is the length of the magnesium-cored wire, m;

$Mg_c$  is the magnesium content in one meter of the magnesium-cored wire, kg/m.

Magnesium recovery is constant and characteristic for Mg-treatment method. It means that 42% recovery which is in our case the minimum, was calculated for the highest length of a nodulariser wire equal to 41 m and for higher treatment temperatures, about 1460°C. A controlled decrease of the nodulariser wire length (from 41 mm to 32 m) along with a decline of the treatment temperature enabled the residual magnesium

content to be kept in its optimal limit range from 0.045 to 0.06 wt.% (Fig. 3), and the magnesium recovery to increase up to 55%. The cost analysis was made for the optimized process of molten alloy Mg- and inoculation treatment, carried out with two cored wire injections method. The following calculations were made:

- Mg-treatment with cored wire (properties: wire weight = 0.225 kg/m; price per 1 kg of wire = 2.35 €; weight of molten alloy in ladle = 941 kg; length of wire = 32 m), hence  $32 \text{ m} \cdot 0.225 \text{ kg/m} = 7.20 \text{ kg} \cdot 2.35 \text{ €/kg} = 16.92 \text{ €}$ . Cored wire cost per 1000 kg of molten alloy = 17.98 €.
- Inoculation treatment with cored wire (properties: wire weight = 0.240 kg/m; price per 1 kg of wire = 2.27 €; length of wire = 28 m), hence  $28 \text{ m} \cdot 0.240 \text{ kg/m} = 6.72 \text{ kg} \cdot 2.27 \text{ €/kg} = 15.25 \text{ €}$ . Cored wire cost per 1000 kg of molten alloy = 16.21 €.

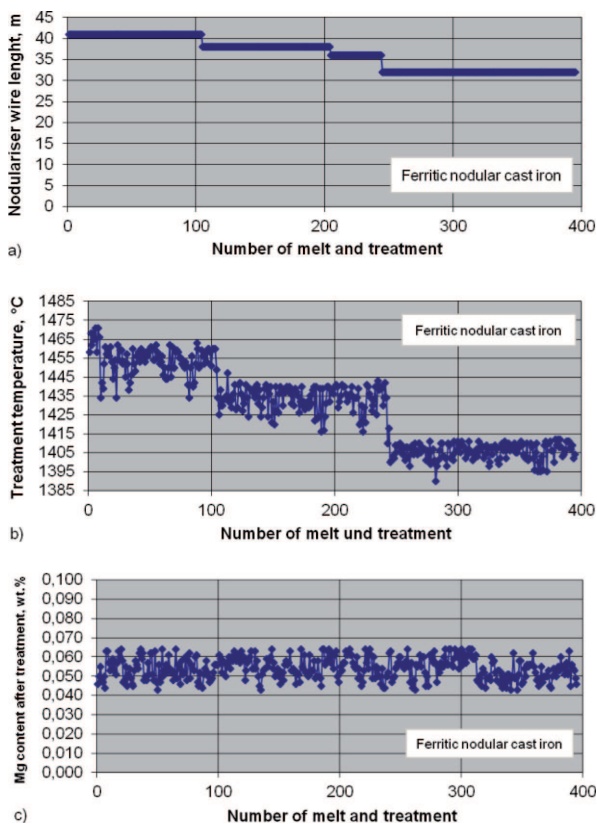


Fig. 3. Optimization of the length of nodulariser wire (a) treatment temperature, (b) and residual magnesium content (c) carried out during experiments for SiMo ductile cast iron

TABLE 1

Chemical composition of carbide present in SiMo ductile cast iron (EN-GJS-SiMo40-6 Grade) casting

Element	Area 1		Area 2	
	at. %	wt. %	at. %	wt. %
Fe	39.7	56.5	22.3	43.2
Mo	10.5	25.7	7.6	25.1
C	43.7	13.4	66.0	27.5
Si	6.2	4.4	4.2	4.1

TABLE 2  
Mechanical properties of SiMo ductile cast iron (EN-GJS-SiMo40-6 Grade) in "YIP" block standard cast during experiment

Properties	UTS, MPa	El, %	HB <sub>2.5/187.5</sub>	YS, MPa
min . limit	480	8	190	380
max . limit	–	–	240	–
Results	603	14	226	464

The final cost of 1000 kg alloy treated with Mg- and inoculant wires was equal to 34.19 € and it is about 4,94 € less than the treatment cost of not optimized process. Correlation between the magnesium recovery and the treatment temperatures is presented in Fig. 4.

The mean values of parameters which influence magnesium recovery are summarized in Table 3. They are taken from production process before and after optimization. The results of experiments allowed to determine residual magnesium content based on a initial sulfur content, a total weight of pure magnesium (length of nodulariser wire), a weight- and a treatment temperature of molten alloy in the ladle.

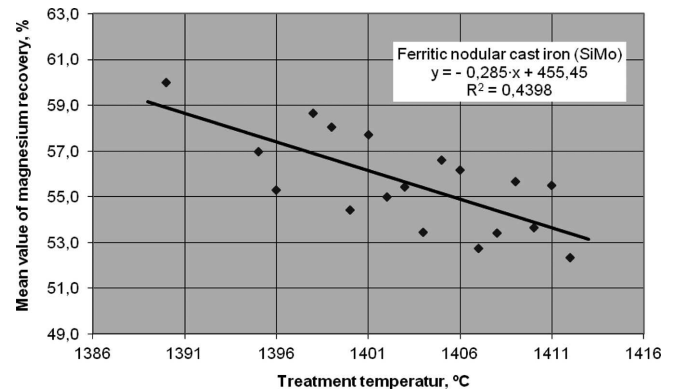


Fig. 4. Magnesium recovery mean values versus the range of optimized temperature of molten alloy treatment

TABLE 3

Parameters of cored wire injection 2PE- 9 method in production of ferritic SiMo ductile cast iron

	Initial process (not optimized)	Process optimized
	Parameter mean values	
$\Delta S$ , wt. %	0.002	0.004
Mg, wt. %	0.054	0.054
m, kg	944	941
L, m	41	32
Mg <sub>c</sub> , kg/m	0.0312	0.0305
$\eta_{Mg}$ , %	41	55
Cost, €/1000kg	39.13	34.19
T, °C	1454	1406
v, m/min(t,s)	13(185)	14.5(132)

Comparing to the old technique that has been used in the foundry so far, the innovative way of Mg- and inoculation

treatment with two cored wires being fed into a drum ladle offers the following advantages:

- safe work conditions in a foundry, because of Mg-treatment is combined with a treatment chamber, ladle cover and fume exhaust;
- automation of the process, which guaranties flexibility under variable initial parameters, like sulphur content in molten alloy, treatment temperature, weight of molten alloy and magnesium weight in a wire  $\varnothing$  9 mm;
- no preparation of nodulariser and inoculant separate batches;
- data storing in a computerized control device, which enables the process to be controlled and analyzed;
- saving up to 95 grades of temperature loss thanks to the use of only one ladle in the whole production process of ferritic SiMo nodular cast iron (Fig. 5);
- one, common ladle type in process means saving high investment cost for a “well-designed” vertical treatment ladle;
- lower number of ladles resulting in manpower reduction, as well as better logistics for ladles and molten alloy in the foundry;

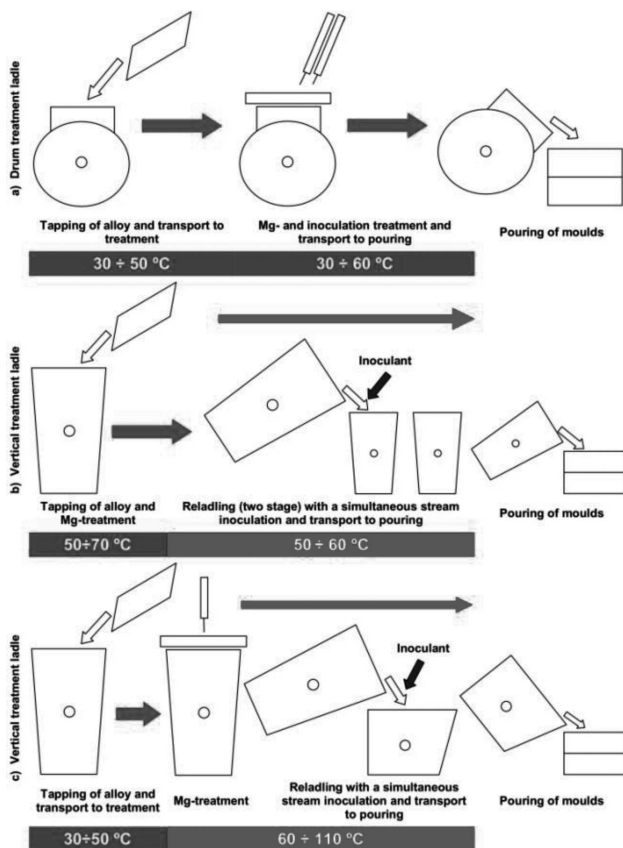


Fig. 5. Comparison of an innovative way of Mg- and inoculation treatment in (*2PE-9* method) a drum ladle a) with the old method that was used in foundry before b) and the classic technique being used in foundries c)

- reduction of the refractory consumption and labour needed for the refractory maintenance;
- energy savings;
- less carbon oxidation;
- very good pouring conditions of thin-wall castings due to a reserve of pouring temperature;

- better homogeneity of melt because of turbulent mixing during the whole Mg- treatment process;
- increase of Mg-treatment weight as well as an increase of pouring weight, due to a better geometry of the drum ladle, which is not blocked by narrowness of the pouring line of the moulding machine;
- increase of efficiency.

All those advantages guaranty stability, quality, economy and efficiency of this production process.

#### 4. Conclusions

Based on performed studies on ferritic SiMo ductile cast iron production with the innovative technique of Mg- and inoculation treatment of molten alloy in the drum ladle (*2PE-9* method), the following conclusion have been drawn:

- Vertical treatment ladle, with a min. ratio (H/D) of 2:1 is not necessary to obtain an effective and stable process of Mg-treatment. Basing on results from these tests, and using the H/D optimal ratio from HTM method [9] it can be said that in case of vertical treatment ladles, the approximate 1:1 of the molten alloy column height to its diameter is enough to obtain an optimal and satisfactory production process of nodular cast iron. In our case a H/D ratio is equal to 0.75 and placed within the optimal range from 0.7 to 0.9.
- From the practical point of view, it is important to find optimal and satisfactory minima of: freeboard height, vertical and horizontal dimensions of molten alloy in the treatment ladle. These parameters should be defined empirically in each foundry where the process of Mg-treatment is carried out. One should not forget about safety in production processes. It is also not necessary to have a 90° angle of magnesium-cored wire against molten alloy surface. This factor can be chosen empirically as well. Mg-treatment process in the drum ladle gives constant and homogeneous mixing of molten liquid metal (alloy).
- This is an important step, without any doubts creating a possibility to obtain high-quality castings with Mg- and inoculation treatment of molten alloy in the drum treatment ladle. Results from ferritic SiMo ductile cast iron production proved that this method has gained full approval of the foundry industry. Optimized production process of ferritic ductile cast iron is effective and shows a good magnesium recovery.
- One ladle in the process can be used as a treatment- transport and pouring ladle, which saves up to 95 grades of temperature loss and gives foundries a big advantage, due to the elimination of molten alloy transfer from the vertical treatment ladle to the pouring one (Fig. 5). Cutting of costs can be seen in short term; in manpower, raw materials, energy and investment.

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