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Carburization process rate in production of synthetic cast iron

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ABSTRACT

Purpose: The main goal of the paper was to determine the possibility of synthetic cast iron production on base of steel and process scraps as well as the carburization effectiveness, realized with three methods - fully described in main text.

Design/methodology/approach: Each of described methods has undoubted advantages but also has a number of disadvantages. In foundry engineering practice the most essential parameters of this process are to obtain as high as possible degree of carbon assimilation from carburizer, in as short as possible time, with high process repeatability.

Findings: Decrease of share or elimination the whole amount of the pig iron from charge materials causes reduction cost of gray or ductile cast irons melt. Now the very important issue is working out the effective and, repeatable in industrial conditions, carburization method.

Research limitations/implications: Obtained results of experiment on carburization in electric arc furnaces allow to apply pneumatic carburization method in a dozen of domestic foundries. Described in main text researches concern inductive furnaces, which are the wideness group of melting furnaces applied in foundry engineering. Basis on results of these research authors have affirmed that the method characterized with the most carburization effectiveness is the pneumatic injection of carburizer in stream of carrying gas.

Practical implications: Industrial application of pneumatic carburization method unfortunately required significant financial outlay on devices purchase. Considerably cheaper method, but characterized with less repeatability is an addition of carburizer to solid charge.

Originality/value: Realized experiment is a part of statutory researches, which are carried out in Foundry Department of Institute of Engineering Materials and Biomaterials and supply us with not only utilitarian value – worked out effective method for carburization in industrial conditions, but also experience value – rate change of carbon content increase in function of time for changeable parameters of liquid metal.

Keywords: Casting, Powder injection, Carburizing

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

In foundry engineering are still searched new methods that create new possibilities to decrease cost of castings productions with keeping, at the same time, its high quality. Still increasing economic competition and quality and strength requirements, which are put to foundry products, causes applying of new technologies. It is clear visible in process of charge materials selecting, when the partially or whole pig iron from charge material are eliminated, moreover when the more expensive materials are replaced by the cheaper ones (steel scrap and process scrap). In such cast iron melting process come into begin the carbon deficiency in liquid alloy and the necessity of its addition. Now a few methods of liquid metal carburization for electric arc and induction furnaces exist. There are:

- addition of solid carburizer to charge in solid,
- addition of solid carburizer on surface of liquid metal,
- addition of solid carburizer into tapping spout,
- addition of solid carburizer as a cored wire,
- pneumatic injection of solid carburizer to liquid metal.

Each of them has undoubted advantages but has a number of disadvantages.

In practice the most essential carburization process's parameters are to obtain high degree of carbon assimilation from carburizer, in short time, with high process repeatability.

Below are presented results experiments for carburizing with three methods:

1. addition of solid carburizer to charge in solid,
2. addition of solid carburizer on surface of liquid metal,
3. pneumatic injection of solid carburizer to liquid metal.

The aim of experiment was determination the possibility of synthetic cast iron production basis on steel and process scrap.

2. Carburization process essence

During metallurgical reactions analysis it is necessary to take into account the reaction rate in aim of find out factors, which may be conductive to acceleration given process. Carburization is a process of carbon dissolving from solid carburizer in liquid metal. It is heterogeneous process, that consist of stage each following other in specific order [11,13], namely:

- carbon separation from carburizer and formation boundary layer at carburizer surface (Figure 1),
- diffusing movement of carbon through boundary layer adjacent to carburizer surface,
- leading carbon deeper into liquid metal

Decisive influence on dissolving rate in heterogenous system have a rate of slowest process, which in considering case is carbon diffusion through boundary layer adjacent to carburizer surface.

Taking into account course of component change between two phases phenomena, often the boundaries layers model of Nerrst are used. In many works [5] the equations takes into account influence of some factors on rate of component concentration change in reacting phases are cited.

$$\frac{dC}{dt} = \frac{D_c}{\delta}\cdot\frac{F}{V}(C_{\max} - C) = k_c(C_{\max} - C) \tag{1}$$

where:

C - carbon concentration in liquid metal in %,

C_{max} - carbon concentration adequate for saturated state in given conditions in %,

D_c - diffusion coefficient in $m^2 s^{-1}$,

F – phases adjacent surface in m^2,

V – volume of phase in which component contents is changing in m^3,

δ - thickness of boundary diffusion layer in m,

k_c- mass transfer between carburizer and liquid metal coefficient (carburization constant).

Molar concentration may be replaced, with high approximation, by weight concentration. Integrating equation (15) follow equation was obtained:

$$C = C_{\max}[1 - \exp(-k_c\tau)] \tag{2}$$

The graph of equation (2) is exponential curve, is shown in Figure 2. As could be see from graph the carburization of Fe alloy course on the beginning process fast and next as carbon concentration in alloy increase, the rate of carburization decrease as practically after long time cease.

Outline of carbon concentration in liquid metal is presented in Figure 1. If carburization coursing in conditions that assure invariability of k_c coefficient in time so rate of alloy carburization in that moment is the bigger, the bigger is concentration of saturation C_{max}, which decrease, in technical Fe alloy, with temperature decreasing and silica and phosphorus contents increasing. Carburization rate increase with value of k_c coefficient increasing.

In case of carburizer include a bigger amount of ash, carburization course in conditions which make impossible its removing from carburizer surface, then as carbon dissolving the pure surface carburizer decrease as a results of its use up. Cruicial influence on these coefficient have ratio of surface of phases (between which component change take place) adhere and they volume (*F/V*). By the its ratio change in significant way the reaction course may be accelerate. In the same time, what could be see, its small value may exert an slow dawn influence on component change.

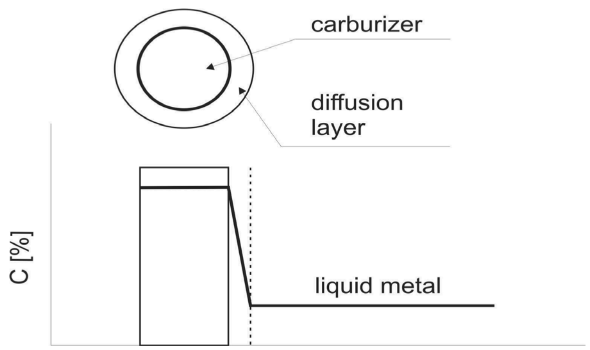

Fig. 1. Carbon concentration

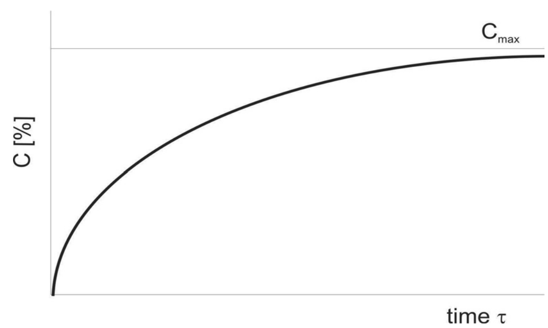

Fig. 2. Carburization curve

Taking into account that interfacial surface decrease proceeding by the exponential curve, its may be write [13]:

$$F = F_o \exp(-a\tau) \tag{3}$$

where:
F - interfacial surface in m^2,
F_o - interfacial surface in moment of carburization begins in m^2,
a - proportional coefficient, which is the mean of rate of interfacial surface change in s^{-1},
τ - carburization time in s.

Application of methods, where the value of adjacent surface and solution volume ratio increasing, makes possible to significantly increase of metallurgical reaction rate. In pneumatic injection method the fine grain materials with high surface development are used what significantly intensifying conducted metallurgical processes. Analyzing equation (1), it could be see that on reaction rate have influence also other factors such as: diffusion rate and thickness of boundary diffusion layer (Figure 2).

Diffusion rate of liquid phases component are small, but diffusion lengths are often considerable. Possibility of diffusion accelerates by the temperature changes, for the sake of limited temperature range of metallurgical processes are insignificant. However we may the aim at decrease diffusion length by putting the liquid phases, in which component change coursing, into moving. Leading the reacting component to vicinity of phase boundaries and leading out reactions products from place they occur plays significant part in whole process rate.

Using forced liquid metal movement may, in significant way influence at course of metallurgical reaction accelerate. It may be obtained by taking advantages of metal bath movement caused by electromagnetic field in inductive furnaces or by pneumatic injection powdered carburizer.

3. Guidelines of researches

Experiments were carried out in electric coreless induction furnace capacity - 20 kg. Using such furnace makes possible to carry out melts in wide range and precision controlling of temperature. Therefore in this furnace we could get high stability of carburization process, unattainable in other furnaces. Thanks to intensive metal bath movement, due to rotary currents occurring in such furnaces that ensure intensive mixing of liquid metal without necessary of mechanical mixing, carburization process proceeds faster. It connects with bigger contact layer of liquid metal to carburizer particle as a result of melt bath rotary. The intensity of this process control is possible thanks to applying furnaces with different power and frequency.

From priori experiences follow that the best carburization coefficients may be obtain in process of graphite inserting. Therefore in describing experiments scrap of graphite electrodes has been used. It had graphite content on level 96% and very small amount of impurities (ash and sulfur). In experiments graphite about granulation 0-1.6 mm and 5-8 mm has been used. Selection of such carburizer granulation was dictated by two factors. First follows from that for fine carburizers are generally considered to the best results could be obtained. It assure big surface of contact between liquid metal and carburizer, what in consequence causes increase of process course speed. Second factor is possibility of the materials loose moving in pipe of pneumatic conveying devices, for which the maximum diameter of particles should not be bigger than 1/3 diameter of conveying pipeline. That's way material with 5-8 mm particles diameter could not be use during pneumatic carburization. The result of mesh analysis for carburizer about 0-1,6mm fraction are presented in Figure 3. Equivalent diameter of its carburizer is 0.339 mm.

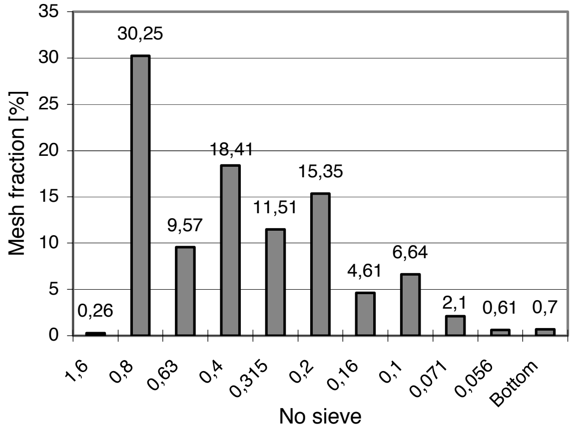

Fig. 3. Results of mesh analysis for carburizer 0-1.6 mm fraction

4. Carburizer adding to charge in solid

Steel scrap about 0.46% carbon content together with milled graphite was loaded into induction furnace crucible. After melted, metal bath was preheated to temperature of 1450°C, and next the specimen for chemical analysis was taken. The chemical analysis for carbon and sulfur contents determination was carried out with LECO devices. In Table 1 are presented obtained results of measurements and calculations.

Essential factor of carburizaton process is carburization effectiveness, which could be determined with equation:

$$E = m_m \frac{(C_k - C_p)}{m \cdot C_x} \tag{4}$$

C_p [%] – carbon content at the beginning of the process [%],
C_k [%] – carbon content at the end of the process,
m_m [Mg] – metal mass,
m [Mg] – mass of the carburising material [Mg],
C_x [%] – carbon content in the carburising material [%].

In carburization processes the coefficient determines carbon content increasing per time are used it is called carburization rate, calculated with equation [11]:
Carburization rate:

$$S = \frac{(C_k - C_p)}{t} \tag{5}$$

t - time of carburizing [s]

Carburization processes are often carried in furnaces about different capacity. Authors inserted to carburization processes analysis the same carburization rate, determined with equation [11]:

$$S_j = \frac{S}{m_m} \qquad (6)$$

Admitted parameter significantly better describe carburization process and become much universal, independent from liquid metal mass. That gives possibility to compare obtained carburisation rate in different furnace unit. Analysis of pneumatic carburisation process revealed that application of this coefficient makes possible to obtain much higher statistical parameters of equation describing influence of individual quantities on carburisation process [7].

In caburization method by putting carburizer to charge materials on furnace bottom the carburisation rate and unitary carburisation rate were not analysed for the sake through lack of possibilities to time of course process determination. This time not be equal with metal melting time.

Table 1.
Comparison of results obtained in each melt carburised with addition of solid carburizer onto bottom of furnace

No of melt	Fraction [mm]	m_m [kg]	m [kg]	C_p [%]	C_k [%]	E [%]
1.1	0-1.6	11.0	0.15	0.46	1.56	84.9
3.2	0-1.6	11.0	0.15	2.38	3.30	71.0
4.3	5-8	11.0	0.15	0.46	1.27	62.5

In this method of carburization effectiveness was changing in range of 62.5-84.9%. The biggest effectiveness has been obtained for carburisation with fine carburizer and for carbon content on level 0.46% at the beginning of the process. Using carburizer in chunks caused decrease of effectiveness to 62.5%. From experiment's results follow that effectiveness significantly decreases for the carbon content in metal bath at the beginning of the process increases. Authors anticipate carrying out further cycle of experiments in aim of influence of granulation and the type of carburizer on process efficiency determination. Using the anthracite, naturals graphite as well as petroleum coke is anticipated. Specificity of this method consist on that carburizer is heated along with metal charge. Before carburisers applied in this method are not put such high demands as in other methods (granulation, homogeneity, humidity). Essential is that carburizer includes as high as possible amount of carbon and as low as possible amount of sulphur.

5. Carburizer on liquid metal surface

After the metallic charge was melted and the right temperature (1450°C) was reached, the specimen for chemical analysis was taken. Next the weighted portion of carburizer was put on liquid metal surfaces and the process of taking specimens, with quartz pipe, in specific time interval, for chemical analysis was being.

In Table 2 and Figure 4 obtained measurements and calculations results and growth rate of carbon content in time are presented.

Effectiveness of carburization in range 60.9-91% has been obtained for this method. The biggest effectiveness has been obtained for carburisation by adding chunks of carburizer on liquid metal surface.

Table 2.
Comparison of results obtained in each melt carburised with addition of carburizer on metal bath surface.

No of melt	Fraction [mm]	m_m [kg]	m [kg]	C_p [%]	C_k [%]	E [%]
1.4	0-1.6	11.0	0.15	1.56	2.59	79.5
2.6	0-1.6	11.0	0.15	1.25	2.23	79.2
3.7	0-1.6	11.0	0.15	3.30	4.09	60.9
4.8	0-1.6	11.0	0.15	1.27	2.45	91.0
4.9	5-8	11.0	0.15	2.45	3.36	70.2

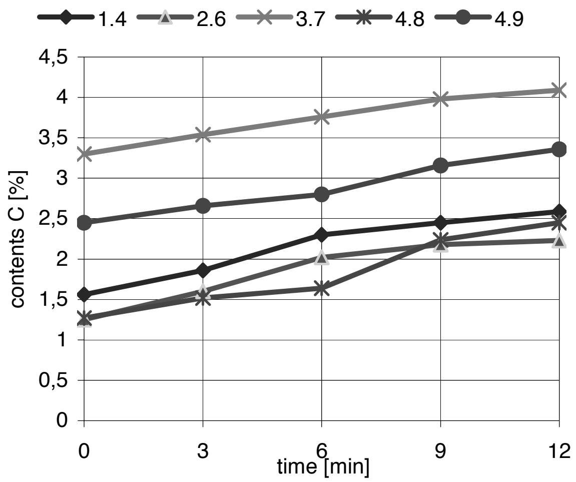

Fig. 4. Carbon content growth rate during carburisation process in addition of carburizer on liquid metal surface method

Considering the influence of carbon content at the beginning of the process on carburisation effectiveness follows that this factor decreases. Using fine-grain carburisers causes arising a layer of graphite on liquid metal surface. Therefore surface carburizer - liquid metal is decreasing, because contact with metal bath have only the closest thin layer. The next layers come into contact with liquid metal after the first layer solubilized. Duration of melt for this method lengthened even above 100%. Because time of waiting for graphite solubilization lengthening. Some acceleration may be obtained by the mechanical mixing of liquid metal but in industrial applications this is difficult by reason of significant depth of induction furnaces reason.

6. Injection of carburizer

Inserting of fine-grain carburizer in stream of carrying gas causes that surface of carburizer-liquid metal contact is very big, in that reason process's rate and effectiveness are very high. But applying this method requires high knowledge about diphase stream flow [6]. In addition the gas mixes liquid metal and products of carburization process are very fast leaving the reaction zone. Movement of carburizer particles also causes that the thickness of diffusion layer decreases what as a results accelerates, between carburizer and liquid metal, process of mass exchange [5,12]. Mentioned above advantages were caused applications of carburization by pneumatic injection to liquid metal in electric arc furnaces in many Polish foundries [10].

During analyze of process of powdered material injection in carried gas stream may be distinguished in it several elements. Powdered reacting substance, carried gas, batching and control system, and transportation system, construction and insert way of the lance, liquid metal properties, and phenomenon occurring during injection of gas-powder mixture to metal batch. Each of them has several characteristic features or properties. In the Figure 5 comparison of basic factors characterized process of pneumatic injection powders are presented. This process besides technological and economical dimension has human factor taken into account very rare. It makes possible to decrease of smelters work onerous. Injection of big amount powdered materials in carried gas stream eliminates physical hard work more over application of devices and lance manipulators automation reduce device service to one person.

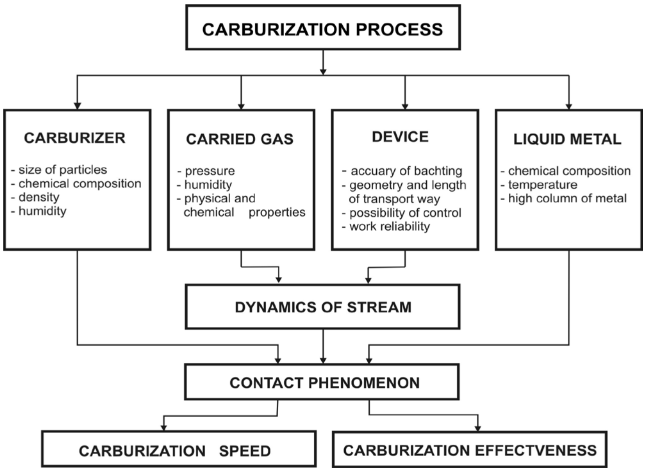

Fig. 5. Course of powder pneumatic injection process

Usefulness of carburization by pneumatic injection to liquid metal method in depend on specific foundry realities may be considered in many aspects,.

In case of using pig iron as a charge this method makes possible partially or even completely to eliminate and replace it with steel scrap, what in consequence give:

- melt cost reduction - price difference of these charge materials,
- use bigger amount of steel scrap which is low useful material for low carbon content sake,, in many cases for cast iron foundry,

Describing method makes possible in pig iron-less melting process:

- certain and quick correction of carbon content after melted metal charge materials (shortening carburization time and as a results melt time)
- production of different cast iron range, even nodular cast iron which required higher carbon content, basis on process and steel scrap,
- reduction of graphite materials dusting in comparison to traditional methods, carburizer are injected under the liquid metal surface,
- furnace servicing facilitation, by elimination hand carburizer loading and it replacing with accurate pneumatic batching.

6.1. Stand of gas-operated carburizing

The main part of the device is a 3 dm^3 volume pressure tank 1 (Figure 6 and Figure 7). Such volume ensures material proportioning properly portion and makes possible its increase. At the upper part of the tank, a bell seal 4 is situated, and a mixing chamber 2 below. For pressure relief of the tank after the termination of each working cycle, a venting valve is mounted on the tank. Reducers 6 and 7 control pressure of gas supplied to the tank. To supply or cut off the gas supply serve master valves 5 and 9. The valves (bell 4 closure and opening of mixing chamber 2, master 5 and 9) are started manually.

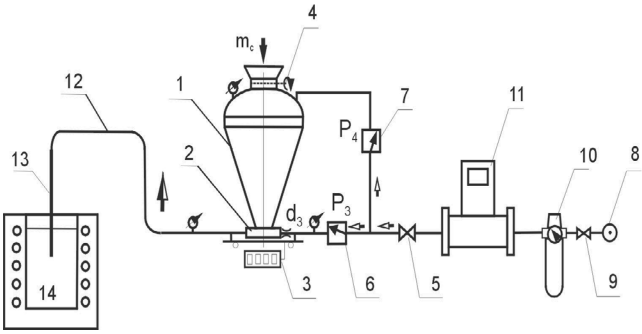

Fig. 6. Stand of gas-operated metal bath carburising scheme

Fig. 7. Device for carburizer proportioning

The tank is on a strain gauge scale 3, which indications are displayed on the control panel. In its initial position, the balance indicates a mass of material in the tank (net). It shows a quantity of material, at the moment of starting the haulage cycle, which has been inserted into liquid metal. For displaying the mass left in the device the haulage have to be switch off. It is very comfortable for the staff. A pipe 12, terminated in a lance 13, which is inserted into an induction furnace 14, transports carburizer. The lance diameter was 5 mm. As a carrying gas for pneumatic conveying the argon taking from cylinder 8 was used. In supply installation also the filter 10 was applied. Thermal gauge of flow 11 was used for gas flow intensity measure.

Before begin the technological tests, experiments make possible to determine profile of proportioning device work were carried out. Instead of furnace (Figure 5) the receive device was applied. Transported material was grounded scrap of graphite electrodes about 0-1.6mm granularity. Experiments were carried out with 4, 5, 6, 8 mm lance diameter. Overpressure in supply system was changed in range 100 – 300kPa. By the using different nozzles diameter in mixing chamber the following ranges of transportation parameters changes have been obtained:

- gas flow intensity m_g = 0.000367-0.0034 kg/s,
- material flow intensity m_c = 0.0035-0.086 kg/s,
- speed of gas on lance muzzle w = 4.75-120.25 m/s,
- mix mass concentration 3.74-119.16 kg/kg.

In processes of pneumatic injection powder into liquid metal more essentially is obtain the right speeds on lance muzzle than economical coefficient of moving, as it take place in case of pneumatic transport. For selection proper diphase stream parameters (gas and material flow intensity) tentatively researches were carried out. They consist on test melts performed in which flow parameters of devices were changed. These melts were realized in range of gas flow intensity 50÷70 l/min, lance diameter 5mm, efficiency 0.05-0.08 kg/s. It turned out that for these parameters a big splashing of liquid metal takes place with dipped lance. Injection with lance being above liquid metal surface had not brought expected results, because carburizer stayed on surface and without addition mechanical steering it was not dissolving in liquid metal. High value of graphite flow intensity caused that significant part of it, despite dipped lance, surfaced caused that obtained carburization efficiency was on level 30-40 %. Basis on these tests established that gas flow intensity should not cross range 30-40 l/min. Supply overpressure amount 100 kPa, overpressure in proportioning device amount 20 kPa. These ensured obtain gas flow intensity on level m_g=0.00047 kg/s and material flow intensity on level m_c=0.010638 kg/s. Priori experiments also reveals that use the air as carrying gas cases very intense liquid metal splashing. It is a result of two reasons. First is that one of air component is oxygen which significantly intensify carbon combustion. Second is a contents humidity and oil impurity in air. Despite applied dewaterer in system part of these impurities are floating in gas stream into metal bath cases its addition splashing. Application of argon significantly reduces both these factors. But owing to economical factors in industrial processes instead of argon may be applied significantly cheaper nitrogen.

6.2. Course of carburizing process

After the metallic charge was melted and the right temperature (1450^{o}C) was reached, the specimen for chemical analysis was taken. Next the weighted portion of carburizer was poured into the tank of batching device. After open gas supply valves, lance had been immersed and carburizer was being batched into liquid metal. After injection of whole portion of carburizer, material supply and gas supply was cut. Specimen for chemical analysis was taken right after end of process. In table 3 are presented results of carburising process effectiveness.

Table 3.
Comparison of results obtained in each melt carburised with pneumatic injection of carburizer to liquid metal

No of melt	Fraction [mm]	m_m [kg]	m [kg]	C_p [%]	C_k [%]	E [%]
5.1	0.21	0.7	0.49	14	0.09	80.2
5.2	0.7	1.23	0.53	14	0.09	86.8
5.3	1.23	1.8	0.57	14	0.09	93.3
5.4	1.8	2.35	0.55	14	0.09	90.1
5.5	2.35	2.86	0.51	14	0.09	83.5
5.6	2.86	3.28	0.42	14	0.09	68.8
5.7	3.28	3.68	0.4	14	0.09	65.5
5.8	3.68	4.06	0.38	14	0.09	62.2

In Figure 8 obtained carburization efficiency for individual experiments and in Figure 9 carburization efficiency changes in dependence on initial carbon content in metal bath are presented.

In this method effectiveness in range 62 – 93% has been obtained. It may be observed that effectiveness decreasing along with carbon content.

Using too high carburizer flow intensity caused lower carburisation efficiency in test 5.1 and 5.2. It caused surfacing part of carburizer and as a result efficiency decreasing in that test and it increasing in test 5.3.

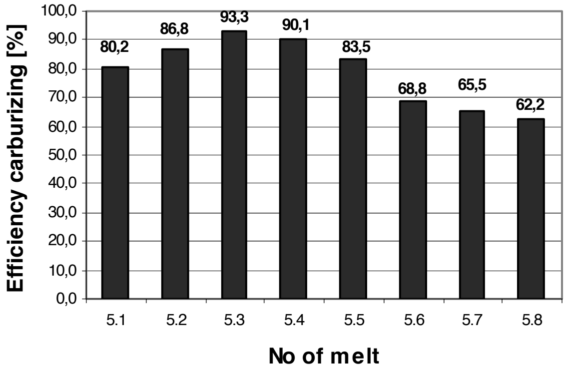

Fig. 8. Obtained efficiency of pneumatic carburization for each measures

Advantage of this method is very short time of carurization. Practically right after end of material batching (with well matched parameters of diphase stream), carburizer is solubilized by liquid metal. The right course of carburisation process dependent on selection right pneumatic transport parameters what the tentatively researches proved. Its mean that in industrial applications determination of these parameters should be work depending on individual demanding of foundry and size of furnace in which the process are realized.

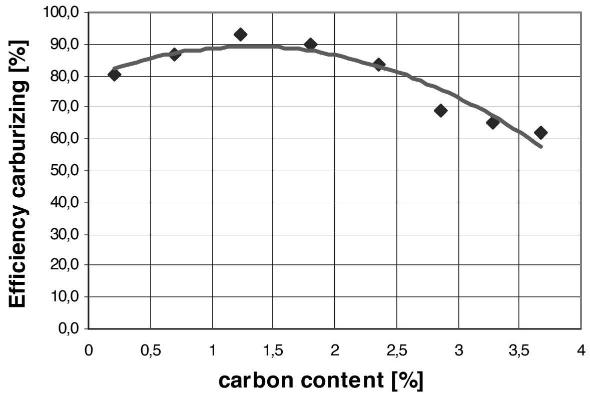

Fig. 9. Carburization efficiency in function of carbon content in liquid metal at begin of process

Pneumatic injection of carburizer to liquid metal is modern method applied in synthetic cast iron production with precision carbon content control. Unfortunately this process requires application of batching device and gas supply installation. Next disadvantage is a metal splashing during course of carburizer batching process. It requires application the furnace cover and selection proper diphase stream parameters injection to metal bath.

7. Summary

Experiment for metal bath carburizing in electric induction furnace with three methods show that melted high quality cast iron basis on only steel and process scrap is possible. Tested methods of carburization make possibility to obtain degree of making carbon use in range of 60-91%. Selection of carburizer type, for each method, and parameters of its insertion (in case of pneumatic carburization) is necessary. Carried out researches in field of cast irons, obtained in these ways, quality (not presented in this work) [1,2,14,15], have shown that there are no differences in properties of synthetic cast iron and cast iron melted from pig iron. It concerns as well as gray cast iron and ductile cast iron but only on condition that proper quality of steel scrap have been assured. Significant decreases costs of cast iron melt causes by limitation or elimination of pig iron from charge material.

Addition of carburizer to solid charge materials makes possible to obtain high effectiveness. But this method not secures right repeatability of process therefore it caused necessity of carburization by other method [3].

Addition of carburizer on liquid metal surface method unfortunately significantly lengthens melt's time and in practice it may be used only for replenishing small carbon deficiency.

Method of the carburizer pneumatic injection makes possible to obtain high effectiveness, short process's time and its right repeatability. But requires significant financial outlay on proportioning devices purchase and also requires carrying gas supply. By research worker of Foundry Department in Institute of Engineering Materials and Biomaterials, Silesian University of Technology, have been carried out researches for pneumatic injection of solid particles into liquid metallic composite matrix [4] and pneumatic injection of alloy additions into metal bath [8,9,10].

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