

# Melting of Grey Cast Iron Based on Steel Scrap Using Silicon Carbide

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## Abstract

The paper presents the issue of synthetic cast iron production in the electric induction furnace exclusively on the steel scrap base. Silicon carbide and synthetic graphite were used as carburizers. The carburizers were introduced with solid charge or added on the liquid metal surface. The chemical analysis of the produced cast iron, the carburization efficiency and microstructure features were presented in the paper. It was stated that ferrosilicon can be replaced by silicon carbide during the synthetic cast iron melting process. However, due to its chemical composition (30% C and 70% Si) which causes significant silicon content in iron increase, the carbon deficit can be partly compensated by the carburizer introduction. Moreover it was shown that the best carbon and silicon assimilation rate is obtained where the silicon carbide is being introduced together with solid charge. When it is thrown onto liquid alloy surface the efficiency of the process is almost two times less and the melting process lasts dozen minutes long. The microstructure of the cast iron produced with the silicon carbide shows more bulky graphite flakes than inside the microstructure of cast iron produced on the pig iron base.

**Keywords:** Synthetic cast iron, Grey cast iron, Silicon carbide, Ferrous alloys carburization, Cast iron microstructure

## 1. Introduction

Synthetic cast iron melting on the steel scrap base only (without the pig iron in solid charge) was presented in many previously published papers [1-3]. Pig iron elimination from the solid charge requires liquid alloy carburizing process. Therefore a good selection of the carburization method and the carburizer must be done. So far the anthracite, synthetic graphite and petroleum coke were used as carburizers [4-6]. The experimental results shown that the carburizer has a significant impact on the produced cast iron properties. It concerns the carburization efficiency and as a consequence the carburizer consumption, the mechanical properties and the cast iron microstructure, too [7,8].

The research proved the possibility of synthetic grey cast iron production exclusively on the steel scrap and carburizers base.

This iron possess less impurities content as sulfur and phosphorus in comparison to cast iron melted on the pig iron base. The experiments shown that the phenomenon of the microstructure heredity appears – some features are transferred from charging materials into produced cast iron. In this case the heredity is based on the features of the carburizers transferred into cast iron. It was stated that it is possible to produce the cast iron of similar chemical composition and even better quality indexes when cheaper charging materials are being used.

The experiments led to the conclusions that the best charging materials from the carburization efficiency point of view are: synthetic graphites, petroleum coke, natural graphites and the anthracite [4-6]. When the anthracite is added on the molten alloy surface the high efficiency can be obtained, too, but it requires higher liquid bath overheating and longer processing time for the carburizer proper dissolution. The efficiency of the carburizer

addition together with the solid charge in induction furnace is in range from 70 to 96%. Normally it is not difficult to achieve over 80% carburization efficiency for every carburizer with very good repeatability, but it requires keeping the process parameters in strictly adjusted range. When the carburizer is added on the liquid alloy surface melted in the induction furnace the carburization efficiency is less and is situated between 63 and 81%.

The synthetic cast iron melting requires the silicon deficit in alloy chemical composition compensation. So far it was conducted by ferrosilicon addition into liquid metal during the final melting process stage. This paper presents the experiments where FeSi was replaced by silicon carbide.

After the literature data analysis it can be concluded the silicon carbide dissolves much slower than FeSi so it is a source of many crystallization nuclei. These nuclei life is much longer so the silicon carbide usage can significantly extend the cast iron inoculation process duration. The mechanism of this process has not been completely understood yet, but it was proved that during the SiC dissolution inside the cast iron its particles are surrounded by the graphite clusters. This is the result of the local alloy oversaturation with Si and C. The graphite clusters are thermodynamically metastable over some time period so they play a very important role in nucleation process and eutectic graphite creation. The ferrosilicon dissolution can also promote the graphite clusters appearing but due to its higher dissolution rate these clusters remain stable over a short time period only. The silicon carbide addition causes that graphite clusters are present much longer than those obtained when the ferrosilicon is introduced. The creation of graphite clusters around of many SiC particles decreases carbon content in the rest of alloy volume so the nucleation starts in higher temperature. That is why the silicon carbide usage results in liquidus temperature increase and in more eutectic cells number when compared to the alloy processing by the ferrosilicon addition [9,10].

## 2. Silicon carbide

Silicon carbide SiC (popularly known as carborundum) is a chemical compound consisted of 70% wt. of silicon and 30% wt. of carbon. It is a product of high temperature synthesis of silicon dioxide with carbon. The process is carried out in resistance furnace (invented by Acheson) which works similarly to carbonaceous materials graphitization furnace. The raw materials for silicon carbide production are: silica sand with SiO<sub>2</sub> content over 98%, petroleum coke with ash content not higher than 1.0%, rock-salt and sawdust. These materials have a grain size from 0.5 to 2 mm and after thorough drying process they are placed inside the furnace. The furnace is through in shape and length from 10 to 20 m and width from 2 to 3 m. The electrodes supply the electrical current and are situated inside the frontal furnace walls. Under low temperature such mixture has a small electrical conductivity. Therefore in the electrodes axis along the furnace the conductive core appears made of crushed electrode graphite. During the heating the sawdust is carbonized. It allows removing the volatile parts created inside the furnace due to the sodium chloride reaction with the Fe and Al reduction products, which lowers the properties of the produced SiC. The heating process lasts typically one twenty-four hours period and a maximum

temperature equals 2000°C. Produced in the furnace sintered block of several products possess the layered structure presented in the Fig. 1 [10-12]. The coarse silicon carbide of the best quality creates the layer directly surrounding the graphite core. The next layer is fine silicon carbide (less valuable) which is surrounded by the Si<sub>2</sub>C<sub>2</sub>O so-called 'siloksykon' of transient chemical composition [11].

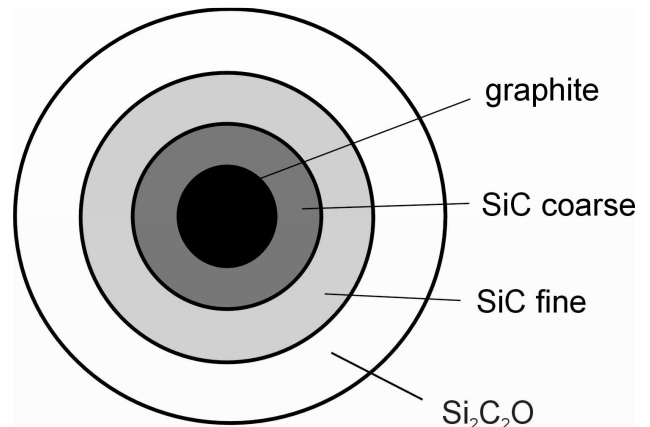


Fig. 1. Cross-section of block of sintered products made in resistance furnace used for carborundum production [12]

Then coarse silicon carbide fraction is enriched during the process of graphite, silicon, FeSi and AlSi elimination with use of hydrosulfuric acid and electromagnets [12,13]. The silicon carbide color depends on the amount and type of impurities being present in it. The general properties of the silicon carbide are listed in Table 1 [12,13].

Table 1. Silicon carbide properties

Property	SiC green	SiC black	SiC metallurgical
Minimum SiC content, %	97	96	88
Maximum Fe <sub>2</sub> O <sub>3</sub> content, %	1.0	1.0	1.0
Maximum C content, %	0.2	0.3	0.3
Maximum magnetic fraction, %	0.4	0.4	0.5
Transparent mineral admixture, %	1.5	2.0	2.0
Opaque mineral admixture, %	1.5	2.0	2.0
Density, g/cm <sup>3</sup>	3.1-3.2	3.1-3.2	3.1-3.2

Totally pure silicon carbide is colorless. Its hardness is similar to diamond's hardness (SiC hardness according to Mohs' scale equals 9-10 while diamond hardness equals 10). That is why it is commonly used as abrasive material. It is especially good for plastics machining which have high hardness and low tensile strength. Thanks to its high thermal and chemical resistance it is used for crucibles and refractory pipes manufacturing. The ability for electric current conductivity resulting from SiC

semiconducting properties, makes possible to produce from this material the heating elements for use in electric heating furnaces.

### 3. Experimental procedure

During the experiments the grey cast iron melts on the steel scrap base of various chemical compositions were carried out. They were prepared exclusively on the steel scrap base and the graphite carburizer addition. In all melts the silicon content was compensated by the silicon carbide addition into solid charge or ferrosilicon addition on the liquid metal surface immediately after the charge was melted down. The grey cast iron melt was carried out on the foundry pig iron base for comparison. The steel scrap in solid charge amount was 10 kg. The iron was melted in high frequency electric induction furnace of 20kg capacity. The chemical composition of the steel scrap used during the experiments was presented in Table 2.

Table 2.

Chemical composition of the steel scrap

No.	C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cu [%]
Z1	0.20	0.27	1.28	0.015	0.027	0.19
Z2	0.07	0.00	0.63	0.016	0.001	0.00

The synthetic graphite labeled GS was used as a carburizer during the iron melting and its chemical composition was presented in Table 3.

Table 3.

Chemical composition of the graphite carburizer

Carburizer	Chemical composition					
	C [%]	S [%]	Volatiles [%]	Ash [%]	N [%]	H [%]
GS	99.35	0.040	0.25	0.57	0.01	0.01

For carburization and silicon deficit compensation the silicon carbide of metallurgical grade and 'black' silicon carbide of chemical composition presented in Table 1 were used. Additionally for silicon deficit compensation the ferrosilicon was used and its chemical composition was: 75% Si, 1,5% Al, 0,2% C. The complete charging material selection was presented in Table 4.

In the melt labeled W5m2sf the silicon carbide was added on the liquid metal surface. The melt labeled W6synth is that carried out on the steel scrap base only. The melt labeled W7pig means the cast iron produced on the pig iron base. The last two melts were carried out to compare the microstructure of the obtained cast iron grades. In the table the label  $M_{met}$  means the metallic solid charge weight. In the melts W0-W6 it is weight of the steel scrap and in the melt W7pig it is total weight of steel scrap and foundry pig iron. FeSi, SiC and carburizer (GS) denote consequently weight of ferrosilicon, silicon carbide and the carburizer added into solid charge.

Table 4.

Solid charging materials selection

Melt label	$M_{met}$ kg	FeSi kg	SiC kg	GS kg
W0m1	9.18	0.00	0.38	0.17
W1m1	10.18	0.19	0.48	0.06
W2cz1	11.70	0.00	0.35	0.31
W4m2	9.24	0.00	0.29	0.27
W5m2sf	9.30	0.00	0.32	0.30
W6synth	11.59	0.30	0.00	0.44
W7pig	10.52	0.12	0.00	0.00

During each melt the samples were taken to make chemical analysis and the solidification and crystallization curves were recorded. The chemical composition of the produced cast iron was presented in Table 5.

Table 5.

Chemical composition of the produced cast iron

Melt label	C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cu [%]
W0m1	3.25	2.00	0.64	0.019	0.0140	0.058
W1m1	3.05	2.21	0.69	0.022	0.016	0.052
W2cz1	3.36	1.88	0.57	0.017	0.012	0.034
W4m2	3.24	2.04	0.68	0.016	0.013	0.029
W5m2sf	3.37	0.95	0.56	0.019	0.014	0.073
W6synth.	3.30	1.96	0.46	0.033	0.024	0.028
W7pig	3.32	1.95	0.57	0.044	0.020	0.200

The eutectic saturation ratio  $S_C$  (see Table 6) was calculated from the equation (1):

$$S_C = \frac{\%C}{\%C_{eut}} = \frac{\%C}{4.26 - 0.31 \cdot Si - 0.33 \cdot P} \quad (1)$$

The important parameter characterizing various additions introduction from the technological point of view is the efficiency (effectiveness, chemical element assimilation in liquid alloy). In the case of these experiments the efficiency is calculated for the carbon and silicon assimilation rate. The estimated efficiency decides how much silicon carbide must be added to obtain planned increase of these elements in the molten alloy. The carburization efficiency (effectiveness)  $E_C$  or silicon by molten metal assimilation rate  $E_{Si}$  can be described by the relationship:

$$E = M_m \frac{C_k - C_p}{M_{SiC}} \cdot 100\% \quad (2)$$

where:  $C_p$  – initial carbon or silicon content in solid charge in %,  $C_k$  – final carbon or silicon content in the cast iron in %,  $M_m$  – molten alloy mass in kg,  $M_{SiC}$  – amount of silicon carbide added in kg.

The calculations of carbon and silicon assimilation rate by the liquid metal are imprecise in some extent because the superior goal was to obtain the hypoeutectic cast iron class GSL200 or GSL 250. This is the reason to ensure the specific chemical composition. When only SiC is added in solid charge the final

carbon content is too small. Therefore into solid charge some amount of the synthetic graphite was added, too. On the base of wide experience in the carburization the process efficiency was estimated on the level of  $E_C=90\%$ . The results of carburization efficiency and eutectic saturation ratio were presented in Table 6.

Table 6.

Charging materials used during the experiments

Melt label	$S_c$ -	$E_C$ [%]	$E_{SiC}$ [%]	$E_C + E_{SiC}$ [%]
W0m1	0.894	28.59	49.53	78.12
W1m1	0.855	-	-	-
W2cz1	0.915	27.85	59.47	87.32
W4m2	0.894	14.91	66.75	81.67
W5m2sf	0.851	9.43	25.69	35.12
W6synth	0.906	-	-	-
W7pig	0.912	-	-	-

The analysis of the eutectic saturation ratio shows that it is inside the range of 0.85-0.91. All cast iron grades produced in the experiments are the hypoeutectic ones.

The calculations of carbon or silicon assimilation were carried out for the total mass of added silicon carbide (assuming 90% SiC in metallurgical grade and 97% SiC for the black grade). The same calculations can be carried out for the carbon content of 30% C and Si content of 70% Si.

The experimental results show that more efficient method of silicon carbide is its dosing into solid charge than adding onto liquid metal surface. This shows the carbon and silicon assimilation rate in the first addition method as well as liquid metal observation where after solid charge is melted down there were no unreacted SiC on the liquid surface. Where SiC was added onto liquid metal besides the additional metal bath mixing even after 10 minutes the significant amount of unreacted silicon carbide remained what proved twice less efficiency of carbon and silicon utilization in the molten alloy.

During the analysis of the total efficiency of utilization of both elements (carbon and silicon) with SiC it can be observed that there are some small differences between particular melts. While individual analysis of the carbon and silicon utilization is conducted much bigger differences can be observed (for example  $E_C$  in melts W0m1 and W4m2). In both cases the metallurgical silicon carbide grade was used but from two different suppliers. So it should be further checked if this is some kind of regularity of only single case.

## 4. Cast iron microstructure

In the case of cast iron melting on the base of the steel scrap the cast iron microstructure is often questioned. Therefore during these experiments the metallographic samples were prepared for all the melts. The microstructure of the produced cast iron was presented in Fig. 2-6. For the purpose of cast iron matrix observation the samples were then etched in 3% nital reagent. The photographs of the etched microstructures for the each melt were presented in Fig. 7-11.

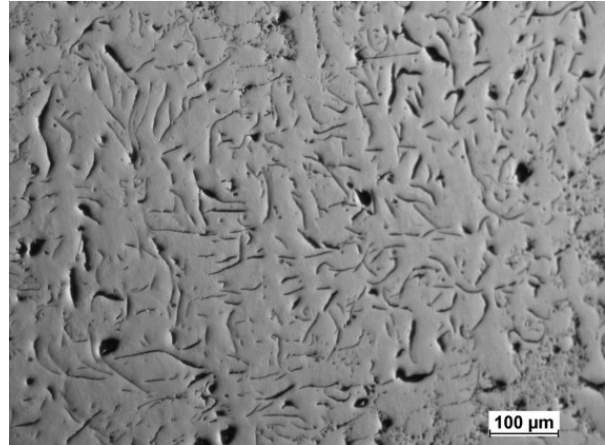


Fig. 2. Cast iron W0m1 (SiCmet1) microstructure

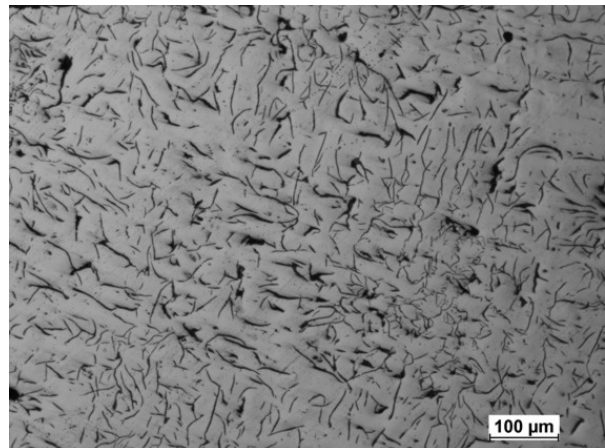


Fig. 3. Cast iron W2cz1 (SiCcz1) microstructure

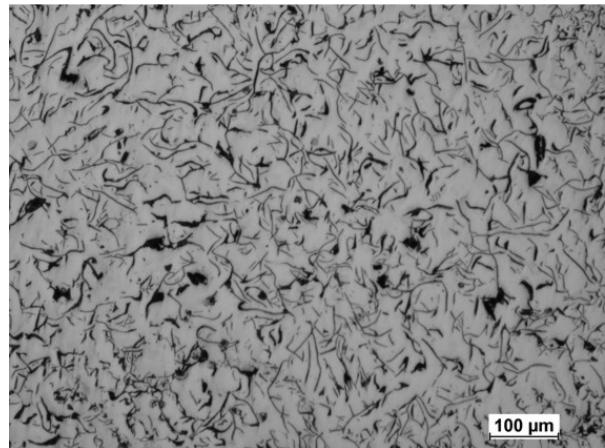


Fig. 4. Cast iron W4m2 (SiCm2) microstructure

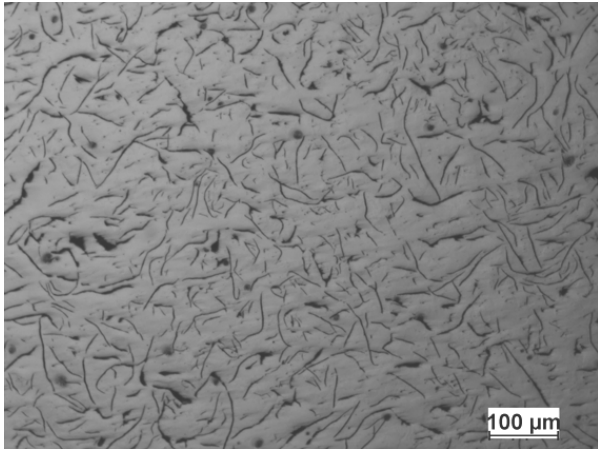


Fig. 5. Cast iron W6synth (FeSi75) microstructure

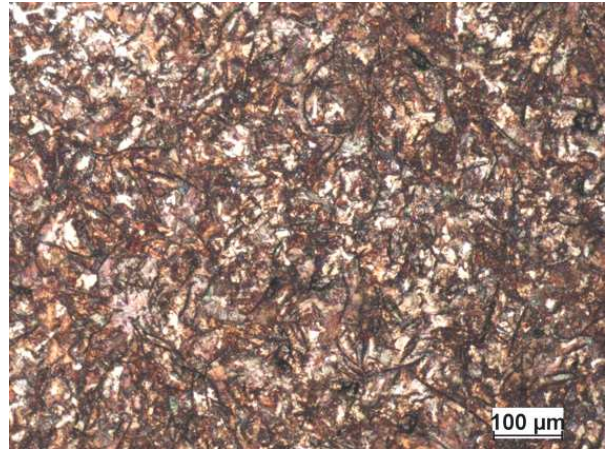


Fig. 8. Cast iron W2cz1 (SiCcz1) matrix

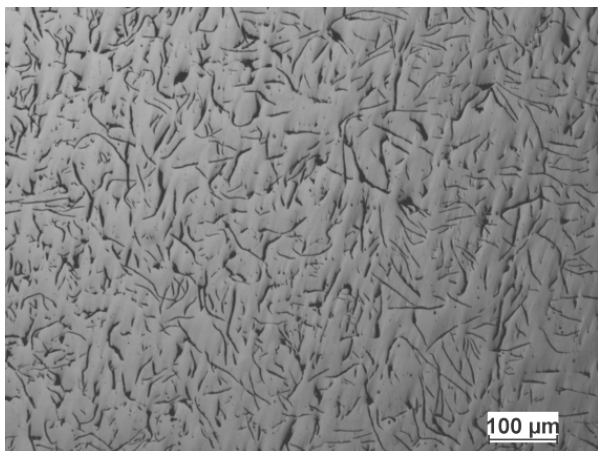


Fig. 6. Cast iron W7pig (FeSi75) microstructure

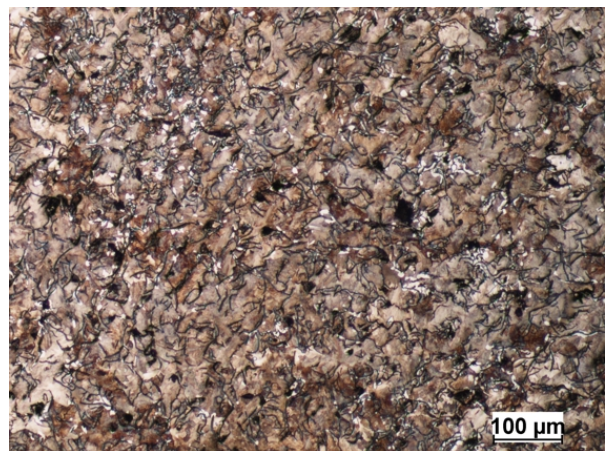


Fig. 9. Cast iron W4m2 (SiCm2) matrix

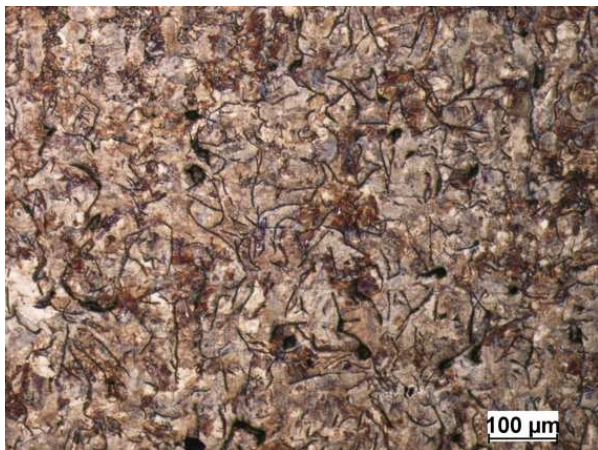


Fig. 7. Cast iron W0m1 (SiCmet1) matrix

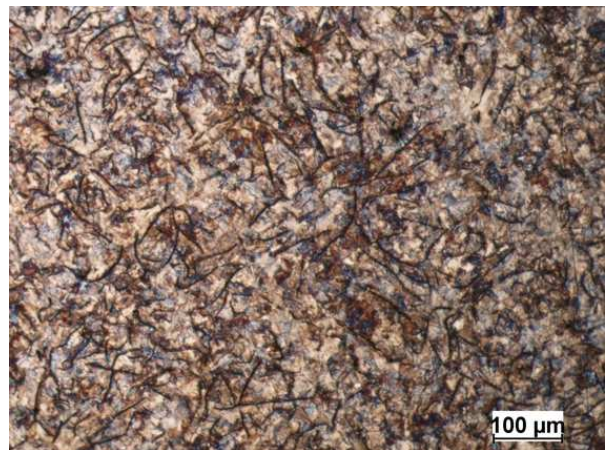


Fig. 10. Cast iron W6synth (FeSi75) matrix



Fig. 11. Cast iron W7pig (FeSi75) matrix

After the photographs analysis it was stated that for both the cast iron melted on the pig iron base and that produced on the steel scrap base where the silicon deficit was compensated with silicon carbide addition, some differences between graphite precipitation shape and its amount and size can occur. The largest group was the fields with uniform flake graphite precipitations. Some areas of orderly oriented interdendritic graphite flakes appear and the fields of ‘whirled’ precipitations shape, too. In the obtained synthetic cast iron microstructures produced with use of silicon carbide more bulky graphite flakes in comparison to that iron melted on the base of pig iron can be observed.

On the base of matrix analysis inside the produced synthetic cast iron (Fig. 7-11) it can be stated that in majority of the samples the pearlitic matrix appears or pearlitic one with the only small amount of ferrite inside it.

## 5. Conclusions

The carried out experiments shown that synthetic cast iron can be produced exclusively on the base of steel scrap with the part of carburizer replacement by the silicon carbide. It enables in the same time to compensate small silicon deficit occurring. The produced cast iron has a larger graphite precipitations amount. Additionally these precipitations are slightly thicker.

The best method of silicon carbide addition from the carbon and silicon assimilation ratio point of view is its addition into solid charge. When SiC is added onto liquid metal surface the efficiency can decrease twice and the melting time must be enhanced of dozen minutes.

The efficiency of the carbon utilization when the SiC was added into solid charge was  $E_C=14.9-28.6\%$ , whereas silicon assimilation ratio was  $E_{Si}= 49.5-66.7\%$ , besides similar silicon carbide chemical composition. The total efficiency of both elements utilization changed in very tight range 78.1-81.6%.

On the solidification and crystallization curves recorded so far the significant differences between liquidus temperature for the particular melts were not observed. The literature suggests in some places that silicon carbide should increase this temperature point [9].

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