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# Influence of Charge Materials on the Metallurgical Quality of Gray Cast Iron

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## Abstract

The article presents the influence of the percentage share of pig iron and steel scrap on the chemical composition, physicochemical and mechanical properties. Using an induction furnace, 6 melts were carried out with a variable amount of pig iron in the charge from 0 to 50%. For carburizing, a RANCO 9905 carburizer with a carbon content of 99.2% was used. After melting and introducing FeSi75, temperature measurement was carried out and the metal was superheated to 1500°C. The next step was to pour the samples for chemical analysis, DTA (Derivation Thermal Analysis) and strength and hardness from the melting furnace without inoculation. The last step was to carry out the inoculation by introducing 0.3% barium inoculant into the vat and pouring samplers for DTA analysis. The inoculation was carried out solely to determine changes in DTA parameters, mainly $T_{emin}$, compared to castings without inoculation.

**Keywords:** Gray cast iron, Thermal analysis, Cast iron properties, Charge materials, Cast iron inoculation

## 1. Introduction

The correct selection of the charge materials has a huge influence on the effectiveness of the cast iron melting process. The grade of the obtained cast iron depends on the type and percentage of the individual components of the charge, as well as the furnace used. The charge materials can be divided into: basic materials (the main materials of the smelted alloy), auxiliary materials and alloy additives (additives changing the chemical composition or carriers of alloying additives) and materials removing impurities [1,2,3].

An important role in the selection of charge materials plays price, availability and their quality. There is a strong correlation between the cost of total melting and the price and availability of materials such as returned scrap, iron scrap, and steel scrap, which is directly related to the need for a carburizer, which increases the cost of production. Pig iron can be used to produce traditional cast iron. It is a key element of the charge, in many cases accounting for even half of its mass. Typically, it contains 3.5-4.5% C and is a blast furnace product. This group of materials includes hematite, processing, special and synthetic pig iron. In order to obtain the appropriate carbon content for specific grade of cast iron with the pig iron in the charge, the dilution operation, involving the introduction of steel scrap, should be applied.

It is also possible to carry out the cast iron melting process without pig iron, creating so-called "synthetic" high purity cast iron. The pig iron is replaced by steel scrap, and the carbon deficit is supplemented by carburizer. The auxiliary charge materials are ferroalloys, i.e. iron alloys with elements such as silicon, manganese, molybdenum, chromium and others.

Very rarely, pure additives are added to the liquid metal due to too large difference in the melting point, high vapor pressure and strong affinity to oxygen. For this reason, it is common to use iron alloys instead. They can be introduced into liquid metal directly into a ladle, a runner or a furnace. Ferroalloys should be dry and oxide-free so as not disturb the melting process. Carburizing materials, called carburizers, are specially prepared materials for casting processes. These materials, thanks to the progress of the foundry industry, have gained popularity and the offer on the market has significantly improved over the last several years. In the past, production waste from the industry producing carbon electrodes was used. Carburizers can be divided into graphite and non-graphite ones. Graphite carburizers are natural graphite and synthetic graphite. The group of non-graphite materials includes: anthracite, petroleum coke, pitch coke, coke breeze. The choice of carburizing material by the foundry is determined by both economic and technical considerations. The carburizer should have a low ash, water, volatile matter and sulfur content, and at the same time a high carbon content [1,2,4,5].

One of the modern methods of testing the metallurgical quality of cast iron is the DTA thermal analysis. The essence of the study is the registration of the solidification temperature curve T (t) of a given material as well as the derivative over time, recognized as the crystallization curve T '(t). The analysis process begins after pouring the liquid metal into a specially prepared cup with a thermocouple that allows temperature measurement. The data from the thermocouple is sent to the recording and processing equipment, and then saved. The cooling curve allows to observe changes in temperature during the process of cooling the metal. It determines two characteristic points, called crystallization stops, the first of which reflects the temperature of the beginning of crystallization (liquidus), while the second determines the temperature of the end of solidification (solidus).

The first derivative is calculated at the same time as the temperature measurement. Thanks to the curve determining the cooling derivative, parameters such as $T_{liquidus}$, $T_{emin}$, $T_{emax}$, $T_{solidus}$, $R_{ec}$, VPS can be determined, which were described in the research part of this article.

Thanks to the use of DTA analysis, it is possible to determine the characteristic temperatures of formation of appropriate phases during solidification, the tendency to the formation of shrinkage defects and porosity, the number of graphite nuclei in cast iron, the tendency to form cementite in cast iron, the degree of spheroidization and the type of microstructure as well as the predicted mechanical properties. Thanks to the examination, it is possible to reduce production costs through careful analysis, as well as to minimize production errors in the early stage of production [6,7,8].

# 2. Experimental procedure

## 2.1. Methods of investigation and results

The aim of the research was to determine the influence of charge materials on the metallurgical quality of gray cast iron. The experiments were carried out in the induction furnace with a capacity of 20 kg. Six melts were made with a different proportion of pig iron and steel scrap. The pig iron content varied from 0 to 50%. After calculating the share of charge materials and weighing them out, the charge components were placed together with the carburizer in the furnace. RANCO 9905 carburizer with a carbon content of 99.2% was used for carburizing. After melting and adding FeSi75, the temperature was measured and the metal was superheated to 1500°C. The next step was to pour the sampler for thermal derivation analysis (QC4010 sampler by Electro-Nite with a K-type thermocouple) and to collect a sample for chemical analysis (SAF DO400 sampler, 4 mm thick, manufactured by Electro-Nite). The last step was to carry out the inoculation by introducing 0.3% barium inoculant SB5 into the vat during pouring from the furnace and pouring the samplers for DTA analysis. Inoculation was performed solely to determine changes in DTA parameters compared to cast without inoculation. Table 1 shows the amount of charge materials used for each cast iron melting process. Table 2 shows the chemical composition of pig iron and scrap used for melting. As mentioned earlier, six melts were carried out, noted as W1 to W6.

The chemical composition of the samples was tested on a LECO plasma spectrometer. The obtained results are presented in Table 3. The carbon equivalent CE and the eutectic saturation factor Sc were calculated for all heats. The formula [1] was used to calculate the carbon equivalent CE::

$$CE = C + 0.31Si + 0.33P + 0.40S - 0.027Mn \quad (1)$$

where: C, Si, P, Mn, S -% content of carbon, silicon, phosphorus, manganese and sulfur in the sample.

The dependence [2] was used to calculate the degree of eutectiveness (Sc).

$$Sc= CE/4.3 \quad (2)$$

The obtained results of the chemical composition allow to conclude that similar contents of essential elements such as carbon and silicon were obtained, which will allow to clearly determine the impact of pig iron variability on the parameters of DTA analysis. The introduction of a good carburizer causes its complete dissolution, and the efficiency of using carbon from the carburizer is approx. 95%. Noteworthy is also the very low content of sulfur and phosphorus in the cast iron. Taking into account the criterion of chemical composition, it can be concluded that obtaining the appropriate content of carbon and silicon in the cast iron after eliminating pig iron from the charge does not cause problems when carburizing with synthetic graphite and adding ferrosilicon FeSi, provided that a sufficiently high carburizing temperature and a high degree of mixing are obtained. The deficit of carbon and silicon can be supplemented by introducing metallurgical silicon carbide SiC into the solid charge.

Table 1.
Charge materials

| Material | W1 0%pig iron | W2 10%pig iron | W3 20%pig iron | W4 30%pig iron | W5 40%pig iron | W6 50%pig iron |
|---|---|---|---|---|---|---|
| Pig iron [kg] | 0.00 | 1.10 | 1.90 | 2.80 | 3.90 | 4.70 |
| Steel scrap [kg] | 9.00 | 8.50 | 7.70 | 6.60 | 5.80 | 4.70 |
| Carburizer [kg] | 0.330 | 0.310 | 0.270 | 0.220 | 0.185 | 0.140 |
| FeSi75 [kg] | 0.220 | 0.220 | 0.215 | 0.195 | 0.190 | 0.175 |

Table 2.
Chemical composition of pig iron and steel scrap

| Material | C [ %] | Si [ %] | Mn [ %] | S [ %] | P [ %] |
|---|---|---|---|---|---|
| Pig iron | 4.55 | 0.73 | 0.03 | 0.015 | 0.042 |
| Steel scrap | 0.21 | 0.4 | 1.39 | 0.011 | 0.020 |

Table 3.
Chemical composition of melts

| Melt | Content [%] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | Si | P | Cu | Cr | S | CE | Sc |
| W1 | 3.56 | 0.75 | 1.93 | 0.029 | 0.102 | 0.073 | 0.012 | 4.15 | 0.97 |
| W2 | 3.55 | 0.77 | 2.01 | 0.033 | 0.051 | 0.054 | 0.013 | 4.17 | 0.97 |
| W3 | 3.59 | 0.78 | 1.91 | 0.033 | 0.014 | 0.027 | 0.015 | 4.18 | 0.97 |
| W4 | 3.53 | 0.77 | 1.95 | 0.036 | 0.050 | 0.063 | 0.016 | 4.13 | 0.96 |
| W5 | 3.54 | 0.71 | 1.90 | 0.046 | 0.038 | 0.041 | 0.012 | 4.13 | 0.96 |
| W6 | 3.60 | 0.72 | 1.87 | 0.043 | 0.007 | 0.029 | 0.013 | 4.18 | 0.97 |

For the DTA analysis, a converter for recording the solidification point and cooling of the metal in the cup was used. On the basis of the cooling curve, its first derivative was calculated and the crystallization curve was determined. The curves for some of the melts without inoculation are shown in Figs. 1-3 and after inoculation when pouring from the furnace to the ladle (Fig. 4-6).

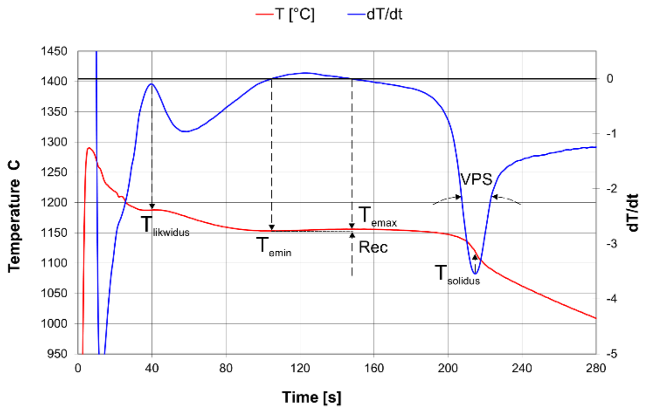

Fig. 1. Thermal analysis curve for the W2 melt

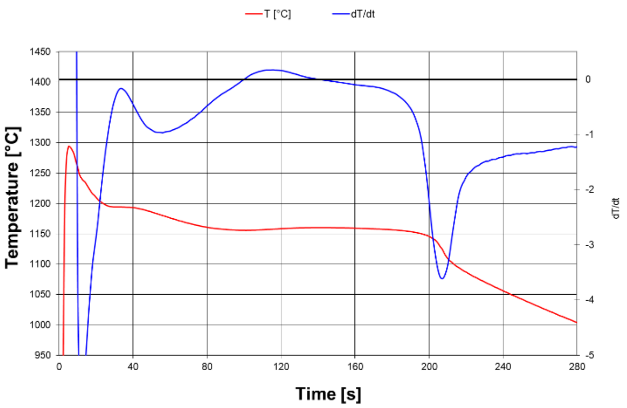

Fig. 2. Thermal analysis curve for the W3 melt

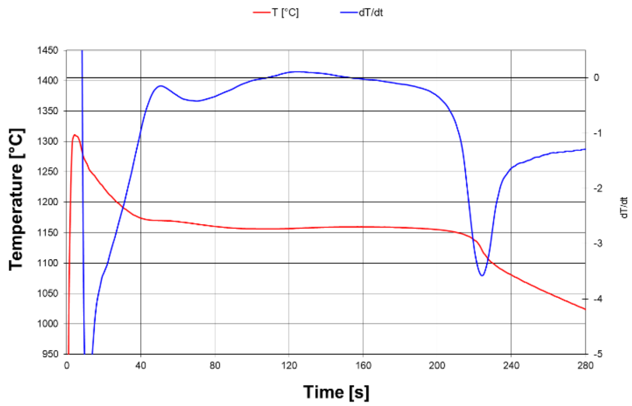

Fig. 3. Thermal analysis curve for the W5

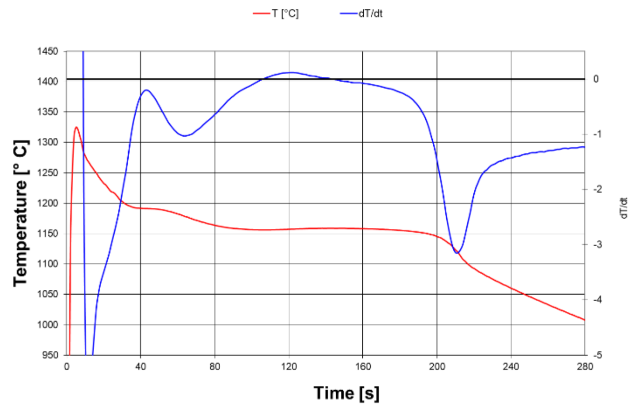

Fig. 4. Thermal analysis curve for the W2 melt after inoculation

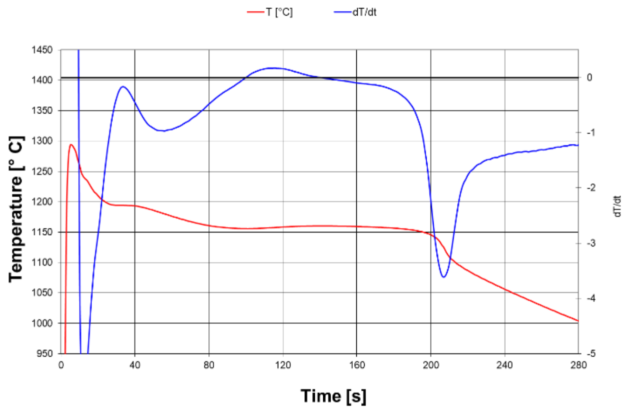

Fig. 5. Thermal analysis curve for the W3 melt after inoculation

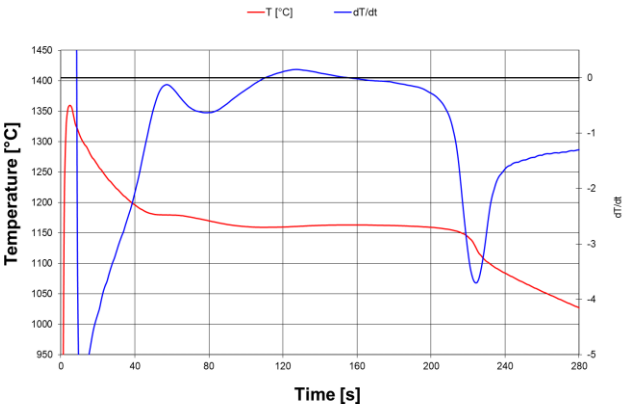

Fig. 6. Thermal analysis curve for the W5 melt after inoculation

Table 4 summarizes the characteristic temperatures and parameters determined from the recorded cooling and crystallization curves for all melts. Cups after inoculation were also poured in order to determine its effect on the change of DTA parameters, mainly $T_{emin}$. The results are presented in Table 5. Figures 7-9 show the dependencies for individual casts without preconditioning.

Table 4.
Results from thermal analysis of melts without inoculation

| Parameters DTA | W1 | W2 | W3 | W4 |
|---|---|---|---|---|
| $T_{likwidus}$ [°C] | 1176.2 | 1187.6 | 1194.5 | 1199.7 |
| $T_{emin}$ [°C] | 1151.2 | 1153.5 | 1156.1 | 1156.6 |
| $T_{emax}$ [°C] | 1152.5 | 1156.1 | 1160.4 | 1161.4 |
| $T_{solidus}$ [°C] | 1109.5 | 1116.9 | 1125.4 | 1121.7 |
| Rec [°C] | 1.3 | 2.6 | 4.3 | 4.8 |
| VPS [-] | 18 | 18 | 18 | 19 |
| | **W5** | **W6** | | |
| $T_{likwidus}$ [°C] | 1169.5 | 1174.0 | | |
| $T_{emin}$ [°C] | 1156.0 | 1156.8 | | |
| $T_{emax}$ [°C] | 1161.6 | 1162 | | |
| $T_{solidus}$ [°C] | 1122.1 | 1124.6 | | |
| Rec [°C] | 5.6 | 5.2 | | |
| VPS [-] | 19 | 26 | | |

Table 5.
Results from thermal analysis of melts after inoculation

| Parameters ATD | W1 inoc. | W2 inoc. | W3 inoc. | W4 inoc. |
|---|---|---|---|---|
| $T_{likwidus}$ [°C] | 1167.5 | 1191.2 | 1195.0 | 1203.5 |
| $T_{emin}$ [°C] | 1157.6 | 1158.2 | 1160.7 | 1161.3 |
| $T_{emax}$ [°C] | 1159.3 | 1158.9 | 1162.5 | 1164.0 |
| $T_{solidus}$ [°C] | 1115.7 | 1120.3 | 1122.5 | 1123.8 |
| Rec [°C] | 1.7 | 2.7 | 2.8 | 2.7 |
| VPS [-] | 21 | 23 | 19 | 17 |
| | **W5 inoc.** | **W6 inoc.** | | |
| $T_{likwidus}$ [°C] | 1179.2 | 1211.0 | | |
| $T_{emin}$ [°C] | 1158.9 | 1158.1 | | |
| $T_{emax}$ [°C] | 1162.8 | 1161.3 | | |
| $T_{solidus}$ [°C] | 1121.6 | 1125.9 | | |
| Rec [°C] | 3.9 | 3.2 | | |
| VPS [-] | 16 | 18 | | |

Description of DTA parameters:

**$T_{likwidus}$** - temperature at which the first solid particles are formed: the solidification process begins. It is shown as a horizontal plateau due to the precipitation of primary austenite in hypoeutectic cast iron and as the minimum temperature for eutectic alloys
**$T_{emin}$** - the minimum temperature reached during the solidification of the eutectic. At this point, the latent heat of crystallization is equal to the heat given of cooling
**$T_{emax}$** - the maximum temperature reached during the solidification of the eutectic
**$T_{sol}$** - the temperature at which the cast iron completely solidified.
**VPS** - the indicator of transition of cast iron from the semi-solid state in permanent. Parameter strongly related to the formation of shrinkage
**Rec** - the difference between the maximum and minimum temperature of eutectic solidification. Parameter related to the amount of formed graphite.

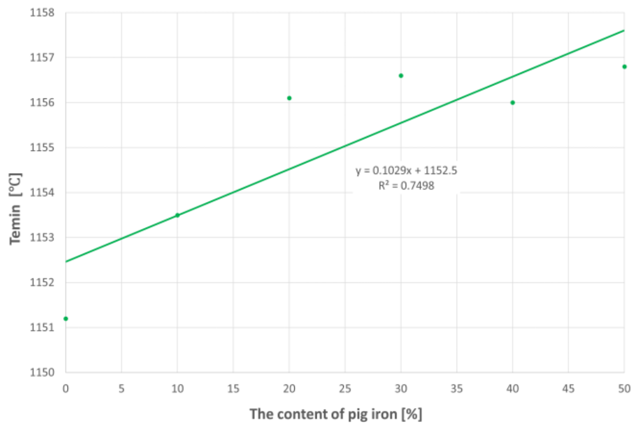

Fig. 7. $T_{emin}$ values for individual melts

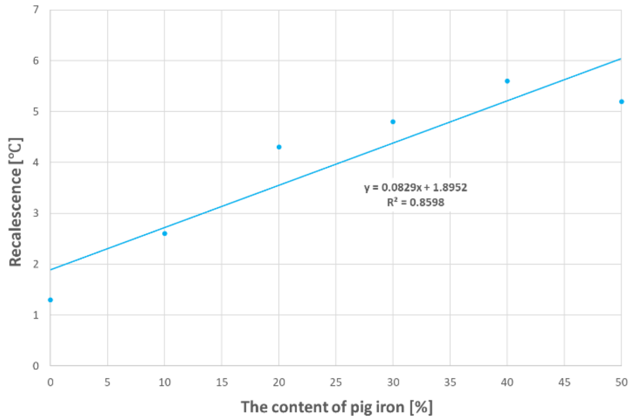


Fig.8. Recalescence values for individual melts

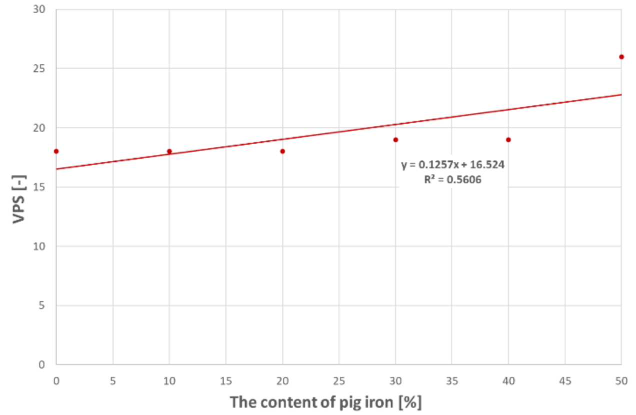


Fig.9. VPS values for individual melts

The minimum solidification point of the $T_{emin}$ eutectic is considered to be the most important indicator of cast iron nucleation. Higher value of the temperature indicates better level of nucleation. Below 1135°C, nucleation is considered low and there is a high risk of primary carbides appearing in the casting. Between 1135°C and 1145°C, nucleation is considered optimal, and the risk of the appearance of primary carbides depends on the thickness of the casting wall. Above 1145°C, the nucleation is very good and there is no risk of primary carbides appearing. In all performed melts, the $T_{emin}$ value above 1151.2°C was achieved. The $T_{emin}$ value increases with the amount of pig iron in the charge. The most dynamic growth was observed for the melt with the share of 0 to 20% pig iron. Increasing the share of pig iron from 20% to 50% did not cause significant changes in $T_{emin}$.

Recalescence (Rec) is related to the amount of graphite formed. The optimal recalescence value for gray cast iron without inoculation is between 4 and 9 ° C. With the increase in the share of pig iron, an increase in the recalescence value was observed. Values in line with the required values were achieved for melts with pig iron content of 20% and more.

VPS is an indicator of transition of cast iron from the semi-solid state in permanent. Parameter is strongly related to the formation of shrinkage. For gray cast iron without inoculation, the optimal values range from 16 to 23 Values in accordance with the requirements were achieved for all melts except for W6. In the case of gray cast iron, the determination of the shrinkage tendency is not correct, because with the increase in the share of pig iron, the cast iron should show better metallurgical quality.

In order to compare changes in $T_{emin}$ after inoculation, differences $\Delta T_{emin}$ were determined. The relationship is shown in Fig. 10. With the increase in the share of pig iron, the increase in $T_{emin}$ after inoculation was less pronounced. The highest increase in the level of graphite nucleation in cast iron was observed for the melt without pig iron.

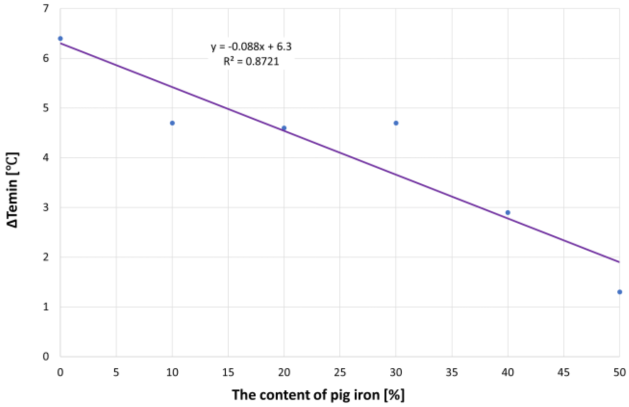


Fig. 10. Differences in $T_{emin}$ before and after preconditioning for casts depending on the percentage of pig iron in the charge

In order to perform mechanical tests, samples from the casts without inoculation were subjected to a static tensile test using a testing machine. The Brinell hardness was also measured. Analyzing the obtained results (Fig. 11) it can be concluded. that the obtained cast irons correspond to the grades GJL 200 to GJL 250. Synthetic cast iron obtained without pig iron has the highest tensile strength and hardness. Tensile strength and hardness decrease linearly as the proportion of pig iron increases.

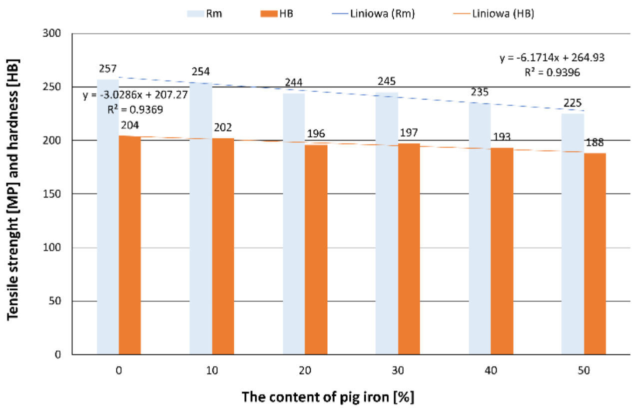


Fig. 11. Tensile strength and Brinell hardness for individual melt

## 3. Conclusions

The selection of appropriate charge materials allows to achieve the required chemical composition of the melt for the specific grade of cast iron. In the time of dynamically changing material prices, the selection of an appropriate composition (pig iron, steel scrap, returned scrap, carburizer, ferroalloys) allows to reduce the costs of melting without a significant loss of the metallurgical quality of cast iron.

Based on the tests carried out with a variable amount of pig iron in the charge, the following conclusions can be drawn:

– regardless of the charge composition used, high values of the minimum eutectic temperature Temin were achieved for cast iron without inoculation, which indicates the high level of graphite nucleation in the cast iron. The increase in the share of pig iron in the melt increases the $T_{emin}$, which makes it possible to reduce the added inoculant ensuring the solidification of cast iron in the stable Fe-C system,
– consistent with the required values of the VPS parameter for cast iron without inoculation associated with the formation of shrinkage cavities were achieved for all heats except for W6. In the case of gray cast iron, the determination of the shrinkage tendency is not correct, because with the increase in the share of pig iron, the cast iron should show better metallurgical quality,
– with the increase in the share of pig iron in the charge for cast iron without inoculation, an increase in the recalescence value was noticed. Values in line with the required values were achieved for melts with pig iron content of 20% and more,
– with the increase in the share of pig iron, the increase in Temin after inoculation was smaller. The greatest increase in the level of graphite nucleation in cast iron was observed for the melt without the use of pig iron, which confirms the fact that the use of inoculation is not necessary for larger shares of pig iron,
– the results of mechanical tests show that synthetic cast iron without inoculation has the best strength properties and the highest hardness. Increasing the content of pig iron in the charge results in a decrease in tensile strength and hardness.

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