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The Influence of Selected Melting Parameters on the Physical and Chemical Properties of Cast Iron

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Abstract

This paper presents the problems related to smelting gray and ductile cast iron. Special attention is paid to the metallurgical quality of cast iron. It depends on the type of furnace, charge materials and the special combination of charge, overheating and holding temperature, melting time, modification and spheroidization method. The evaluation of metallurgical quality has been performed by using derivative-thermal analysis (DTA). During the smelting process and secondary metallurgy, the ITACA system was used allowing to obtain information on alloy characteristic temperatures (Tliquidus, TeMin, TeMax, Tsolidus), VPS value, recalescence value, IGQ coefficient, nucleation gauge, porosity etc. The results of investigations and calculations are displayed in the form of graphs and dependencies. It has been shown that the derivative-thermal analysis (DTA) is an effective complement of chemical analysis and it has been found that both the increase in temperature and metal holding time have a negative impact on the metallurgical quality of liquid metal. The metallurgical quality can be improved by using proper composition of charge materials and modifiers.

Keywords: Gray and ductile cast iron, Derivative-thermal analysis (DTA), Cast iron properties, Holding time and temperature, Overheating temperature

1. Introduction

The current global weight of casting production reaches 109 million tonnes, 49 million tonnes of which is made of gray cast iron, while 29 million tonnes is made of ductile cast iron [1]. Despite such considerable output cast iron is still subject to many scientific studies conducted by a lot of scientific centers. The studies cover both theoretical problems regarding the solidification process of liquid alloys, the mechanism of graphite insert separation [2,3,4,5], as well as the reasons for casting defects, how to avoid them and simulating the solidification process [6,7,8]. The studies also cover the problems of different composition of charge materials in the charge (reducing the quantity of pig iron, introducing new carburizing materials, using silicone carbide for smelting in electric furnaces) [9,10,11]. There are many studies devoted to modifiers and spheroidizing materials [12,13]. In many cases only trends showing the influence of selected parameters on the quality of smelted alloy are specified. Using both chemical analysis and the derivative-thermal analysis (DTA) to assess cast iron allows us to expand considerably the available scope of information on its properties. It applies to the nucleation gauge (nucleation potential, level, rate), specific temperatures (Tliquidus, TeMin, TeMax, Tsolidus), recalescence value (Rec.), IGQ value, VPS coefficient (Fig. 1).

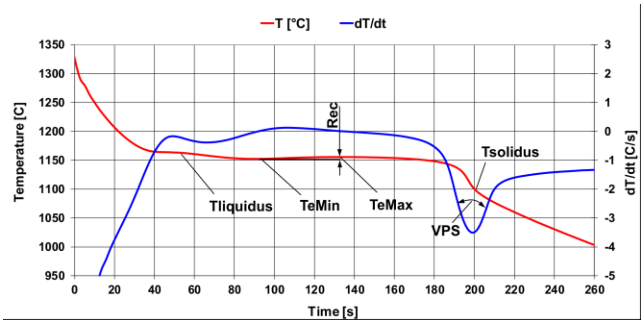

Fig. 1. Specific temperatures and VPS coefficient in the derivative-thermal analysis (DTA)

It is often the case that the changes in the composition of chemical elements occur only to a limited extent, while the derivative-thermal analysis (DTA) shows considerable changes in physical and chemical properties of cast iron, which will be shown in this publication.

The paper presents some results of studies conducted under industrial conditions during smelting gray and ductile cast iron.

2. Factors affecting the structure and properties of cast

The factors affecting the metallurgical quality are presented in Fig.2. Each of them to a greater or lesser extent contributes to changing the physical and chemical properties of alloy.

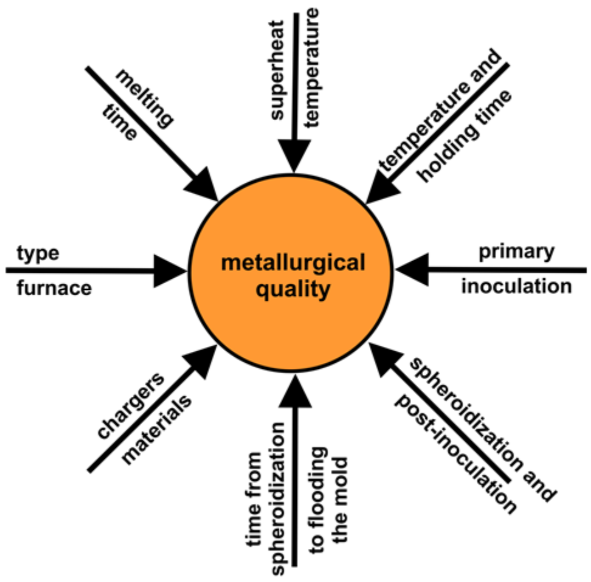

Fig. 2. Factors affecting the metallurgical quality of cast iron

The development of electric medium-frequency induction furnaces and environmental restrictions result in replacing pouring furnaces for cast iron with electric furnaces. An undoubted advantage of the furnaces is their lower environmental emission, more flexible operation mode (they can be used to smelt various grades/types of cast iron), lower level of alloy contaminations (S, P) or considerably lower melting time. Their disadvantages include the necessity to carburize the cast iron and worse nucleation rate coefficients. When analyzing charging materials depending on the cast iron grade (ferritic or pearlitic) proper amounts of pig iron and process scrap should be taken into account. Larger amount of pig iron results in higher smelting costs and forces to provide a low-manganese steel scrap (ferritic cast iron). The most important parameters include the temperature and time of holding liquid cast iron in a smelting or holding furnace. Higher temperature and longer time reduce the quality of liquid alloy (it will be shown below) and increase the cost of smelting. There is no doubt that many of the physical and chemical properties described above can be improved by using a larger amount of properly selected pre-modifier and modifier. However, it results in higher costs. Therefore, the correct physical and chemical properties of alloy should be provided as early as at the initial smelting stage.

By contrast, analyzing the structure and properties of cast leads us to conclusion that a considerable impact on those properties has the mold (Fig. 3) responsible for removing heat from the cast. Very important here is the cast design (wall thickness, heat nodes) and the properly selected pouring system, risers and chills. It is the type of molding compound (bentonite, furan-based) that affects the mold strength, proper ratio of water to active bentonite content and the amount of resin and the level of density, deciding on shrinkage defects. These factors, in turn, will define the speed of cooling, structure and potential cast defects.

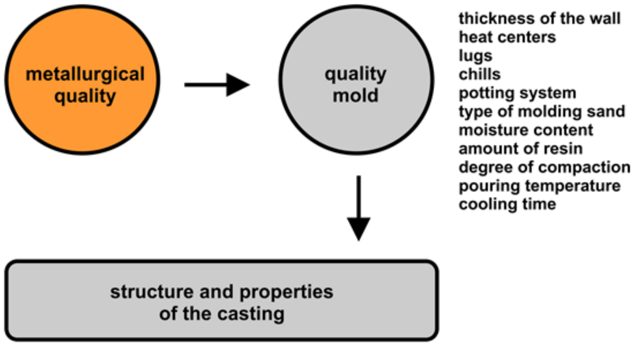

Fig. 3. Factors affecting the structure and properties of cast

3. Methods for assessing the quality of cast iron

The most frequently used methods for assessing cast iron at the stage of smelting include chemical analysis and chill wedge test. However, it has been found that the chemical analysis shows the content of particular chemical elements (which is obviously more important), but it does not reflect the physical and chemical state of the alloy. The best suitable method for this purpose is the derivative-thermal analysis (DTA) that records the cooling curve and the crystallization curve determined based on the it, which is shown in the next section of this paper. Basic parameters analyzed during the melting process include specific alloy temperature (Tliquidus, TeMin, TeMax, Tsolidus), VPS coefficient, recalescence value (Rec.), IGQ value, nucleation rate and porosity. The systems most frequently used in foundries include ITACA [14] used also in the studies presented in the paper and ATAS [15], QUIK-LAB [16]. Because of the fact that the derivative-thermal analysis (DTA) has been described in many literature items [17,18,19], its description in this paper has been omitted.

One of the most important parameters is the minimum temperature achieved during eutectic solidification (TeMin). In this point the latent heat of crystallization equals to the heat released during cooling. TeMin is the most important factor for cast iron nucleation. This point constitutes a limit used to separate the stable system from the metastable one. The higher the temperature the better the nucleation potential. Below 1135°C nucleation is considered low and there is a big risk of primary carbides formation in the cast. Between 1135 °C and 1145 °C nucleation is considered to be optimum, while the risk of primary carbides will depend on the cast wall thickness. Above 1145 °C nucleation is very good and there is no risk of primary carbides.

Tsolidus is a temperature below which cast iron is completely solid. If the temperature is lower than 1080°C, the risk of segregation increases. Then, it is necessary to analyze the cast iron for the occurrence of segregation elements.

TeMax is the maximum eutectic solidification temperature related to the emission of the latent heat of crystallization.

Another parameter includes recalescence (Rec.) being a difference between TeMax (maximum eutectic temperature) and TeMin. This parameter specifies the amount of graphite formed. The optimum value of recalescence for gray cast iron ranges from 4°C to 9°C, while for ductile cast iron its value ranges from 2°C, to 5°C. The low Rec value can indicate a low graphite expansion level. It can cause porosity. This value must be evaluated in the function of nucleation and current position in Fe-C system. A high Rec value is associated with high graphite expansion level and can lead to a mold deformation.

One of the very important parameters we get information about from the derivative curve is the nucleation gauge of liquid metal. It depends i.a. on the alloy temperature, cast iron melting and holding time and the level of carbon and silicon. For the initial cast iron used to produce ductile cast iron, the value of this parameter should be 100. At lower values the nucleation gauge can be increased by adding a modifier, pre-modifier, Fe-Si or, in some cases, graphite. Corrections can be made in the very ladle too.

Another parameter is VPS. This is an indicator of transition rate from semi-solid to solid state. This is not a temperature, this is a value of angle depending on the solidification rate. The VPS parameter is strongly related to shrinkage cavity formation. For the initial cast iron used to manufacture ductile cast iron and in gray cast iron, the value should range from 16 to 23. For ductile cast iron the value should range from 35 to 55. If the VPS values are higher limit values, then the trend to form shrinkage cavities increases. In such a case it is necessary to add a larger amount of modifier. If the indicators are lower, there is a risk of graphite degeneration.

ITACA system suggests using the IGQ value to assess the quality of cast iron. The IGQ is calculated as a weighted average of all parameters that affect the quality of cast iron (Tliquidus, TeMin, VPS, Rec, Tsolidus). The higher the value, the higher the quality of cast iron.

4. Results of study and calculations

As part of the project the metallurgical quality of gray cast iron grade GJL 250 and ductile cast iron grade GJS 400-18, GJS 460-12 and GJS 500-7 were tested. For ductile cast iron the assessment covered the initial and final cast iron after spheroidizing and modification.

Experiments were performed to analyze how the physical and chemical properties of alloy are affected by the following factors:

- charge materials, including pig iron, steel scrap, process scrap, ferroalloys, carburizers,
- overheating temperature,
- chemical composition (change in carbon, silica, manganese and copper levels),
- metal holding time in furnace,
- ladle temperature.

The variation range for individual elements was very wide. The level of carbon ranged from 3.0 to 4.0%, the level of silicon ranged from 1.50 to 3.40%, the level of manganese ranged from 0.05 to 0.70%, while the level of copper was changed within a range from 0.03 to 0.70%. The level of magnesium in the cast iron after completing the spheroidization process ranged from 0.04 to 0.07%. The level of other elements (Cr, Ni, Sn, Pb) and contaminations (P, S) were kept as low as possible as per recommendations provided for a given cast iron grade. The studies conducted allowed us to create a database used to present a few dependencies and observations. By analyzing the VPS angle one can say that it is affected by the carbon level in cast iron (Fig. 4). Increasing the carbon level results in reducing the value of this parameter. The VPS angle will indicate the trend to create shrinkage cavities. Therefore, we cannot obtain this information directly from the chemical analysis.

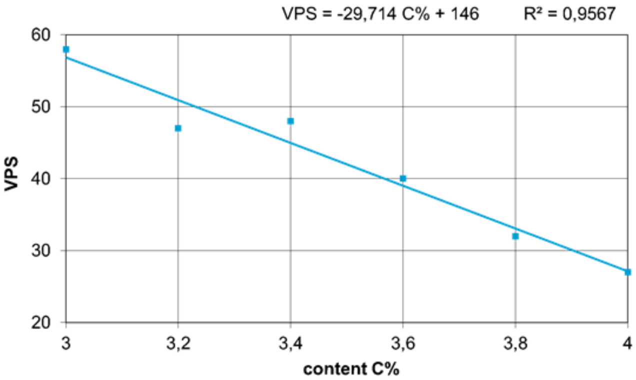

Fig. 4. Influence of cast iron carbon level on VPS angle value

Fig. 5 presents the influence of carbon level on the nucleation rate in the initial cast iron. It can be observed that an increase in carbon level raises the parameter value.

As already mentioned before, a very important parameter was the minimum eutectic temperature (TeMin). Fig. 6 presents the influence of carbon level on TeMin. It can be observed that an increase in carbon level raises the value of TeMin. To provide better nucleation level and a cast free from primary carbides, the temperature should not be lower than 1135°C.

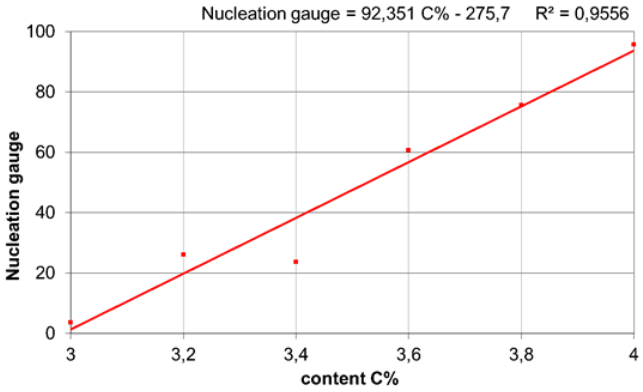

Fig. 5. Influence of carbon level on nucleation gauge

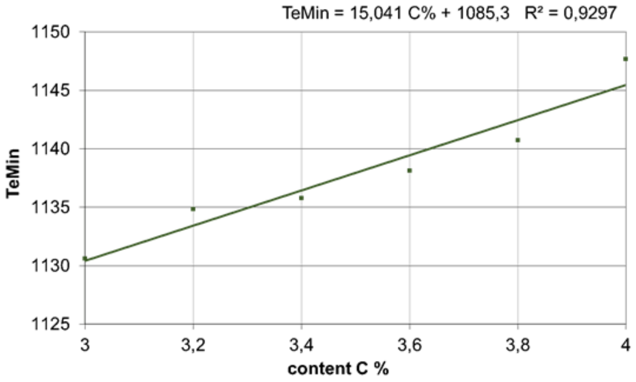

Fig. 6. Influence of carbon level on the minimum eutectic temperature

By using the results of studies conducted an analysis of relation between Temin and Tliquidus has been performed. The liquidus temperature defines the temperature level, at which the first solid particles are formed, i.e. the solidification process begins. Fig. 7 presents a trend line and statistical parameters covering the two temperature values for gray cast iron, and in Fig. 8, for ductile cast iron.

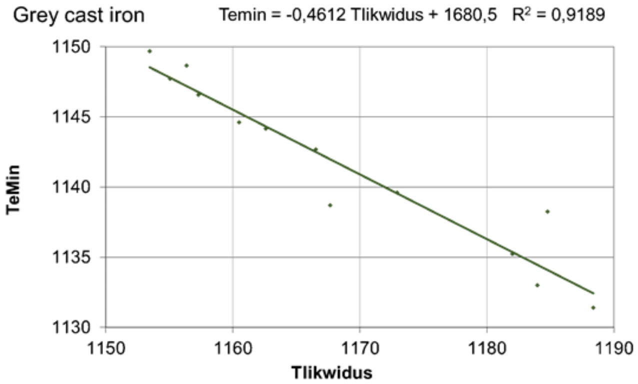

Fig. 7. Dependence between the minimum eutectic temperature and liquidus temperature for gray cast iron

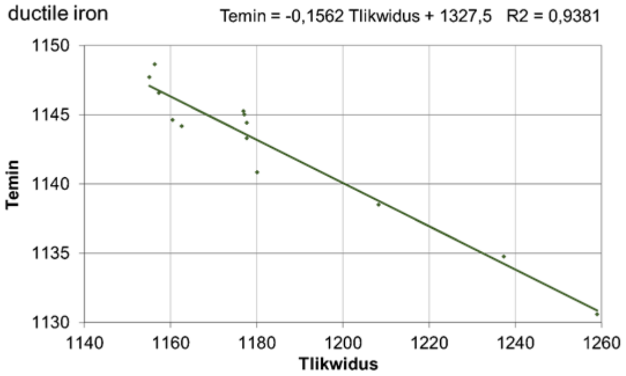

Fig. 8. Dependence between the minimum eutectic temperature and liquidus temperature for ductile cast iron

One of the research areas covered the analysis of how holding temperature and time affect the quality of cast iron. Studies were conducted at temperatures ranging from 1420°C to 1540°C (marked on graph as Temp_1420, Temp_1460, Temp_1500 and Temp_1540, respectively) holding the metal for 120 minutes in the smelting furnace. By analyzing the chemical composition of basic elements (see Fig. 9 for carbon level) it can be observed that at lower temperatures any decrease in carbon level is small, while at 1500°C within 120 minutes the carbon level decreases by 0.2%C. When only chemical analysis results are available, it can be concluded that these values are not excessively high. A slight increase in carbon level at temperatures ranging from 1420°C to 1540°C results probably from dissolving the remains of graphite added at the final stage of smelting in an induction furnace.

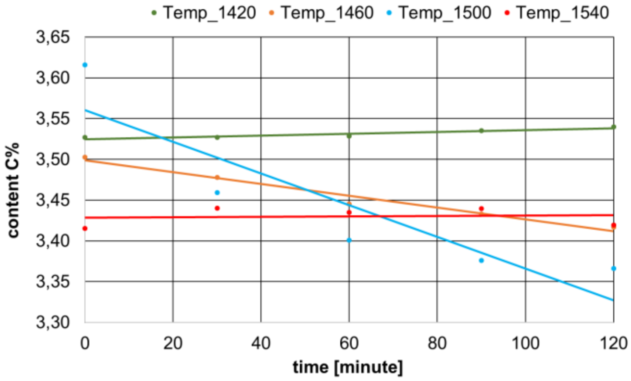

Fig. 9. Influence of holding time and temperature on cast iron carbon level

However, if we focus on the decrease in nucleation rate in the function of temperature and time, the image is completely different (Fig. 10). Using higher holding temperatures and times results in almost complete removal of nuclei. Holding cast iron 120 minutes at 1420°C reduces the nucleation rate by 25%, while holding it at 1540°C reduces the nucleation potential by 90%.

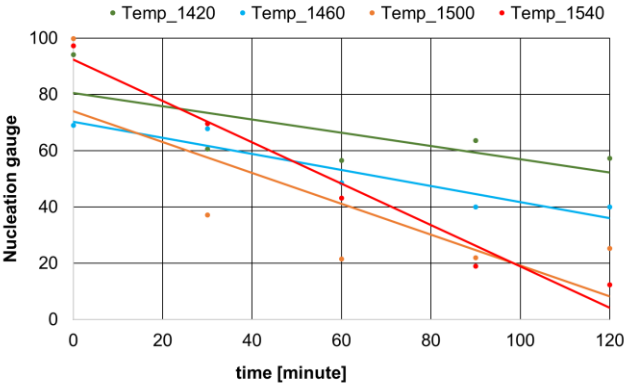

Fig. 10. Influence of holding time and temperature on nucleation gauge

The results obtained are confirmed by the results of microstructure analysis. The most variable parameter describing the cast iron microstructure image according to PN-EN ISO 945-1:2019-09 is, in this case, graphite distribution. Holding cast iron at 1460°C for 120 minutes reduces graphite A distribution from 77% to 66% and at the same time increases graphite E by 6% and forces the appearance of graphite D in an amount of 6%. Holding cast iron at 1540°C reduces graphite A by 19% within 60 minutes. Examples of EN-GJL 250 grade cast iron structures held at 1540°C after 30 minutes (Fig. 11) and 120 minutes (Fig. 12).

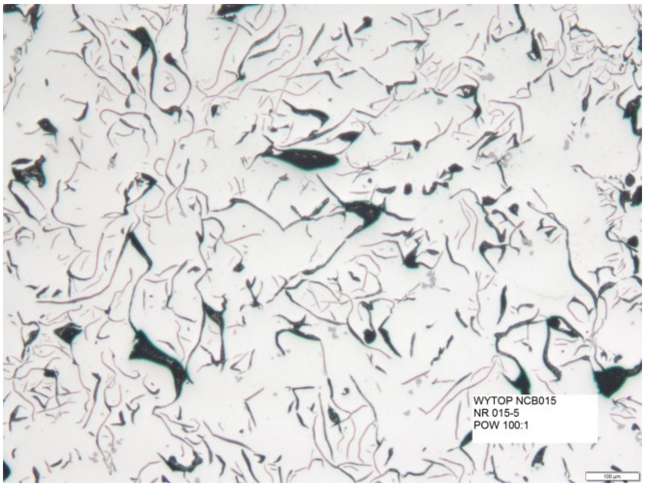

Fig. 11. Images of cast iron structures held at 1540°C for 30 minutes

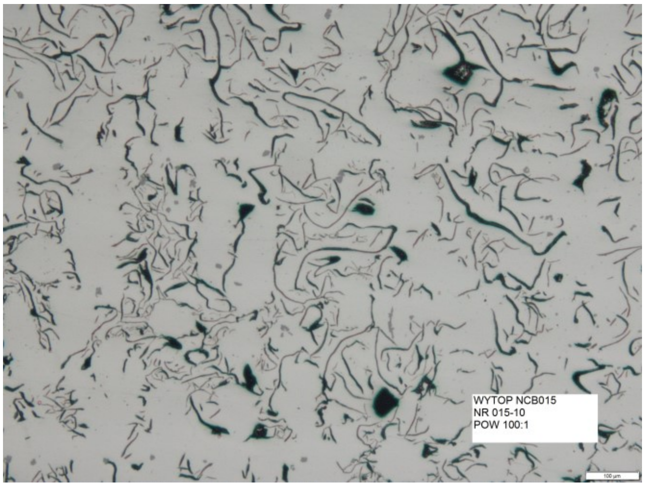

Fig. 12. Images of cast iron structures held at 1540°C for 120 minutes

The influence of cast iron holding time and temperature on IGQ (cast iron quality index) is shown in Fig. 13. As before, it can be observed that holding an alloy at high temperatures reduces the quality of cast iron.

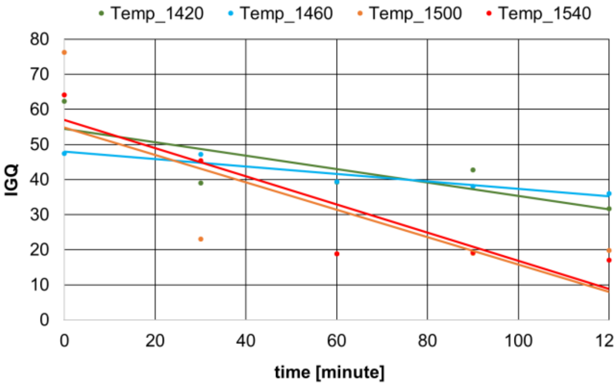

Fig. 13. Influence of holding time and temperature on nucleation gauge

Studies to specify how the overheating temperature affects the nucleation rate have been conducted as well. The studies have been conducted at temperatures ranging from 1430°C to 1580°C, heating up cast iron in the smelting furnace each time by 30°C, collecting a sample for chemical analysis and filling a cup for the derivative-thermal analysis. The results of studies are shown in Fig. 14, where gray cast iron castings are marked as GCI_1 i GCI_2, while the initial cast iron for ductile cast iron production are marked as DI_1 i DI_2, respectively. It has been observed that an increase in overheating temperature reduces the nucleation rate.

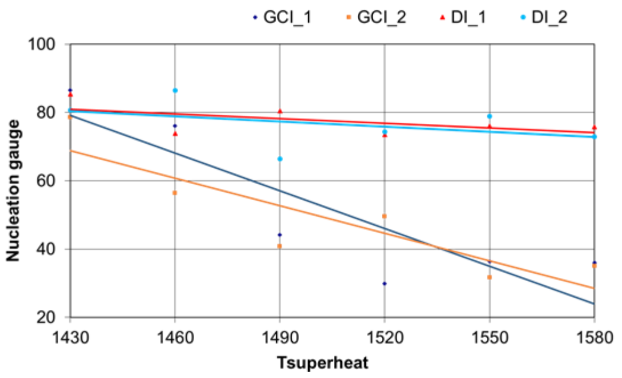

Fig. 14. Influence of overheating temperature on nucleation gauge

When analyzing the presented study results and calculations one can disagree in some cases and say that the use of a proper modifier in an adequate amount will considerably increase the metallurgical quality of cast iron, raising the nucleation rate. It is true, but it will generate additional costs needed to use a lager amount of modifier. Not without significance is here also that the increase in liquid metal temperature and holding the metal for a long period of time increases the smelting costs too.

4. Conclusions

The studies and calculations conducted allow us to come to the following conclusions:

- visible influence of a temperature increase on reducing the nucleation rate, increase in VPS angle and reducing TeMin temperature have been found,
- at an overheating temperature of 1420°C after two hours of holding in a furnace approximately 60% of nuclei still remains, while at 1540°C after 2 hours only 15–25% of nuclei remains,
- no influence of ladle temperature on physical and chemical properties has been found, However, there is a clear influence of ladle temperature on reducing the temperature of cast iron poured into the ladle.

Acknowledgments

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