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SPHEROIDAL CAST IRON FOR WORKS AT LOW TEMPERATURE – REQUIREMENTS, STRUCTURE, PROPERTIES, CONTROL OF THE PRODUCTION PROCESS

Two standardised grades of spheroidal cast iron determined in standard EN PN 1563 – 1997 as: EN-GJS-350 – 22LT (T = –40°C) and EN GJS 400 – 18LT (T = –20°C) are intended for work at low temperatures: –20 and –40°C. The main mechanical property of these cast iron grades is a high impact strength at a work temperature down to: –40°C. A series of controlled melts was performed to optimise the production technology of spheroidal cast iron, which in as-cast state is characterised by ferritic matrix (the best without any pearlite), fine precipitates of nodular graphite and high purity (without non-metallic inclusions). Variable structures of metal charges and various spheroidisation techniques (the modification methods) (slender ladle with a tight cover – Tundish technology as well as the technology with cored wire) were applied in the research. In order to obtain refinement of graphite precipitates and to achieve the ferritic matrix multistage inoculations of technologies were applied. Cast iron was subjected to refining to limit non-metallic inclusions since they decrease the impact strength. The production process of cast iron was controlled by the thermal derivative analysis at the stage of initial cast iron and after its secondary metallurgy (modification and inoculation). It was pointed out, that the reproducible production of cast iron for work at low temperatures was only possible when all elements of the technological process were strictly adhered to. It was pointed out, in the hereby paper, that: it should be strived to maintain Si content not higher than 2.50÷2.60%, which at producing spheroidal cast iron is sometimes difficult and requires using a lot of pig iron in the metal charge. For a fast assessment of the cast iron quality, concerning its impact strength, the proposed – in the hereby paper – index quality (IQu) can be applied. It is determined on the bases of measuring the cast iron hardness and propagation velocity of ultrasound wave.

Keywords: impact strength; ferritic ductile iron; low temperatures; work-of fracture

1. Introduction

Elements of devices, machines and vehicles operating at dynamic loads must be characterised by mechanical properties, which limit possibilities of brittle cracks formations. The most important properties are in this case: ductility (the most often measured by indicator A_5) and impact strength (determined for standardised samples with a notch shaped either „V" (U_v) or „U" (U_u)). These products must be also characterised by sufficient resistance R_m and yield point R_{p02}. Out of several high-quality cast iron grades the described properties are only satisfied by the selected grades of spheroidal cast iron of ferritic or austenitic matrices. Generally, cast iron is technologically easier material than cast steel and due to that it is widely applied. In case when structures or devices operate under ambient conditions ($T \approx 20°C$) spheroidal cast iron EN GJS 400 – 15 [1] is generally applied for production of dynamically loaded elements of vehicles. Such

elements are: connecting rods, piston rings, camshafts, castings of differential gears, elements of vehicle suspensions, elements of braking systems and several other. Railway anchors for attaching rails to cross-ties are produced for the railway system. Cast iron EN GJS 400 – 15 is widely applied in power engineering, especially in wind power engineering, for wind heads or for platforms on which the main structure of windmills is mounted. These cast iron grades were previously known from German standards (DIN 1693 Blat 1 – 1973) as grades GGG 40 and GGG 40.3.

Motorization companies determine additional requirements for cast iron EN GJS 400 15, concerning its impact strength determined in an ambient temperature. For example, CITROEN and PUEGEOT determine the minimal impact strength (at a temperature +20) as U_u > 12 J/cm², while RENAULT requires U_v (T = –40°C) to be higher than 3.0 J [1].

Products intended for operations at low temperatures constitute a certain separate group. Duplex steels and cast irons con-

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tained in standard PN-EN 1563 belong to this group. These are two grades: EN GJS-350-22-LT (for operating at a temperature of –40°C) and EN GJS-400 – 18-LT (for operating at a temperature of –20°C). It is expected that in both cases the impact strength, determined as an average value from three measurements on specimens with „V" notch, will be: $U_v \geq 12J$. For cast iron EN GJS 350 – 22LT its impact strength is determined at a temperature –40°C, while for cast iron EN GJS 400 – 18-LT at a temperature –20°C. All requirements for both cast iron grades are listed in Table 1.

TABLE 1

Requirements of the impact strength of ferritic grades of cast iron EN 1563 intended for operations under dynamic loads

Minimum V-Notch Values from Separately Cast Y2 Ingots [J]			
Material designation	$T = 23 \pm5$ (°C) (three-sample mean)	$T = 20 \pm2$ (°C) (three-sample mean)	$T = 40 \pm2$ (°C) (three-sample mean)
EN-GJS-350-22-LT	—	—	12
EN-GJS-350-22-RT	17	—	—
EN-GJS-400-18-LT	—	12	—
EN-GJS-400-18-RT	14	—	—

Production of cast iron which would satisfy the listed above requirements concerning the impact strength is, as mentioned in several papers, difficult [1÷10]. Regardless of satisfying the condition of obtaining purely ferritic structure and spheroidal graphite precipitates, its impact strength is characterised by scattered results. Thus, there are factors which influence is – from one side – quite essential, but – from another side – weakly recognised. According to the literature data to those weakly known factors belong: ferrite kind, averaged shape of graphite precipitates as well as non-metallic contaminations, which – in large quantities – are formed at the secondary metallurgy of cast iron during its modification and inoculation. Obtaining purely ferritic structure in as-cast state in melts is only possible when a high ability for cast iron graphitization is maintained. It can be achieved when C and Si content in cast iron is high and when its inoculation is properly performed. A favorable factor constitutes also slow cooling, which occurs in thick-walled castings. However, when too much silicon is introduced, the ferrite which is a carbon in iron solution, is becoming substituted by silica ferrite, in which dissolved silicon occurs next to carbon. The effect of changing from normal ferrite to silica ferrite is of a progressive character, the more silicon in cast iron the more silica ferrite. In effect ferrite is strengthened and its hardness increases. These changes lead to a ductility decrease and coupled with it impact strength. Cast irons of increased silicon content are characterised by a decreased impact strength, especially at low temperatures. The influence of silicon content on the impact strength was discussed in several papers. The results of one of them are presented in figure 1 [11]. The influence of silicon within the range: 2.0÷2.7% was tested. Exceeding approximately 2.5% of Si in cast iron causes significantly lower impact strengths within the whole temperature range. Chemical components,

favoring pearlitisation of the matrix (Ni, Cu, Cr and V), exert unfavourable influences. Pearlite is an undesirable component of the metallic matrix of cast iron intended for operations at low temperatures. It is confirmed by the investigation results shown in Fig. 1.
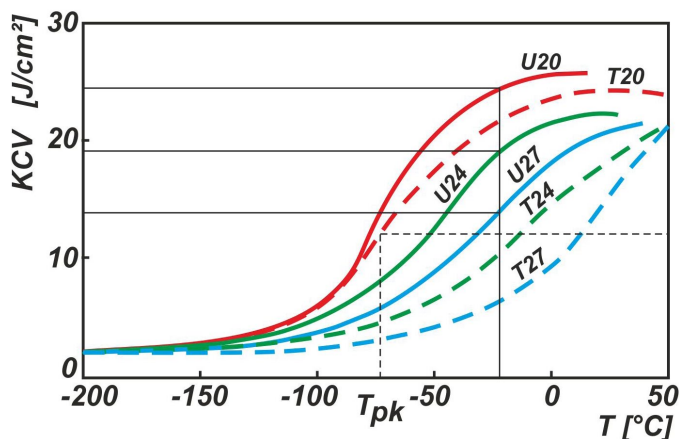

Fig. 1. Influence of a temperature on the impact strength of spheroidal ferritic cast iron containing silicon: Si = 2.0% (U20 and T20); Si – 2.4% (U24, T24) and Si = 2.70% (U27, T27), where U – cast iron containing: Ni, Cu, Cr and V below 0.01%, T – cast iron containing: Ni, Cu, Cr and V – up to the upper value from the range: 0.025-0.030% [11]

It can be seen in Fig. 1, that the impact strength of cast iron decreases when a temperature is decreased. The pathway of this influence, in the described temperature range is not of a linear character, but in the smaller range: from –40°C to +20°C, it is in approximation linear (as investigations of several authors indicate [1,7-9]). The empirical dependence (Eq. (1) [1]) was developed for ferritic cast iron EN GJS 400-15. On average, a decrease of a measurement temperature by 10°C causes the impact strength decrease by 1.70 J.

$$U_V = 0,17 \cdot T + 17,65 \qquad (1)$$

where: T – temperature (°C); U_V – impact strength (J)

The shape of graphite precipitates is essential in forming mechanical properties including resistance, ductility and impact strength. Graphite, from the point of view of the cast iron structure constitutes its internal discontinuity, which lowers resistance, ductility and other mechanical properties. It takes from a few to a dozen or so percent of the surface of the cast iron polished sections. Although in spheroidal cast iron graphite has a favourable form of spheres, the 'spherical degree' of graphite precipitates is variable within wide boundaries. To describe shape of precipitates several coefficients, called shape factors, were developed [10].

Subsequent, weakly recognised structure elements, influencing the ability of spheroidal cast iron for transferring dynamic loads, are hard phases precipitating on grain boundaries (e.g. phosphoric eutectic). Unfavourable is also the presence of non-metallic inclusions, which are formed at all stages of melting and casting technologies. A part of them is formed during metal melting and correcting its composition, then during secondary

metallurgy treatments, such as modification, inoculation, metal reladle and also mould pouring processes. At this last stage the secondary oxidation of metal occurs (known as reoxidation). Out-floating of non-metallic inclusions from the metal bath, accompanied by growing of a slag layer, is rather a slow process. The most often the out-flowing of inclusions is not finished before pouring out of metal from the casting ladle to a mould. Striving for the fast metal pouring after the modification treatment, additionally hinders the self-purifying process of metals. Gaseous refining is one of the most efficient method of the metal bath purification. However – in practice – the refining process is relatively seldom used in producing spheroidal cast iron [13]. The refining process leads to removal of not only non-metallic inclusions but also to lowering the hydrogen and oxygen content, which negatively influences mechanical properties of cast iron, including its impact strength [12].

2. Own investigations

Technology of cast iron production

In order to obtain the ferritic structure in spheroidal cast iron in as-cast state the proper selection of the chemical composition as well as the application of the complex secondary metallurgy is necessary. This secondary metallurgy, apart from the spheroidisation (modification), should also contain proper inoculation. The metallurgical aim, which should be achieved at producing purely ferritic cast iron, is maintaining its high ability for graphitising when metal is solidifying in a mould.

To obtain a high ability for graphitising, cast iron should have near eutectic chemical composition and the inoculation process should be realised in stages. At least two-stage inoculation is necessary, but three-stage inoculation is more beneficial. The structure of the metal charge composition is an important element of this process, since its significant amount constitutes pig iron of a low content of manganese (Mn < 0.15%), phosphor (P < 0.03%), sulphur (S < 0.01%) and also silicon (Si < 1.5%). Secondary metallurgy of liquid metals contains spheroidisation (modification) and inoculation treatments and causes an increase of Si content by at least 1.0% (the most often by higher amounts). This results from the fact of applying low magnesium inoculants FeSiMg and graphitising modifiers, based on FeSi alloys containing 40÷70% Si. Metal charge components should contain respectively less silicon, in order that its content – in the final cast iron composition – would not cause its classifying as low-silicon (Si < 3.0%).

Spheroidal cast iron, which will be characterised by the high impact strength at low temperatures (–20 and –40°C) should have 'purely' ferritic matrix. To achieve this in control samples of Y2 type and in castings, the carbon content should be at a level: C > 3.50% and the silicon content within: 2.40% < Si < 2.65%. On the other side, due to a possibility of silica ferrite formation, cast iron should have a low content of silicon (Si < 2.50%).

A series of melts of spheroidal cast iron was performed in

the laboratory induction furnace of an average frequency. The metal charge contained Pig – Iron of a composition: C-4.55%, Si-0.815%, Mn-0.26%, S-0.009% and P-0.029% as well as cast iron scrap, steel scrap, and ferroalloy (FeSi75). The metal charge was configured in such way as to obtain the final cast iron composition, after (modification) and inoculation, within previously defined boundaries of individual chemical components.

The secondary metallurgy of cast iron, combined with two-stage refining by nitrogen, was performed in the Tundish type ladle (shown in Fig. 1). The cast iron refining was performed in the furnace – after the metal melting and in the ladle – after the modification treatment. Refining processes performed in the furnace (by means of a lance with a gas-permeable insert) and in the treatment ladle (by means of the porous insert/plug placed in the ladle bottom) are shown in Figs 2 and 3. Refining by nitrogen was carried out for approximately 2 minutes in a furnace and for the same time in a ladle.

The modification process was performed by means of low-magnesium foundry alloy FeSiMg6 placed on the ladle bottom together with a modifier and cast iron chips. An amount of foundry alloy was experimentally determined in such way as to obtain cast iron – for casting of specimens – containing Mg
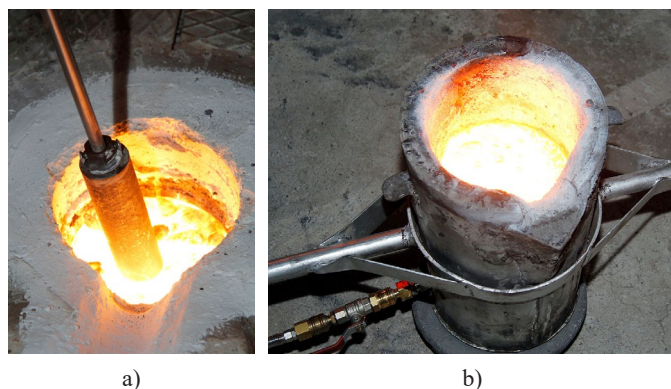

a)   b)

Fig. 2. Tundish type ladle: a) Scheme (1 – cover, 2 – ladle, 3 – thermocouple, 4 – liquid metal), b) Cast iron overflow from a furnace to a ladle
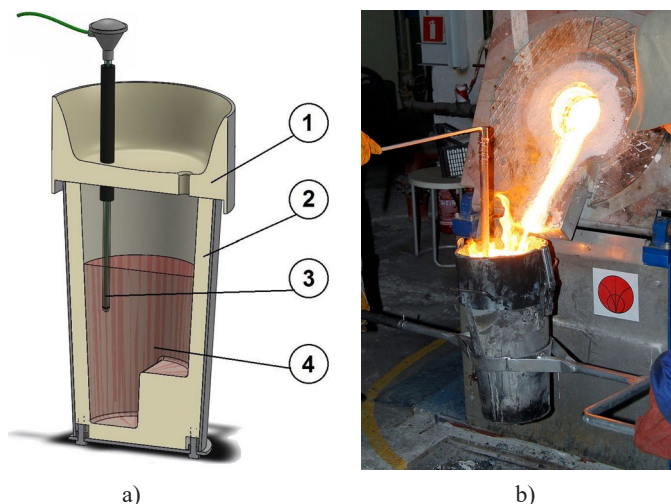

a)   b)

Fig. 3. Cast iron refining by nitrogen: a) by the lance in the furnace; b) by the porous insert/plug placed on the ladle bottom

Chemical compositions of cast iron intended for operations at low temperatures

	C %	Si %	Mn %	P %	S %	Cr %	Ni %	Cu %	Al. %.	Mg %
R16.2	3.80	2.86	0.028	<0.0005	0.008	0.008	0.007	0.007	0.019	0.025
R17.2	4.27	3.01	0.083	0.0229	<0.001	0.023	0.015	<0.005	0.020	0.022
R18.2	4.06	3.44	0.082	0.025	<0.001	0.009	<0.004	0.543	0.018	0.064
R19.2	3.85	2.92	0.068	0.026	<0.001	0.013	<0.003	0.025	0.018	0.054
R20.2	3.73	2.71	0.133	0.020	0.001	0.221	0.012	0.084	0.018	0.035
R21.2	3.32	2.59	0.114	0.044	0.008	0.031	0.016	0.166	0.015	0.037

from a range: 0.03÷0.05%. The modifying process was carried out in three stages: I – during cast iron pouring from the furnace to the ladle 0.20% of a modifier was introduced, II – together with foundry alloy 0.40% of a modifier was introduced on the ladle bottom, III – on the stream, during pouring test bars, 0.20% of a modifier was introduced. This three-stage inoculation provided maintaining the cast iron high ability for graphitisation, which caused refinement of graphite precipitates in cast iron.

Analytical results of chemical composition of melted cast iron are listed in TABLE 2. Generally, cast iron is characterised by a high content of C and Si as well as by a limited content of elements which favour pearlitisation of matrices (Mn, Cr, Ni, Cu) or favour formation of hard and brittle eutectics or phases (P). Maintaining silicon content within wider than optimal range allowed to assess its influence on the cast iron impact strength.
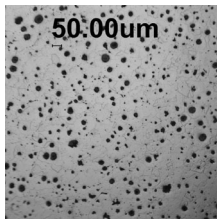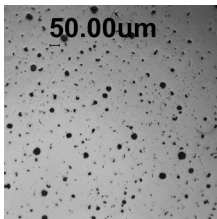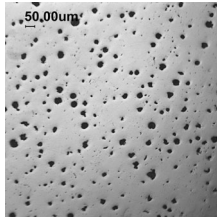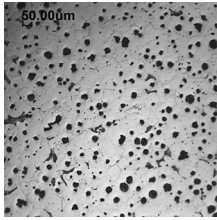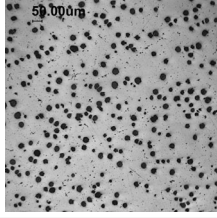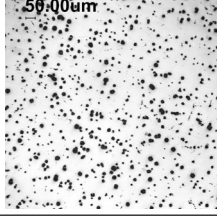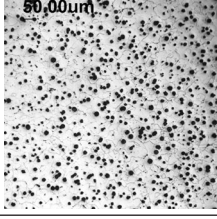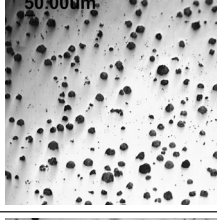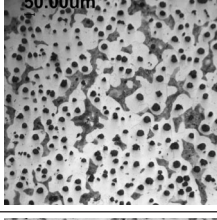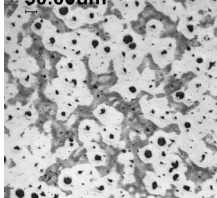
The verification of the produced spheroidal cast iron is being done according to the standardised procedure, which contains casting of control samples Y2 and making from them specimens for testing mechanical properties (R_m, R_{p02}, A_5). Additionally, for cast iron intended for operations at low temperatures, impact strengths are determined (U_v). These tests are carried out for grades: EN GJS 400-15; EN GJS 350-22LT and EN GJS 450-18LT. Previous investigations [6 – 8] indicated that the place on the control sample, from which the specimen for the impact strength test was taken, influenced this test results.

Metallographic structure

The aim of metallurgical efforts was obtaining cast iron of the ferritic matrix with a lot of nodular (spherical) graphite precipitates (>200 1/mm^2). Cast iron structures obtained in successive control samples Y2 are listed in TABLE 3. Their analyses indicate that even small amounts of Cr (melt R20.2) or copper (melts: R18.2 and R21.2) in the cast iron chemical composition cause that in their matrices occurs pearlite, which decreases the cast iron elongation and impact strength. Obtaining the ferritic structure in such cast iron requires applying the thermal treatment (annealing), which sometimes is used in foundries producing cast iron intended for operations at low temperatures. However, this generates additional costs. Thus, due to the matrix kind, cast irons obtained in melts R18.2; R20.2 and R21.2 should be considered as unsuitable, since they do not satisfy the ferritic matrix criterion.

Cast iron structure obtained in control samples

Melt No	Microstructures non-etched metallographic sample	Microstructures etched (nital) metallographic sample
R16.2		
R17.2		
R18.2		
R19.2		
R20.2		
R21.2		

Mechanical properties

Mechanical properties constitute basic criteria in assessments and classifications of cast irons. Investigations were performed on specimens cut out from control samples Y2, and their results are listed in TABLE 4. Cast iron of ferritic-pearlitic structure (R18.2) is characterised by a low ductility and impact strength, which does not allow to classify it into the group of grades suitable for work at low temperatures.

TABLE 4

Results of mechanical properties measurements

Nr	R_m [MPa]	A_5 [%]	HB	U_V [J] (+20°C)	U_V [J] (−20°C)
R16.2	469	18.96	167.1	17.1	9.80
R17.2	473	18.35	168.6	16.3	7.40
R18.2	498	9.96	171.7	9.8	-
R19.2	452	12.2	164.3	13.7	9.81

Out of all tests from four cast iron control samples, properties of which are listed in TABLE 4, only cast iron R16.2 fulfills standard requirements for grade EN GJS 400 18LT. Relatively low impact strength values, regardless of the ferritic matrix and nodular graphite form, is related to too high Si content in cast iron. Supplementary tests indicate that the ferrite micro-hardness increases after exceeding of approximately 2.6% of Si content (Fig. 4). Similar dependencies of the impact strength decreases at higher Si contents were found by other authors [11], Fig. 1. Silica ferrite is less ductile and its presence causes also the impact strength decrease.
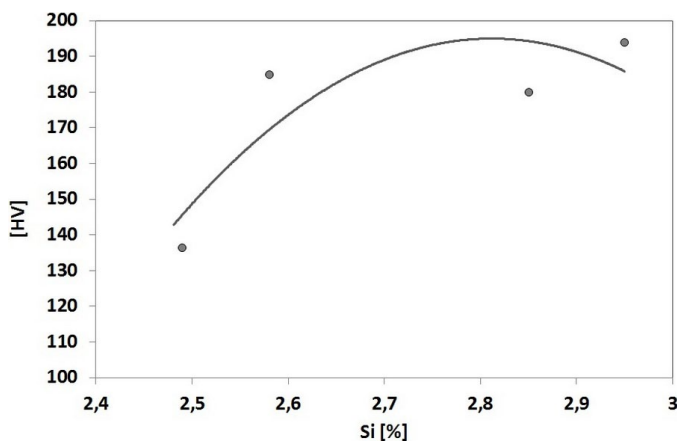
Fig. 4. Influence of the Si content on ferrite micro-hardness in spheroidal cast iron. Measurement of micro-hardness (HV): indenter pressure – 980.7 mN, load time – 10 seconds

Ferritic grades of spheroidal cast iron are characterised by near-eutectic or over-eutectic composition. The high ability for graphitisation favours graphite floating and its inclination for transferring to upper parts of castings. The result of this effect is a tendency for large differences in indicators of mechanical properties of specimens taken from different places of the control sample. Authors of [6] revealed different impact strengths of
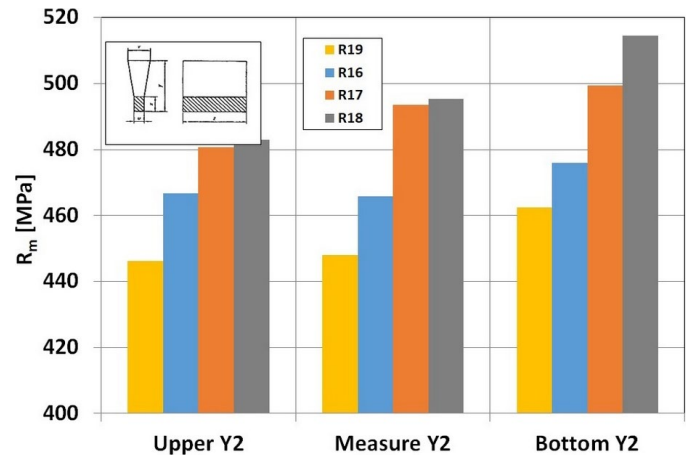
Fig. 5. Influence of the place of Y2 control sample, from which the specimen was taken, on tensile strength R_m

specimens made from the same control sample. The higher situated place of taking specimen from Y2 control sample the lower impact strength. Similar relations were observed by us at testing tensile strength Rm, Fig. 5. This tendency should be taken into consideration in investigations performed on specimens taken from Y2 control samples.

Index Quality (IQ_U) of cast iron

The final assessment of cast iron intended for operations at low temperatures is based on tests of resistance indicators (R_m), elongation (A_5) and impact strength U_v : at –20ºC or –40ºC. However, for the preliminary assessment of cast iron an intermediate method, which would satisfy the fast method criteria and provide results in a relatively short time, should be used.

The authors propose the new, intermediate method of assessing quality of the produced ferritic cast iron, based on the performance of two non-destructive measurements: propagation velocity of ultrasound wave (C_L) and hardness (HB). These tests should be made on Y2 control sample, which is used for making specimens in accordance with the standard EN 1560. Cast iron for operations under dynamic loads should be characterised by the nodular graphite form. The graphite shape indicator can be well and precisely determined by the ultrasound technique [14,15]. The following dependence occurs: the more nodular (spherical) form, the higher wave velocity. In addition, the estimated cast iron of a high impact strength should have purely ferritic matrix. This parameter is the best determined by the cast iron hardness. The known dependence occurs here: the more ferrite in metal matrix, the lower hardness. Thus, the presence of silica ferrite will be causing the hardness increase. On the bases of these two values it is possible to develop the Index Quality of cast iron describing its suitability for operations at low temperatures. It should be of a form of Eq. (2): the higher index quality value, the more suitable cast iron for operations at low temperatures.

$$IQ_U = \frac{C_L}{HB} \qquad (2)$$

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The analysis of results of the performed investigations indicates that, in order to obtain the effect of increasing the 'sensitivity' of IQ for hardness and wave velocity changes, it is better to apply dimensionless values of: wave velocity (S_{CL}) and hardness (S_{HB}). They are defined in TABLE 5. The index quality (IQ_U) of ferritic cast iron, intended for operations under dynamic conditions at low temperatures, is defined by Eq. (3).

TABLE 5

Indices of quality of spheroidal cast iron for operations at low temperatures

No	Index S_{HB}	Index S_{CL}	Index Quality (IQ_U)
1	$S_{HB} = \dfrac{HB_x - HB_{min}}{HB_{max} - HB_{min}}$	$S_{CL} = \dfrac{CL_{max} - CL_x}{CL_{max} - CL_{min}}$	$IQ_U = \dfrac{S_{CL}}{S_{HB}}$

$$IQ_u = \frac{S_{CL}}{S_{HB}} \quad (3)$$

Dependence 3, developed by calculations for spheroidal cast iron with metallic matrix in which ferrite dominates, is presented in figure 6. This dependence was developed for the following variability ranges: $HB = 145 \div 220$, $C_L = 5300 \div 5750$ m/s. To obtain mechanical properties required for cast iron EN GJS 400-18-LT the necessary (but not sufficient) condition is achieving the determined value of the index quality (IQ_U). This cast iron is intended for work at a temperature of minus 20°C, and at this temperature it should achieve impact strength: $U_V > 12$ J. According to the authors investigations [1] the impact strength of ferritic cast iron decreases by 0.17 J/°C when the temperature is decreased by 1°C. Thus, cast iron GJS 400-18LT at a temperature of +20°C should have the impact strength: $U_{V(+20)} > 12 + 0.17*40 > 16.8$ J. According to figure 7 cast iron should be characterised by IQ_U above 30 units. In order to achieve this IQ value the wave velocity should be: $C_L > 5500$ m/s, while hardness: $HB < 160$ HB (Fig.6). Generally, the higher value of IQ_U the higher probability of obtaining cast iron, which satisfies requirements of standard PN- EN 1563.
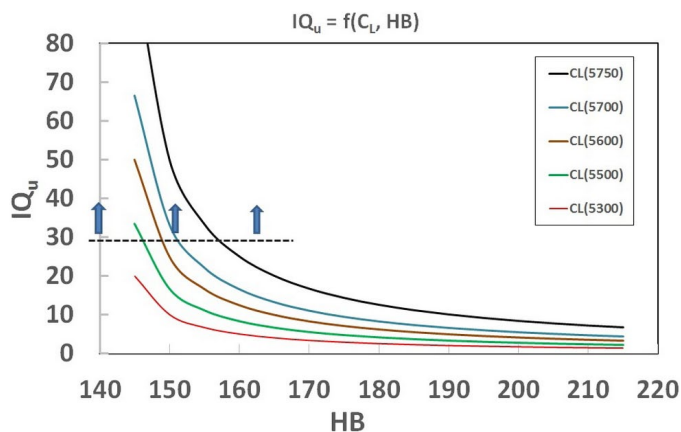

Fig. 6. Index Quality (IQ_u) of spheroidal cast iron based on values of the propagation velocity of ultrasound wave (CL) and hardness (HB)
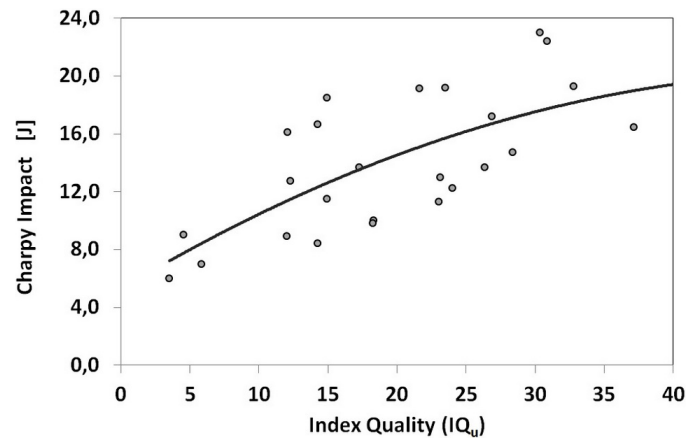

Fig. 7. The relation between the index quality and impact strength of ferritic spheroidal cast iron

The relation $U = f(IQ_U)$ worked out on the bases of series of tests performed on the same specimens is presented in Fig. 7. Measurements of hardness (HB) and wave velocity (C_L) were performed on specimens after the impact strength test. Specimens were prepared from standardised Y2 control samples. Impact strength tests were estimated at a temperature of +20°C. The velocity of the longitudinal ultrasound wave was determined using heads of a frequency of 2.0 MHz. The cast iron index quality (IQ_u) was calculated by means of Eq. (3), according to the accepted procedure. The analysis of results indicates that there is a relatively good relation between IQ_U and the impact strength of ferritic spheroidal cast iron intended for work under dynamic loads.

The new method of the preliminary quality assessment of ferritic cast iron for operations under dynamic loads was developed. On the bases of non-destructive tests of the hardness (HB) and ultrasound wave velocity (C_L) as well as the IQ_U calculation, the preliminary assessment is carried out. This is not a decisive assessment, however it allows to obtain – in a few minutes – the preliminary estimation of the produced cast iron melt. This allows to classify the developed method to the so-called fast methods of testing materials.

3. Conclusions

The production of cast iron intended for operations at low temperatures and dynamic loads, which has to satisfy requirements concerning the impact strength described in standard PN EN 1563-1997 is difficult. When it is assumed that cast iron should be in the as-cast state its production, without a thermal treatment, becomes even more difficult.

It was pointed out, in the hereby paper, that:
- Cast iron should have purely ferritic structure, without silica ferrite which strengthens ferrite increasing its hardness, what leads to the ductility and impact strength decreasing.
- It should be strived to maintain Si content not higher than $2.50 \div 2.60\%$, which at producing spheroidal cast iron

is sometimes difficult and requires using a lot of pig iron in the metal charge.

- For a fast assessment of the cast iron quality, concerning its impact strength, the proposed – in the hereby paper – index quality (IQ_u) can be applied. It is determined on the bases of measuring the cast iron hardness and propagation velocity of ultrasound wave.

- Graphite in cast iron should be characterised by a high spherical index and the number of graphite precipitates in standardised Y2 control sample should exceed 200 pieces in square millimeter.

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