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Structure and mechanical properties of ductile iron GJS-500-7

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ABSTRACT: The paper presents the results of research on mechanical properties (hardness distribution along the cross section towards the cast's core) and on the structures of ductile iron GJS-500-7. The study defines the range and form of the surface layer of cast iron. It has been shown that the surface layer of the working surface of the cast may be shaped within its transition zone.

KEYWORDS: Ductile iron; Hardness distribution; Structures; Transition zone

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RESUMEN: *Estructura y propiedades mecánicas del hierro dúctil GJS-500-7.* El artículo presenta los resultados de la investigación sobre propiedades mecánicas (distribución de la dureza a lo largo de la sección transversal del núcleo de la fundición) y de las estructuras de hierro dúctil GJS-500-7. El estudio define el rango y la forma de la capa superficial de hierro fundido. Se ha mostrado que la capa superficial de la superficie del molde trabajado puede estar conformada dentro de su zona de transición.

PALABRAS CLAVE: Distribución de la dureza; Estructuras; Hierro dúctil; Zona de transición

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1. INTRODUCTION

Practical exploitation of parameters of a technological process as an effective way to enhance the durability and reliability of various elements of appliances and devices has been the subject of interest of numerous research centres. Minimization of technological allowances in the manufacturing process while obtaining the highest performance characteristics across the surface of the finished product, is the essence of optimization of the implementation process. Designing a technological process which aims at obtaining highest properties of a surface layer can be performed in two stages. The first stage consists in the formation of the properties of the surface layer directly in the technological process. Whereas the second stage consists in the formation of the surface layer after the realized technological processes or during manufacturing techniques including: waste machining, finishing and heat treatment or thermal-chemical treatment.

To implement a designed technological process, it is necessary to have lathes and other tools which allow manufacturing of objects of required geometry and with determined properties of the surface layer. Progressive shaping, gradual obtaining accuracy and functional features are characteristic for a technological process. This gradual "realization" of the finished shape depends primarily on the requirements imposed by the manufacturer. The shape and dimensions of the semi-finished products (casts, forgings, rolling bars, glass blank-moulds etc.) may differ substantially from the shape and dimensions of the finished product. These differences (e.g. technological allowances) are most commonly removed by machining. Accurate surfaces cannot be obtained after just one type of treatment, since the machining of deep layers of material produces considerable shear forces caused by elastic, and partly even plastic, deformations of material. In addition, a considerable increase in the temperature of the workpiece generates deformations. These factors result in the division of a technological process onto the following stages: a coarse machining, a shaping (semi-finishing) machining and a finishing machining (Feld, 2013). Figure 1 takes into account factors occurring in each technological process, in which properties of the Cast Surface Layer - CSL (Polish WWO) are already formed in the casting process - the so-called "finished casting".

Cast iron is one of the most common structural materials in mechanical engineering. The recently observed tendency consists on a gradual "switch-over" to the ductile cast iron and ADI-type cast iron. The rapid development in all fields of technology, including metallurgy and foundry, results in the increased application of new alloys of different chemical compositions and better properties that are not yet included in the classification standards. A good example of this is ductile iron, which is described in Polish classification standards but its properties (and the manufacturing process) are being constantly improved. Thus, even specific standards do not cover all issues relating to a single type.

The production of ductile cast iron requires particular care in the maintenance of the chemical composition within precisely defined content limits. The amounts of particular components of the alloy depend on the required properties of materials and wall thickness of the cast. Generally, it can be stated that ductile cast iron contains relatively considerable amounts of carbon, even above 4.0%, and silicon between 2.5 to 3.0%, and insignificant amounts of phosphorus and sulphur.

The structure, and thus the properties of cast iron (in particular its mechanical properties), are also affected by temperature of the cast iron at the spout, casting temperature, the melting method, the type of feedstock, cooling rate, etc. Basing on years of observation, it was found that the decisive factors are (Kuryło, 2013; Kuryło *et al.*, 2015):

– chemical composition, particularly carbon content and silicon (in unalloyed cast iron),
– cooling rate of castings, which largely influences the structure of the metal matrix, as well as the form of graphite.

Malleability and ductility of cast iron are frequently emphasized. So far, ductile iron has only been surpassed by cast steel and occasionally by malleable cast iron. It must be admitted that these properties are only rarely required or used. Vast majority of castings needs to maintain its shape under operating conditions, regardless to their weight. Plasticity, which is understood as the material ability to bend, warp or to undergo other non-destructive plastic deformations, is understood as a measure of safety (in the best case). For some elements, such as gears (gear wheels), their breakage may be even seen as a safe destruction mechanism.

The most valued property in the majority of structures is not plasticity, though, but strength. Especially due to the fact that the basis of design calculations is the yield strength which takes into account the safety factor. It should be emphasized that the yield strength of ductile cast iron substantially exceeds the yield strength of grey cast iron and malleable cast iron, as well as many other non-alloy steels (Kupczyk, 1997; Burakowski, 2013;). Alterations either in a chemical composition or in a metallurgical process, introduced in order to increase the yield point, usually reduce impact toughness.

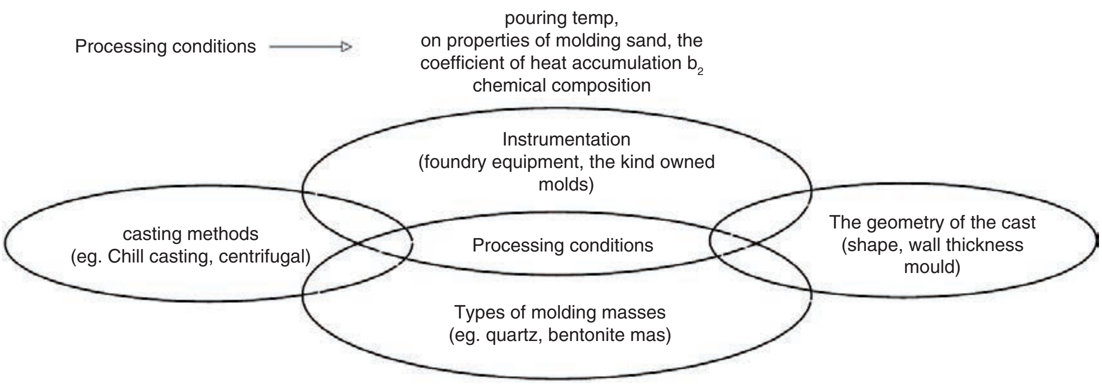


FIGURE 1. The influence of factors presents in each technological process on the formation of a surface layer without further treatments shaping operating surfaces of the product (Kuryło and Janik, 1999).

The main and frequently used feature of ductile cast iron is its good fluidity and low casting shrinkage. Similarly, ductile cast iron has good workability. The relation between cast iron workability and its hardness is shown in Fig. 2. Among the numerous properties of a surface layer of cast iron castings, hardness, measured on the cross section of the wall of a casting, is the most representative (Rudol, 1974; Truś and Jamroz, 1974; Rudol, 1975; Cambell, 2003). Basing on the hardness it is possible to calculate Rm - extemporary tensile strength of ductile iron. However, due to the fact that cast materials are sensitive to wall thicknesses, which are a negative property of cast materials, it is necessary to provide such quality control of castings that would allow verification of the actual tensile strength of the cast's walls (Rudol, 1974).

Truś and Jamroz (1974) argue that only destructive tests involving the cutting of a sample from the cast wall, allow the determination of strength at a given location of a cast.

According to Rudol (1975), the most relevant and meaningful measurements of hardness are the ones that are taken in the important places of the cast. It obviously refers to casts which had previously been deprived of residual stresses. It is also important not to destroy the tested cast, while measuring its hardness, in order to prevent the decrease in its usability properties.

In order to assess the strength properties, thanks to the applied method of calculating of "significant" hardness (Rudol, 1974), it is possible to use micro-hardness measurements. Methods of calculating of extemporary tensile strength of ductile cast iron with the use of hardness and micro-hardness measurements are based on the following relations (Rudol, 1975):

$$R_m = R_{m_{metal\ matrix}} \left(1 - \frac{V_{gr}}{100}\right) \cdot \left(1 - \frac{f}{100}\right) [Pa] \tag{1}$$

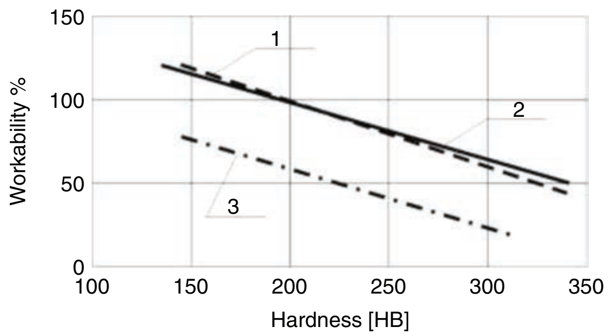


Figure 2. Relation between cast iron workability and its hardness (Janik, 1978) where: 1- cast iron with flake graphite, 2 - ductile cast iron and 3 - malleable, pearlite cast iron.

where: R_m- extemporary tensile strength of ductile cast iron in a tested location (Pa),
$R_{m\ metal\ matrix}$ - extemporary tensile strength of a metal matrix in the tested location [kG mm-^{2}], which can be determined in the measurement of material hardness and using the formula: R_m=$0,35HU$
HU – hardness measured with a standardized method (Rudol, 1974),
V_{gr} - volume occupied by graphite in the cast iron in (%),
f - coefficient dependant on the graphite ratio and the degree of reduction of the continuity of metal matrix caused by graphite in either a flake or nodular form.

Coefficient f is determined from formula

$$f = \frac{V_{gr}}{100}\left(C_{pl} \cdot X + C_{sf} \cdot Y\right) \tag{2}$$

where: C_{pl} - graphite ratio in the form of flakes (%),
C_{sf} - graphite ratio in a nodular form (%),
X - average degree of the continuity reduction of metal matrix by flake graphite, usually amounting to 5,
Y - average degree of reduction of continuity of the metal matrix due to an irregular shape of nodular graphite or due to incandescence carbon.

It must, however, be recognised that $C_{pl}+C_{sf}=100$. The value of Y is determined from relation:

$$Y = 1 + \frac{D-d}{d} \tag{3}$$

where: D - diameter of the circle circumscribed about the graphite,
d - diameter of the circle inscribed in the graphite.

The error of the value of extemporary tensile strength calculated from measurements of the hardness and microhardness of material does not typically exceed 6% of the tensile strength measured with the use of the static tensile test (Rudol, 1974).

The above-described method, although enables the computation of the extemporary tensile strength, requires the use of modern appliances for observation of the quantity of graphite formation etc. Thus, knowing the method of converting "the hardness" onto the extemporary tensile strength it is possible to unambiguously define the properties of the material and the properties of the surface layer of a cast, including casts of ductile cast iron.

2. MATERIALS AND METHODS

2.1. The subject of research

Samples for testing have been made of GJS-500-7 ductile cast iron, and the chemical composition has been presented in Table 1. Cast iron was obtained from a network induction furnace PIK ZGH BOLESŁAW, kiln input 5 T, mould filling temperature 1450 °C.

The samples were cast of moulding sand, the composition of which is given in Table 2.

The preparation of moulding sands was performed in an edge runner mixer Mk 750, the mixing time was 3.5 min (supplied by time feeders).

In order to determine the effect of the heat treatment, which eliminates the polishing effect, a part of the samples was subjected to annealing in a resistance furnace HT-1.18/1800, where the annealing temperature was 830 ºC – graphitizing annealing.

The process parameters are as follows:

- holding time: 3 h
- time after which temperature of 830 ºC has been reached: 11 h
- heating speed: 75.45 °C/h
- cooling time: 24 h

2.2. Structure testing

The metallographic tests included samples obtained from a stepped technological sample. They were cut out at particular distances from the geometric surface of the cast wall (for all discussed wall thicknesses) (Fig. 3). The paper presents selected images only for ranges with significantly different structures, i.e. at depths 0.25, 2.5 and 4.75 mm distant from the cast surface (Table 3).

2.3. Hardness testing

Hardness measurements were accomplished using a Rockwell-type durometer, with an indenter - a steel ball, in the time of 3 to 6 seconds in order to obtain the total load. The tests were carried out according to procedures described in Polish Standards. The following values were assumed: standardized hardness scales B, i.e. pre-load F_0 = 98 N, main load F_1 = 883 N, total load F_c = 980 N, indenter - steel ball 1/16”. Hardness measurements were performed on properly prepared surfaces with the same asperities Ra = 0.63 μm. Three impressions were performed at each determined distance from the geometric surface, and in the stepped sample - at every step.

The studies of hardness distribution on the cross-section of the wall of a cast were performed on the cut samples prepared with Duracryl plus.

Micro-sections, performed by cutting out fragments of stairs, have been presented to illustrate the structural changes in the surface layer of ductile cast iron GJS-500-7 (Fig. 4)

Statistical studies were performed using statistica computer programme and Excel spreadsheet - Analysis ToolPak.

The study of microstructure was performed with the use of a metallographic microscope EPITYP 2. The results of the research were registered in the form of photographs taken with a digital camera attached to the microscope. The research program was selected basing on own preliminary studies (Kuryło and Janik, 2001; Kuryło *et al.,* 2002; Kuryło, 2003; Kuryło *et al.,* 2015) and on the literature (Rudol, 1974; Polański, 1984; Polański, 1997; Klonecki, 1999).

3. RESULTS

3.1. The analysis of the results

The elaboration of the measurement results included the calculations of mean values, whereas the measure of dispersion of the results around the average value was calculated, depending on the number of measurements, either as the spread for $n < 5$ (absolute error is equal to half of the scatter of the measurements), or the standard deviation when $n < 5$.

For the assumed confidence level $p=0.95$ the confidence intervals were determined on the bases of Student’s t-statistics and tables. The following computer programmes were applied: Statistica, Excel - Analysis ToolPak, Maple.

The impact of the thickness of the cast wall as well as the distance from the cast surface (in the case

Table 2. Chemical composition of moulding sand

Component	% of component
Washed quartz sand	85-89%
Special bentonite “S”	8-10%
Pulverized coal	3-5%
Water (moisture)	3-3.5%
Refreshed moulding sand composition	2.5% of fresh compounds

Table 1. Chemical composition of casts made of GJS-500-7 cast iron

	Chemical composition (wt. %)							
Type of cast	C	Si	Mn	P	S	Cr	Mo	Ni
Pre-casts and glass moulds	3.63	2.99	0.193	0.078	0.018	0.025	0.046	0.019

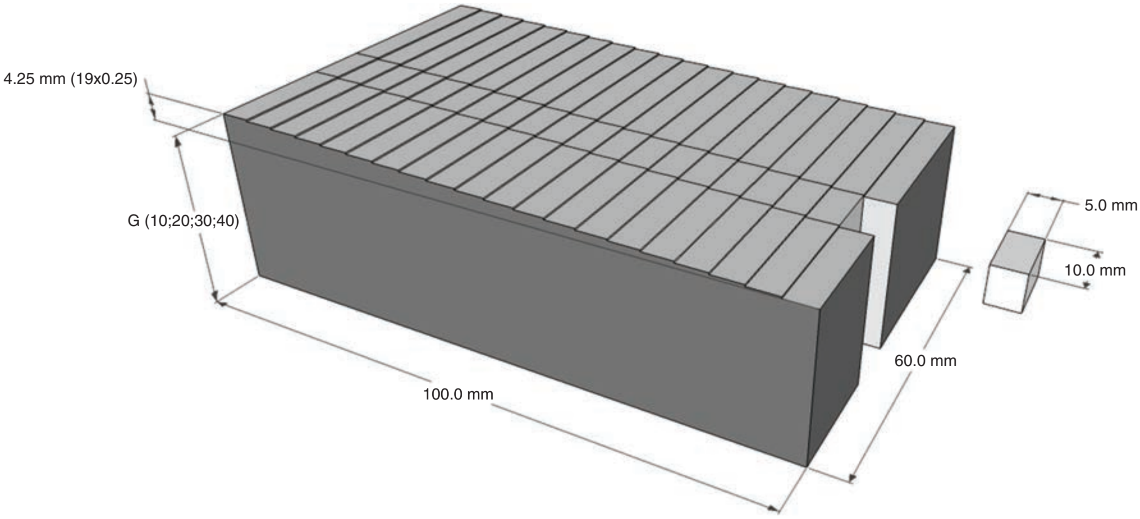


FIGURE 3. Illustration of the method of the sample preparation for metallographic micro-sections.

TABLE 3. Images of graphite formations in samples made of ductile cast iron (GJS-500-7)

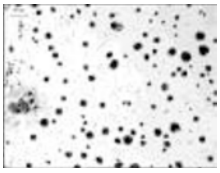
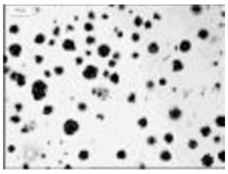
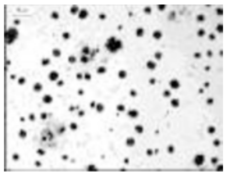
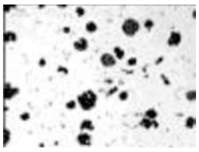
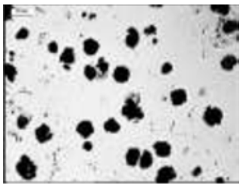
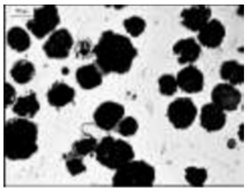
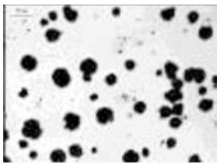
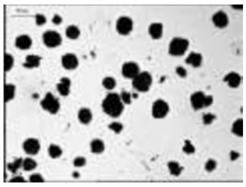
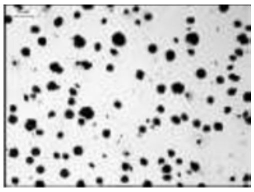
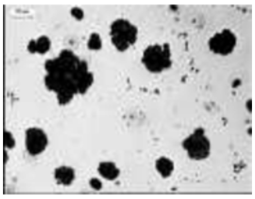
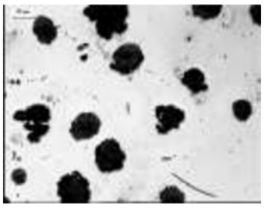
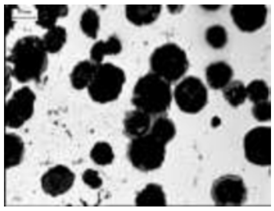
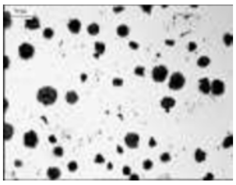
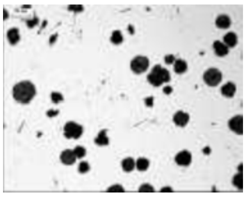
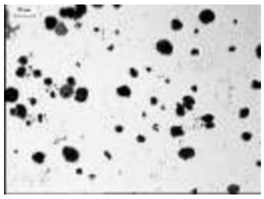
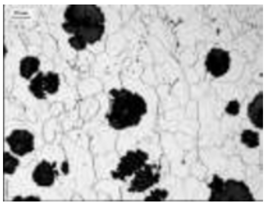
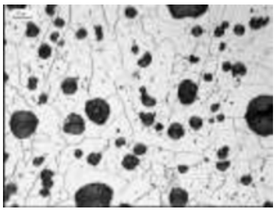
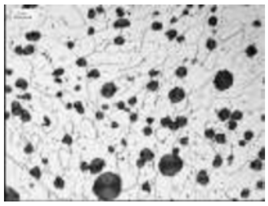
Annealing process	Sample thickness B [mm]	distant from the cast surface [mm]		
		4.75	**2.5**	**0.25**
no	10	 *regular nodular graphite Gf9+ irregular nodular graphite Gf8; the size of graphite – up to 15 + 15-30 µm – Gw15 to Gw25, area occupied by graphite <10%*	 *Gf9, Gw45 to Gw90; area occupied by graphite –10-15%*	 *regular nodular graphite Gf9 + irregular Gf8; the size of the formed graphite – up to 15 + 15-30 µm (Gw5 do Gw15), area occupied by graphite <10%*
yes	10	 *nodular irregular graphite Gf8+ regular nodular graphite Gf9 + vermicular Gf5; the size of graphite – 15-30 µm (Gw25), area occupied by graphite <10%*	 *regular nodular graphite (Gf9) + irregular Gf8 + vermicular Gf5; the size of graphite Gw25 to Gw45, area occupied by graphite 10-15%*	 *regular nodular graphite Gf9+ irregular nodular graphite Gf8; the size of graphite – 60-120 µm (Gw90); area occupied by graphite –25-35%*
no	30	 *irregular nodular graphite Gf8+ regular nodular graphite Gf9; the quantity of the formed graphite – 30-60 + 60-120 µm - Gw45 to Gf90, area occupied by graphite <10%*	 *regular + irregular nodular; Gw45 do Gw90, area occupied by graphite 10-20%*	 *Gf9, Gw45 do Gw90; area occupied by graphite –20-30%*

Table 3. (*continued*)

Annealing process	Sample thickness B [mm]	distant from the cast surface [mm]		
		4.75	**2.5**	**0.25**
yes	30	 *irregular nodular Gf8+ regular nodular graphite Gf9; the quantity of the formed graphite – 30-60 + 60-120 μm (Gw45 do Gf90), area occupied by graphite 10-15%*	 *regular nodular Gf9+ irregular Gf8; the quantity of the formed graphite – 30-60 + 60-120 μm (Gw45 do Gw90), area occupied by graphite 10-20%*	 *regular nodular Gf9; the quantity of the formed graphite – 60-120 um (Gw90); area occupied by graphite –30-40%*
no	40	 *irregular nodular graphite Gf8+ regular nodular graphite Gf9; the quantity of the formed graphite – 30-60 + 60-120 μm (Gw45 do Gf90), area occupied by graphite 10-15%*	 *regula r nodular Gf9+ irregular Gf8; the quantity of the formed graphite – 30-60 + 60-120 μm (Gw45 do Gw90), area occupied by graphite 10-20%*	 *regular nodular Gf9; the quantity of the formed graphite 30 - 120 μm (Gw45 do Gw90), area occupied by graphite –10-15%*
yes	40	 *the formation of nodular graphite in ferritic matrix*	 *the formation of nodular graphite in ferritic matrix.*	 *the formation of nodular graphite in ferritic matrix*

of hardness measurement) was determined by the analysis of variance, at the assumed significance level of test *F-Snedecor* $\alpha = 0.05$.

The following technological parameters were assumed for the hardness analysis:

– thickness of the cast wall – variable x_1,
– distance from the surface towards the core – variable x_2.

The structures were tested separately for annealed and unannealed casts.

A mathematical model, described with the relation presented below, was assumed for the hardness tests (second degree polynomial with double interactions) (Kuryło, 2013; Kuryło *et al.,* 2015):

$$HRB(x_1, x_2, x_3) = b_0 + \sum_{k=1}^{i} b_k x_k + \sum_{k=1}^{i} b_{kk} x_k^2 + \sum_{\substack{k=1 \\ q<k}}^{i} b_{qk} x_q x_k \quad (4)$$

To determine the influence of variables x_1, x_2, x_3 on hardness, the authors assumed multiple regression with a non-linear relation as a mathematical model, basing on the literature and preliminary studies.

The main purpose of the calculation was to determine the regression equation of the second type describing the dependence between the hardness of a ductile iron cast (GJS 500-7) at the cross-section, and the cast wall thickness as well as the distance from the wall surface into the cast core.

This equation takes the following form:

$$T_{HRB} = T_{HRB}\,(g,l) \quad (5)$$

where: T_{HRB}: hardness expressed in units HRB,
g: thickness of the cast wall (mm),
l: distance from the edge of the wall of the cast (mm).

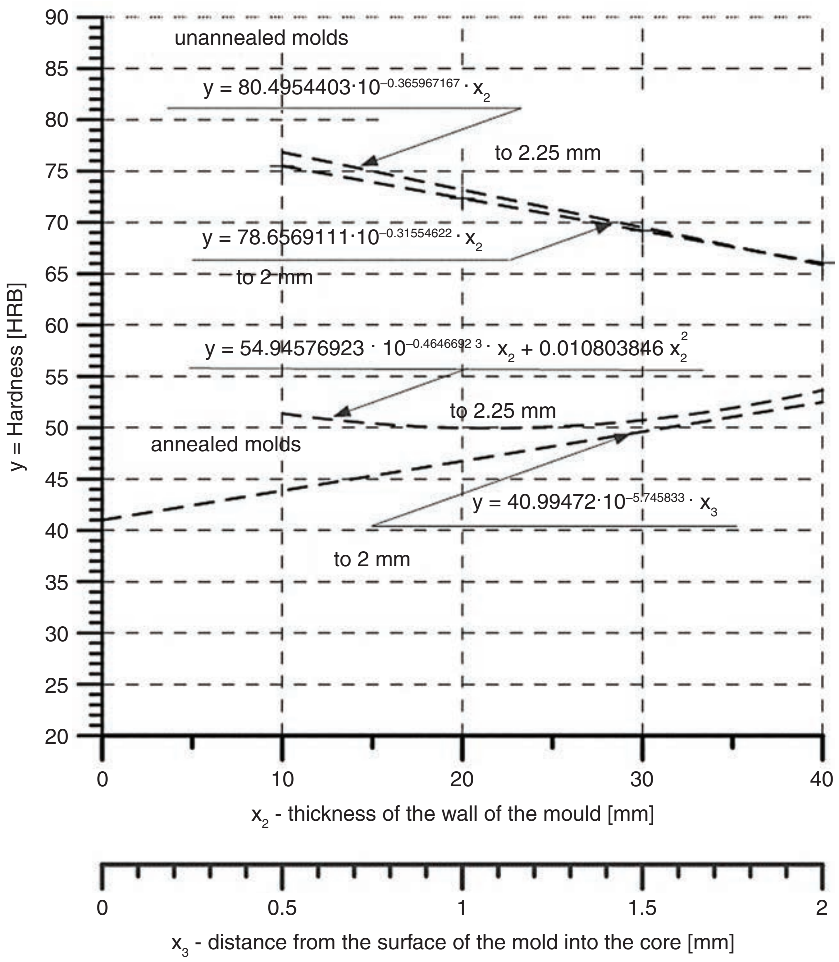


FIGURE 4. Hardness as a function of the wall thickness of a cast made of ductile cast iron $T_{HRB}(x_2)$ and as a function of the distance from the surface towards the core of the cast made of ductile iron $T_{HRB}(x_3)$.

On the basis of the analysis of the structures it was assumed that solutions should be looked for in two ranges of the distance (from the surface of the cast towards the core), i.e. from 0÷2 mm, and from 2.25÷5 mm.

The following ranges of variation of the examined factors were assumed:

x_1 = 10, 20, 30, 40,
x_2 = 0., 0.25 up to 5 at intervals of 0.25.

The statistical analysis of hardness distribution for casts made of cast iron GJS-500-7, resulted in four regression equations describing the dependence between the hardness of the cast, wall thickness and the distance from the surface towards the cast core:

- up to 2 mm for unannealed casts:

$$y = 78.65691111 - 0.31554622x_1 \quad (6)$$

- from 2.25 mm for unannealed casts:

$$y = 80.49544403 - 0.365967167x_1 \quad (7)$$

- up to 2 mm for annealed casts:

$$y = 40.99472 + 5.745833x_2 \quad (8)$$

- from 2.25 mm for annealed casts:

$$y = 54.94576923 - 0.46466923x_1 + 0.010803846x_1^2 \quad (9)$$

The resulting regression equations were evaluated for the significance of regression factors and the adequacy of the regression function - with the use of the *F-Senedecor's* test, compared with a critical test of its value $F_{\alpha,r1,r2}$. For all the examined cases, the hypothesis about the veracity of the regression coefficients should be accepted. Also the hypothesis of the adequacy of the regression function should be adopted for all the examined cases, at the assumed significance level $\alpha = 0.05$.

The results of the examinations of hardness distribution and metallographic structures along the cross-section of a wall of a cast made of ductile cast iron GJS-500-7, which are the essential parameters defining the range and the form of the surface layer of a cast, revealed that the shaped technological surface within the cast surface layer has properties not worse than the one formed within the range of the cast core. Figure 5 presents the cast hardness as a function of the distance from the surface towards the insides of the raw cast, supplied with photographs of metallographic structures for each specific depth.

Other parameters such as stress distributions and microhardness do not present any contraindications, which is reported in the literature (Janik and Kuryło, 1999; Kuryło and Janik, 2000; Kuryło, 2003; Kuryło, 2013; Kuryło *et al.*, 2015). In the unannealed casts within surface layers, hardness distribution depends mainly on the wall thickness. Whereas in annealed casts, the hardness distribution in the surface layer depends mainly on the distance from the wall surface towards the cast core. Graphite in ductile cast iron which differs substantially in shape and distribution from grey cast iron, affects the form of the surface layer of the raw cast. In the transition zone of the surface layer of a raw cast made of ductile cast iron, there is no range of significantly increased hardness. In this aspect, the reduction of technological allowances for treatment is possible up to the size within the determined range, and not, as for the grey cast iron - to the range of the greatest hardness. Only the maintained quality of the surface layer of the article formed within the surface layer of the cast made of ductile cast iron in relation to the cast formed in the core, brings measurable results in the form of reduced allowances and thus the increased yield of the cast iron, reduced tool wear and others, resulting in reduced manufacturing costs. Reducing technological allowances to a minimum allows their removing through a grinding process (Lawrowski, 2008).

4. CONCLUSIONS

The analysis of the structures and the hardness measurements carried out in the surface layer towards the cast core, allow for clear identification of mechanical properties of ductile iron castings.

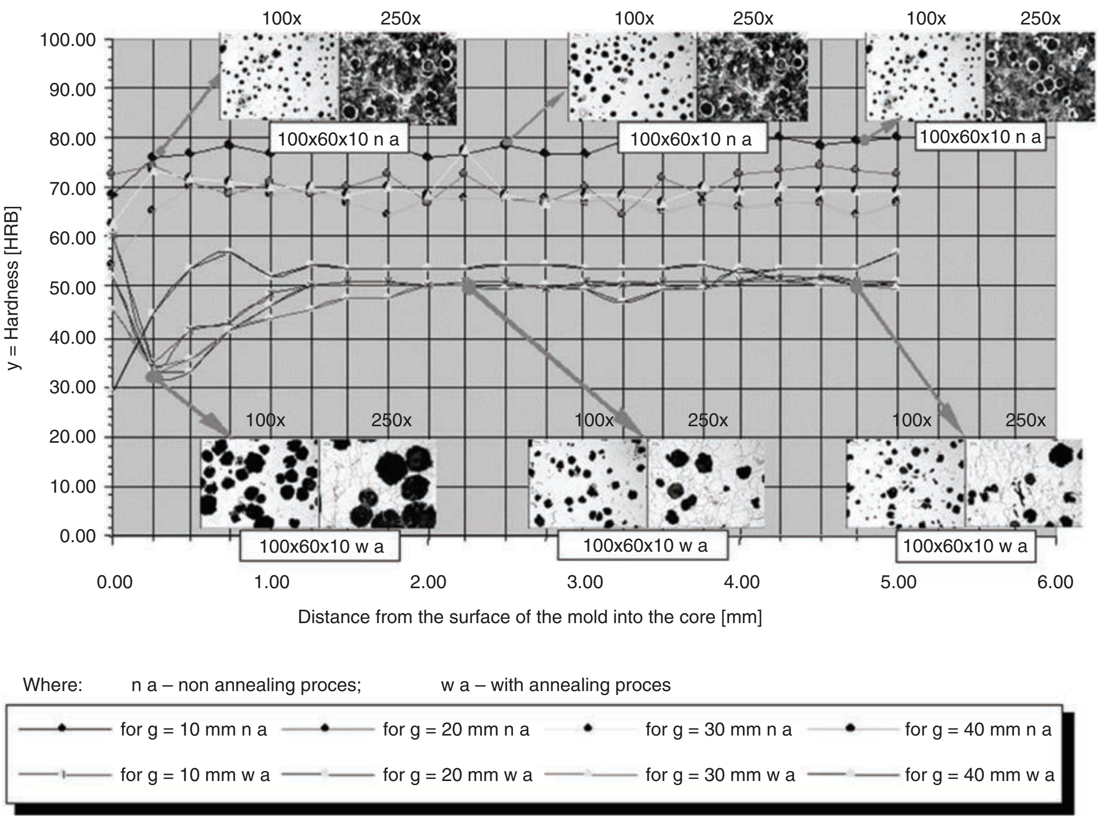


FIGURE 5. Hardness of a cast as a function of distance from the surface of a raw cast towards the marked images of metallographic structures for each characteristic depth.

The results of the analyses are graphically shown in Fig. 4.

Thus, the results of the research allow formulation of the following conclusions:

– it is possible to use the transition zone of the surface layer of a cast made of ductile cast iron by shaping with its range an operational surface layer of the product without interfering into the technology.
– there is no conclusive evidence to use large technological allowances (according to the norms within the range of 3.5 ÷ 5 mm) in the practice. It is purposeful and sufficient to use of technological allowances of approximately 1.5 mm (+0.5 mm).
– the most important parameters affecting the stability of the tribological operational area (for casts made of ductile cast iron GJS-500-7) are the following:
  • the thickness of the cast wall,
  • the application of coolers in the casting process
  • heat treatment (annealing) that is applied to the metallurgical process which allows shaping the product with the machining process.
– the reduction of technological allowances appropriately to the form and the range of the surface layer of the raw cast of ductile cast iron does not deteriorate the properties of the surface layer of the finished product.

It should be noted that the research findings may have practical application in the design of technological processes of manufacturing products of ductile iron GJS-500-7 in volume production.

In such a production processes it is advisable to perform preliminary series to determine the form and range of the surface layer of the raw cast, and then to determine the minimum size of technological allowances. Reducing the allowances for final machining, apart from economic effects, brings ecological effects by increasing the yield in the casting process of ductile iron, which similarly to other types of grey cast iron belongs to materials less harmful to the environment than other alloys of Fe - C, in terms of its manufacturing, as well as the production and the disposal of products.

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