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DUCTILE IRON MICROSTRUCTURE DESIGN USING HEAT TREATMENT PROCESSES

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ABSTRACT
Mechanical properties of the ductile iron strongly depend on its microstructure. Different microstructural constituents result in different values of mechanical and ductile properties of ductile iron castings. One of the possibilities to design (define) microstructure of ductile iron castings is an application of different heat treatment processes. In this paper it is presented the influence of different heat treatment processes on final microstructure and properties of ductile iron samples.

1. INTRODUCTION
Ductile iron is a group of ferrous materials among the cast iron family containing nodular shape graphite particles, which is also known under the names of nodular iron or spheroidal graphite (S.G.) iron. Ductile iron has some superior properties such as high strength, good castability, good machinability, high toughness and low cost. It obtains its good properties by means of its specific chemical composition, matrix and nodular graphite. Depending on the matrix microstructure, ductility and tensile strength of Ductile iron can raise up to 18% and 1500 MPa, respectively. These good properties have made Ductile iron a strong candidate for a vast range of the applications such as these in constructive and automotive industries. Ductile iron is a ternary Fe-C-Si alloy with a typical C and Si content of 3.5-3.9% and 1.8-2.8%, respectively. During the solidification, the carbon in excess of its solubility in solid iron forms graphite. Nodular graphite can be produced by small addition of magnesium or rare earth elements to the cast iron during melt treatment. The big advantage of nodular graphite is its round edges (despite the sharp edges of lamellar graphite) that not only reduces the risk of crack initiation, but also acts as a crack arrester and increases crack propagation

resistance; thus, it promotes higher toughness, fatigue resistance and impact resistance [1, 2, 3, 4].
The final microstructure of Ductile iron highly depends on solidification conditions, chemical composition and casting method. The majority of Ductile iron castings are produced as one of the following types:

FERRITIC DUCTILE IRON - Graphite spheroids in a matrix of ferrite which is basically pure iron. High impact resistance. Relatively good thermal conductivity. High magnetic permeability. Low hysteresis loss. In some exposures, good corrosion resistance. Good machinability

PEARLITIC-FERRITIC DUCTILE IRON - Graphite spheroids in a mixed matrix of ferrite and pearlite. This is the most common grade of Ductile iron. Properties are between those with “fully ferritic” or “fully pearlitic” structures. Good machinability. Usually the least expensive Ductile iron.

PEARLITIC DUCTILE IRON - Graphite spheroids in a matrix of pearlite. Pearlite is a fine aggregate of ferrite and cementite (Fe_3C). Relatively hard. Moderate ductility. High strength. Good wear resistance. Moderate impact resistance. Somewhat reduced thermal conductivity. Low magnetic permeability. High hysteresis loss. Good machinability.

MARTENSITIC DUCTILE IRON (Q&T) - In the “as-cast” condition the alloy is hard and brittle, and seldom used. However, tempered martensite has very high strength and wear resistance.

AUSTENITIC DUCTILE IRON They are never chosen for strength alone. The outstanding features are good corrosion and oxidation resistance, magnetic properties, strength and dimensional stability at elevated temperatures. (Also known as Ductile Ni-Resist).

AUSTEMPERED DUCTILE IRON (ADI) This is the most recent addition to the Ductile iron family and represents a new group of Ductile irons, offering the design engineer a remarkable combination of strength, toughness and wear resistance. ADI is almost double strong as the regular ASTM grades of Ductile iron, whilst still retaining high elongation and toughness characteristics. In addition, ADI offers exceptional wear resistance and fatigue strength, thus enabling designers to reduce component weight and costs for equivalent, or improved performance. The remarkable properties of ADI are developed by a closely controlled heat treatment operation (austempering) which develops a unique matrix structure of needle shaped ferrite (60%) and retained (high carbon) austenite.

The properties of Ductile iron highly depend on the type of matrix phase, alloying elements and amount and shape of a graphite. Increasing the amount of ferrite in the matrix leads to higher ductility but lower strength. In contrast, higher pearlite content causes more strength and lower ductility. In order to minimize the amount of pearlite in Ductile iron, pearlite promoting elements (e.g. Cu, Mn, Sn, Cr) should be minimized and ferrite promoting elements (e.g. Si) should be increased. General shape of the graphite particles (nodularity), the number of nodules per unit area (nodule count) and the overall graphite volume can affect the mechanical properties. In general, higher nodularity results in higher ductility and strength. The amount and type of alloying elements can affect the mechanical properties by changing the matrix phase, nodularity and nodules counts. In addition, the alloying elements

can change the properties e.g. by solid solution hardening, changing the interlamellar space of pearlite and stabilizing austenite at low temperatures [2, 3, 4, 5].
One reason for the phenomenal growth in the use of Ductile iron castings is the high ratio of performance to cost that they offer to the designer and end user. This high value results from many factors, one of which is the control of microstructure and properties that can be achieved in the as-cast condition, enabling a high percentage of ferritic and pearlitic Ductile iron castings to be produced without the extra cost of heat treatment. To obtain the advantage of producing high quality castings as-cast, requires the use of consistent charge materials and the implementation of consistent and effective practices regarding the melting, holding, treating, inoculation and cooling in the mold. By following these practices, especially the use of high purity charges and good inoculation, castings can be produced as-cast essentially free of carbides.
However heat treatment is a valuable and versatile tool for extending both the consistency and range of properties of Ductile iron castings, beyond the limits of those produced in the as-cast condition. Thus, to fully utilize the potential of Ductile iron castings, the designer should be aware of the wide range of heat treatments available for Ductile irons, and its response to these heat treatments [5].

2. EXPERIMENTAL PART

2.1. Material for investigation

Idea for the experimental part of this paper is to explaine the influence of different heat treatments on microstructure and mechanical properties of a Ductile iron. Three different heat treatment processes were applayed (Annealing-Ferritizing, Normalization, and Austempering). Initial material was non-alloyed Ductile iron with perlitic-ferritic microstructure. Chemical composition of the Ductile iron used in this experiment was C: 3.29 wt.%, Mn: 0.31%, Si: 2.53%, P: 0.015%, S: 0.013%, Cr: 0.053%, Ni: 0.81%, Cu: 0.51%, Mg: 0.031%, Mo: 0.002%, Ti: 0.004%, Sn: 0.006%, V: 0.003%, W: 0.004%. Microstructure of the base material is presented at the Figures 1 and 2. Average value of tensile strength of the initial material was 696 MPa and hardness of 251HB.

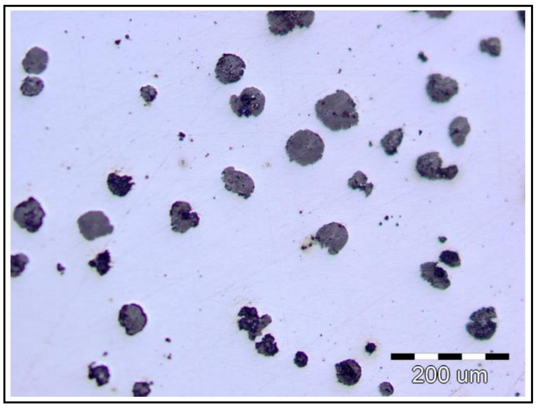

Figure 1. Microstructure of the initial Ductile iron (as polished), 200x

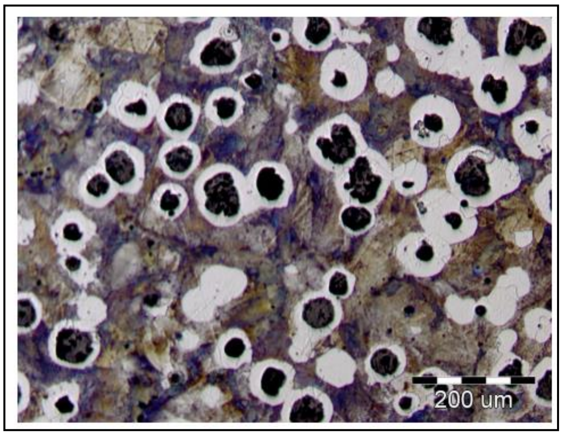

Figure 2. Microstructure of the initial Ductile iron (as etched), 200x

2.2. Sample preparation

Samples for tensile test were cut in as cast condition. Set of three samples were prepared for the a.m. types of heat treatment and set of three samples for as cast material testing. In total twelve samples were prepared for complete investigation. Samples were prepared according to the standard BAS EN 10059-1/98 (Figure 3) [6].

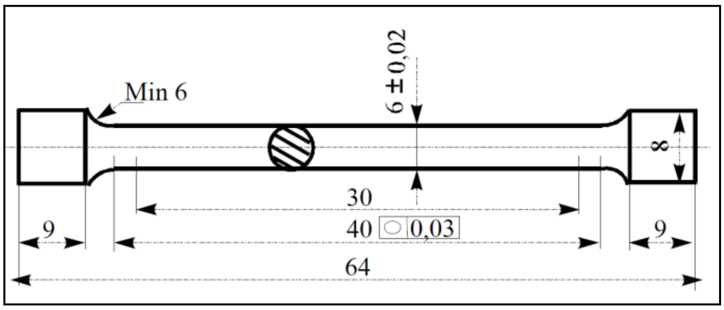

Figure 3. Tensile test sample

2.3. Heat treatment of the samples

Nine samples were subjected to different heat treatment processes. All nine samples were put into the induction furnace at a room temperature and heated up together with the furnace. After reaching 870 °C, the tepereature was held for 80 minutes. After 80 minutes of austenitization of the samples, three of them were removed from the furnace and left to cool to room temperature at the air, another three samples were transfered to another furnace with the liquid KNO_3 salt and held for another 90 minutes for tempering at temperature of 300 °C and after that cooling at the air to room temperature. The remaining three samples were left at the induction furnace to cool down to temperature of 720 °C and held at that temperature for another 120 minutes, and at the end cooled in the furnace to a room temperature. Heat treatment parameters for all nine samples are presented in the diagram on Figure 4.

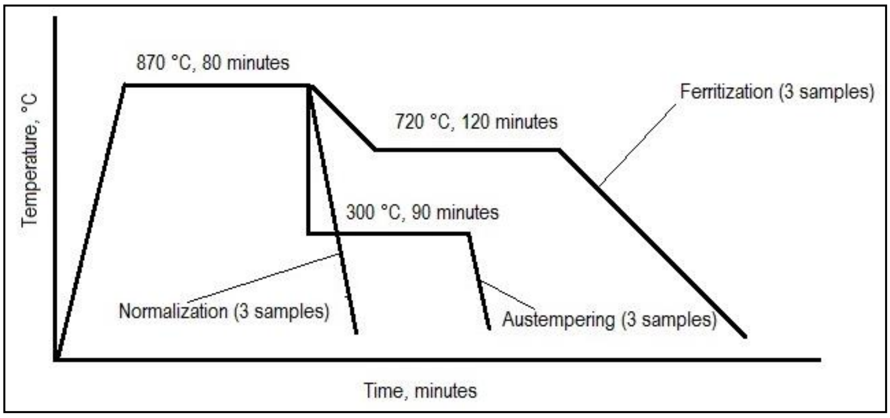

Figure 4. Heat treatment parameters

3. RESULTS AND DISCCUSSION

3.1. Mechanical properties and metalography investigation

After heat treatment all samples were cleaned up and subjected to the mechanical properties investigation, according to the standard BAS EN 100002:2002. Metallography samples were cut from the samples after investigation of mechanical properties [7].

Feritization (Annealing) heat treatment

Mechanical properties after annealing heat treatment are presented in Table 1.

Table 1. Mechanical properties after annealing heat treatment

Sample number	Condition	Tensile strength, Rm, [MPa]	Average Tensile strength, R_m, [MPa]	Hardness HB
1	Annealed (Ferritization)	453	452	182
2		453		
3		451		

Microstructure of the Ductile iron samples after feritization (annealing) is presented at the Figure 5.

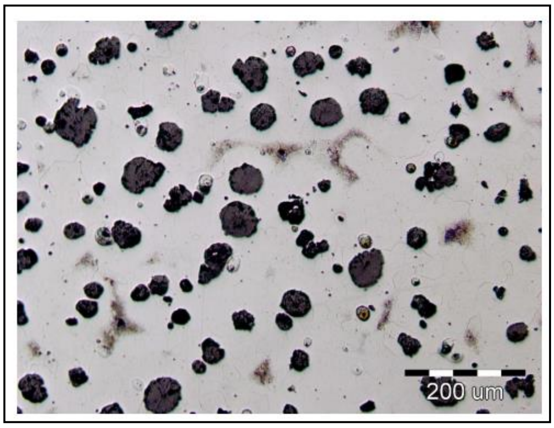

Figure 5. Microstructure of the Ductile iron samples after annealing, 200x

Analyzyng the microstructure of the samples at the Figure 5, can be concluded that metalic matrix is predominantly ferritic with very smal portion of pearlite. Heat treatment proces was successful and according to the mechanical properties (Table 1), material can be classified as ferritic grade of Ductile iron.

Normalizing heat treatment

Mechanical properties after normalizing heat treatment are presented at the Table 2.

Table 2. Mechanical properties after normalizing heat treatment

Sample number	Condition	Tensile strength, Rm, [MPa]	Average Tensile strength, R_m, [MPa]	Hardness HV10
1	Normalized	804	845	555
2		838		
3		892		

Microstructure of Ductile iron samples after normalizing heat treatment is presented at the Figure 6.

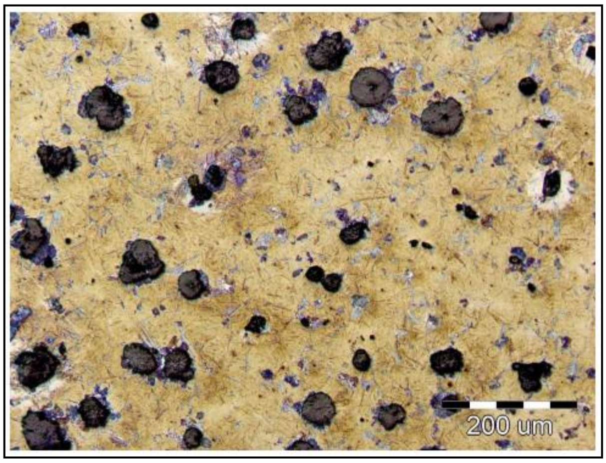

Figure 6. Microstructure of the Ductile iron samples after normalizing, 100x

Analyzyng the microstructure of the samples at the Figure 6, can be concluded that metalic matrix is predominantly pearlitic with very smal portion of martensite. Heat treatment proces was successful and according to the mechanical properties (Table 2), material can be classified as pearlitic grade of Ductile iron. Presence of small portion of martensite for some purposes is unwanted and heat treatment parameters have to be set, to avoid martensite in the microstructure.

Austempering heat treatment

Mechanical properties after austempering heat treatment are presented at the Table 3.

Table 3. Mechanical properties after austempering heat treatment

Sample number	Condition	Tensile strength, Rm, [MPa]	Average Tensile strength, R_m, [MPa]	Hardness HV10
1	Austempered	1484	1456	464
2		1443		
3		1442		

Microstructure of the Ductile iron samples after austempering heat treatment is presented at the Figure 7.

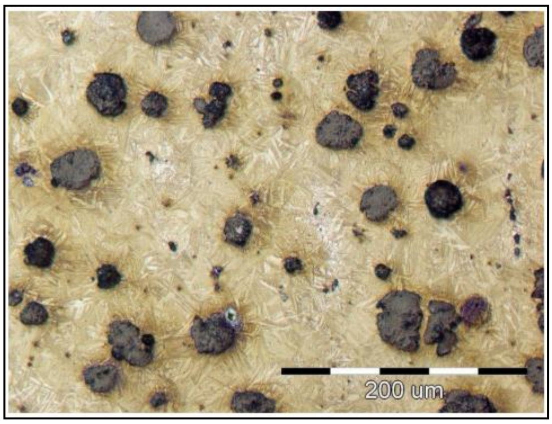

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Figure 7. Microstructure of the Ductile iron samples after austempering, 100x

Analizyng the microstructure of the samples at the Figure 7, can be concluded that metalic matrix is fully ausferritic (acciculare ferrite and stable austenite). Heat treatment proces was succsesful and according to the mechanical properties (Table 3), material can be classified as ADI grade of Ductile iron.

4. CONCLUSIONS

- Setting different heat treatment parameters it is possible to design desired microstructure and final properties of the Ductile iron.
- Changing microstructure of the Ductile iron changes mechanical and ductile properties considerably.
- Comparing the results from the Tables 1 and 3 (annealed and austempered samples) is noticeable that tensile strength is increased for more than 300%, bearing in mind that it is the same starting material.

6. LITERATURE

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