THE OUTLOOK UPON AUSTENITISING THE MATRIX OF DUCTILE IRON

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ABSTRACT

The study discusses the problem of austenitising the matrix of ductile iron during heat treatment. The following issues have been considered: carburising of metallic matrix, carbon solution rate in matrix, effect of time and temperature of austenitising and the role played by graphite.

Key words: austenitising, ductile iron, matrix

1. INTRODUCTION

The technology of ductile iron fabrication includes the process of heat treatment. It plays a very important part in the formation of structure and properties, both mechanical and technological, of iron castings. The aim of the heat treatment is, among others, increasing the level of mechanical and plastic properties, and improving the abrasion wear resistance and toughness.

Some heat treatment operations include preheating to and holding at supercritical temperature (above Ac₁). This treatment is related with the process of austenitising the cast iron metallic matrix. Austenitising of the matrix is considered the step very important in the treatment of ductile iron, as it confers to cast iron the desired structure of matrix. The composition of matrix structure determines the properties and performance characteristics of iron castings, and consequently, it ensures the failure-free operation of machines and equipment.

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The effect of austenitising depends on various factors, such as: the chemical composition of cast iron, matrix, the initial structure of cast iron before heat treatment, the characteristics of graphite precipitates, the temperature and time of preheating, and finally, the random distribution of elements in eutectic grains and the grain growth rate.

Upon heating, the transformation of austenite in cast iron matrix assumes a course different than the eutectoidal transformation in steel. In steel, austenite is formed from pearlite as the first constituent (the eutectoidal transformation $Ac_1$), ferrite is the next one to form (allotropic transformation $Ac_3$). The conditions of cast iron austenitising should be chosen in a careful way to ensure the presence of homogeneous austenite inside the eutectic grains. This promotes formation of the required structure of the matrix due to the conducted operation of heat treatment.

In the technology of casting production, in view of recent tendencies to produce high-duty cast iron, its heat treatment acquires particular significance, since the best means of matching effectively the mechanical and plastic properties with toughness are still searched for. The discussion of heat treatment, besides general guidelines for its practical execution, should also comprise a detailed analysis of the individual steps. Therefore the authors of this study have come to a conclusion that problems discussed here should be regarded as a source of supplementary information, further to the reference sources available so far on modern founding of high-duty cast iron. The subjects related in this study can be effectively combined with research focussed on an improvement of cast materials through various aspects of material optimising, including knowledge-based fabrication technologies (European Grants).

2. AUSTENITISING OF MATRIX

During heat treatment of cast iron, preheating in a temperature range of 30-100°C above the point $Ac_{1,2}$, is called austenitising of cast iron matrix. The aim of this process is to form the structure of homogeneous austenite in the matrix. The temperature is comprised within a range of 800-950°C. In practice, however, austenitising is usually conducted within the range of 850-930°C.

When discussing the process of alloy austenitising, it should be noted that, compared with steel, the presence of graphite in cast iron causes some important differences in the structure. When preheating the steel at a temperature higher than the temperature of the eutectoidal transformation, the carbon from cementite is dissolving in austenite up to a content corresponding to the required grade of steel. In cast iron, on the other hand, carbon is present in either bound form as Fe$_3$C or as free graphite. Immediately upon exceeding the temperature $Ac_{1,2}$ at the beginning of cast iron holding, the content of carbon in austenite is still very low; only after a longer lapse of time austenite becomes saturated with carbon originating from graphite. The concentration of carbon in austenite is approaching an equilibrium content, corresponding largely to line E'S' in phase diagram of Fe-C alloys [1-4].
H. Oleszycki [5] states that the formation of austenite in cast iron matrix starts as early as during preheating and that the transformation is still going on during holding. Upon exceeding the temperature of eutectoidal transformation $A_c1,1$ the following processes are successively occurring: transformation $\alpha + Fe_3C \rightarrow \gamma$, dissolution of the remaining lamellae of eutectoidal cementite in colonies of pearlite, reducing the non-uniform distribution of carbon, first, and of the alloying elements in austenite (homogenising), next. This sequence of the phenomena which occur during austenitising treatment refers to the cast iron with pearlitic matrix. A similar statement has been made by D.A. Harris and R.J. Maitland [6] as regards the ferritic-pearlitic matrix.

In the matrix of cast iron, the eutectoidal transformation starts in the colonies of pearlite, on the boundaries of eutectic grains, which is mainly due to the presence of manganese in these regions, reducing the temperature of eutectoidal transformation $A_c1$. On the other hand, the first nuclei of austenite appear in pearlite at the eutectoidal cementite-ferrite phase boundary. The ferrite present in pearlite contains less of silicon than the free ferrite. Shifting of the ferrite-austenite transformation front towards ferrite depends on the content of silicon and on the rate of its diffusion from ferrite to austenite. The rate at which the front of transformation is shifting towards ferrite is as high as the rate of displacement of the cementite-austenite phase boundary towards cementite [1,5,7,8].

The austenite formed in the colonies of pearlite is non-homogeneous; there are nodules, and even lamellae of non-dissolved cementite. On the boundaries of pearlite colonies, austenite is non-homogeneous in respect of carbon content. It is much more saturated with carbon and characterised by certain stability. Increasing the temperature further increases the rate of eutectoidal transformation in eutectic grains. Therefore, thus formed austenite is less saturated with carbon when approaching the temperature $A_c1,2$, although new volumes of carbon originating from decomposition of $Fe_3C$ are supplied. This austenite contains 0.08% C. The examinations of structure during eutectoidal transformation within the range of temperatures $A_c1,1 \rightarrow A_c1,2$ indicate that the only source for carbon to saturate austenite is the cementite present in pearlite [5,7]. This has also been confirmed by [6,9]. Only in [10] the authors are of opinion that in this respect austenite is enriched also with carbon originating from the precipitates of graphite.

3. CARBON CONTENT IN MATRIX

N. Darwish and R. Elliot [1] state a relationship that exists between the temperature of austenitising and silicon content in cast iron vs carbon concentration in austenite. Theoretically, this value for Fe-C-Si alloys can be determined from the following formula:
\[ C^A_\gamma = \frac{t_\gamma}{420} - 0.17(Si) - 0.95 \% \]  \hspace{1cm} (1)

where:
- \( C^A_\gamma \) - carbon concentration in phase \( \gamma \) during austenitising \%,
- \( t_\gamma \) - temperature of austenitising \(^\circ\)C,
- Si - silicon content in cast iron \%.

Using formula (1), the diagram in Figure 1 was plotted. It confronts the values calculated and determined experimentally by the authors in [1] and [9]. In [9] the research was conducted on ferritic ductile iron containing: 3.26\% C; 2.64\% Si; 0.92\% Mn; 0.14\% P; 0.06\% S and 0.093\% Cr \((A_{c1.1}=798^\circ\text{C} \text{ and } A_{c1.2}=833^\circ\text{C})\) (line 2), while in [1] they investigated ductile iron (90 \% pearlite) containing: 3.60\% C; 2.80\% Si; 0.016\% Mn; 0.01\% P; 0.01 \% S; 0.040\% Mg; 0.06\% Cr; 1.02\% Ni and 0.90\% Cu (line 4), and ductile iron (60 \% ferrite) containing: 3.80\% C; 2.77\% Si; 0.037\% Mn; 0.03\% P; 0.02\% S; 0.034\% Mg; 0.02\% Cr; 0.07\% Ni and 0.33\% Cu (line 5).

In Figure 1 one can observe a good consistency with experiments achieved by the authors of [1]. Some significant discrepancies have been observed to exist between lines 1 and 2, i.e. between carbon concentrations in austenite determined in [9]. The differences may be due to a method used for the measurement of carbon content in austenite.

H. Oleszycki [5] states that the austenite in pearlitic-ferritic ductile iron (3.45\% C; 2.52\% Si; 1.14\% Mn; 0.10\% P; 0.008\% S), formed at a temperature close to \( A_{c1.1} \) contains large amounts of carbon (0.78\%). This carbon content in austenite considerably exceeds the equilibrium level typical of a eutectoidal point which, according to C. Podrzucki [4], in unalloyed cast iron is \( C_{zw} = 0.69\% \), while in alloyed grade - \( C_{zw} \) is comprised in a range of 0.53-0.65\% with silicon content of 1.70-2.24\%.

Using X-rays it was determined that carbon concentration in martensitic ductile iron changes over a wide range of values. After preheating at a rate of 50K/s the pearlitic cast iron with 1.5\% Si and quenching from 900\^\circ\text{C}, the matrix contains 0.25-0.83\% C; with 4\% Si the carbon content in the matrix is 0.15-0.82\%. After quenching from the temperature \( t_\gamma = 1100^\circ\text{C} \), applying the same preheating rate, the matrix of ferritic ductile iron with 1.5\% Si has carbon concentration in a range of 0.15-0.97 \%, while in the cast iron with 4 \% Si this value is 0.14-0.83\% [11].

The technical literature tends to describe the mechanism of carbon enrichment (carburising) during austenitising of ductile iron with pearlitic and pearlitic-ferritic matrix. Opinions vary as regards the case of ferritic matrix.
4. EFFECT OF SILICON

Opinions prevail, and in most cases tend to be consistent, that besides the temperature $t_y$, carbon content in austenite depends on the chemical composition, and specially on the silicon content in metallic matrix. This has been well proved by formula (1). The remaining chemical elements present in unalloyed and low-alloyed cast irons have but little effect on carbon concentration $C^A_T$.

The eutectoidal transformation in ferritic matrix is accompanied by silicon diffusion from ferrite to austenite. As a result of this phenomenon, thus formed austenite contains silicon, but its content is lower than in the base ferrite. The ferrite most saturated with silicon is adhering to the ferrite-graphite phase boundary.
Therefore saturation of ferrite with carbon takes place at a temperature the higher, the higher is the preheating rate [8,10,11].

Saturation of austenite with carbon originating from graphite precipitates is non-uniform, which is obviously resulting from silicon affecting carbon diffusion. In the austenite forming within the regions characterised by increased content of silicon, the rate of carbon diffusion is lower than in the regions of lower silicon content. Due to this, near the spheroids of graphite, the eutectoidal transformation takes place as the last one [5,9,11].

The effect of silicon on the minimal temperature of austenitising at which the ductile iron matrix will gain 90-95% austenite content during the transformation $\alpha \rightarrow \gamma$ is plotted in Figure 2. The data referred to in this figure are for silicon content of up to 3.2%. The part of the curve above this value (black dotted line) was extrapolated.

Increasing silicon content in cast iron allows raising the temperature of eutectoidal transformation [14]. The authors of [15] share this point of view, additionally stating that it extends the range of temperatures $A_{C1,1}$-$A_{C1,2}$. Chromium also raises this temperature, while manganese and nickel make it decrease [4,14,16].

5. TEMPERATURE AND TIME OF AUSTENITISING

Raising the temperature above $A_{C1,2}$ accelerates the process of matrix austenitising, increases carbon solution rate in austenite originating from graphite precipitates and contributes to its homogenising and growth of grains [1,3-7,11,12,13,17-21].
In heat treatment of ductile iron, including the austenitising process, the temperature $T$ is usually adjusted to a higher supercritical level, taking into account the as-cast structure of iron. In studies discussed here the temperature $A_{c1,2}$ is not always quoted, although it can prove quite helpful in establishing the preheating regime.

In the base cast iron with pearlitic matrix, the saturation of austenite with carbon is reached in a time much shorter than in the case of ferritic matrix [1,4,5,9,10,17]. In foundry practice [1-3,23-25] the time of cast iron holding is usually in the range of 20-210 minutes. According to [26], the minimal time of austenitising should be $\tau_\gamma = 60$ minutes. On the other hand, the authors of [27] state that the time longer than 15 minutes ($t_\gamma = 820-860^\circ C$) has practically no major effect of the mechanical properties of ADI.

The studies conducted by H. Koch and K. Herfurth enabled determination of carbon content in the matrix of ductile iron of the following chemical composition: 3.26% C; 2.64% Si; 0.92% Mn; 0.14% P; 0.06% S and 0.093% Cr. The pearlitic cast iron after 10 s austenitising at a temperature $t_\gamma = 850^\circ C$ contains 0.60% C and this content remains stable for 20 minutes, while austenite at a temperature of 1000°C already contains over 1.20% C. At this temperature, austenite is enriched with carbon from the dissolving graphite.

Compared with pearlitic matrix, the ferritic matrix definitely changes the kinetics of ductile iron transformation $\alpha \rightarrow \gamma$. The plotted curves of the kinetics of this transformation are shown in [9].

With raising temperature $T$, austenite in cast iron gets enriched with carbon. The saturation with carbon during holding of cast iron is expressed by an increase on the time-related function, most intense at the initial stage (Figure 3). According to the kinetics of austenitising, reaching an equilibrium level of carbon concentration in the austenitic cast iron with Ni and Cu takes the time longer than in the austenitic cast iron containing Cu.

M.M. Shea and E.F. Rnytz [27], investigating unalloyed ductile iron containing: 3.51% C; 2.88% Si; 0.54% Mn; 0.003% P; 0.012% S and 0.053% Mg, have stated that full saturation of austenite with carbon takes place after the time $\tau_\gamma = 45$ min of holding at a temperature $t_\gamma = 950^\circ C$ (Figure 4), while during austenitising at a temperature $t_\gamma = 850^\circ C$ after the time $\tau_\gamma = 30$ and 75 minutes, single envelopes of ferrite are visible around the precipitates of graphite. The examinations made by microprobe revealed a uniform distribution of carbon content in austenite irrespective of the conditions of austenitising. The values of carbon content in austenite are very close to equilibrium. The saturation of austenite with carbon after 15 minute holding at a temperature $t_\gamma = 950^\circ C$ is only slightly lower than the equilibrium value.

The temperature and time of austenitising affect the dimensions of austenite grains [5,6,28]. Holding within the temperature range of 840-925°C does not result in any more significant grain growth [5,6].
Fig. 3.  Effect of temperature $t_\gamma$ and austenitising time $\tau_\gamma$ on carbon content $C^A_\gamma$ in ductile iron matrix containing: a) Cu, b) Ni and Cu [1].

Rys. 3. Wpływ temperatury $t_\gamma$ i czasu austenityzowania $\tau_\gamma$ na zawartość węgla $C^A_\gamma$ w osnowie żeliwa sferoidalnego zawierającego: a) Cu, b) Ni i Cu [1]

Fig. 4.  Effect of austenitising temperature $t_\gamma$ and time $\tau_\gamma$ on carbon content $C^A_\gamma$ in austenitic ductile iron [27].

Rys. 4. Wpływ temperatury $t_\gamma$ i czasu $\tau_\gamma$ austenityzowania na zawartość węgla $C^A_\gamma$ w austenicie żeliwa sferoidalnego [27]

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From a review of technical literature it follows that when selecting the temperature of austenitising one should allow for its effect on the size of grains and on different phenomena which may occur on the grain boundaries.

6. THE ROLE OF GRAPHITE

In the process of cast iron austenitising treatment, the precipitates of graphite play a very important part, as they supply carbon inside the alloy and contribute to carburising of the matrix. The content of spheroidal graphite, and the distribution and diameter of its precipitates affect the solution saturation ratio and the degree of homogenising \( \gamma \) during austenitising. The evolution degree of the graphite precipitates surface affects the kinetics of transformation, viz. the higher is this degree, the earlier is the time when the transformation begins, and the higher is the critical cooling rate necessary for the formation of ausferrite or martensite [4,5,22,29]. While holding the cast iron at supercritical temperature, the graphite gets enveloped with austenite. With this time elapsing, the austenite envelope is enriched with carbon originating from graphite. The front of enrichment is shifting towards the eutectic grain boundaries. Hence the diffusion-induced movement of carbon volume to the cast iron matrix depends on the geometrical features of the elements of eutectic grains, i.e. on the spheroidal graphite shape and eutectic grains diameter. Making now an assumption, simplified for the sake of theoretical considerations, that the eutectic grains are of a spheroidal shape, it will be possible to examine the time necessary for austenite to get enriched with carbon at a predetermined temperature of austenitising. This problem is very important for the process of austenitising, but not investigated in detail as yet. Therefore further theoretical and practical studies are necessary.

7. SUMMARY

In past times the economic considerations did not make the heat treatment of ductile iron castings feasible. At present, the heat treatment is an important step in development of iron castings production. The spheroidal shape of graphite in ductile iron enables utilising to maximum degree the properties of metal matrix which means that changes in this matrix proceeding due to heat treatment will contribute to a great extent to better combination of the mechanical and utilisation properties.

Normalising, quenching and tempering (toughening) as well as austempering - all of these operations, including the operation of austenitising, can increase the strength, ductility and toughness as well as abrasion wear resistance.

Normalising of unalloyed ductile iron improves its tensile strength compared with the starting values obtained in as-cast state. The improvement is due to recrystallising of eutectoidal mixture, in which pearlite dispersion rate is definitely much higher. The problems related with normalising are the subject of dissertations...
described in technical and scientific literature; they were also comprehensively in monograph [5].

Martensitic structure in castings gives them high abrasion wear resistance, but to obtain high tensile strength of cast iron, i.e. comprised in a range of 800-900 MPa, the cast iron should be subjected to toughening. After this heat treatment we obtain the grade according to EN-GJS-800-2 or EN-GJS-900-2 (PN-EN 1563:2000).

In the technology of making castings from ADI, austempering is an inherent part of the whole production cycle. The cast iron having ausferrite in its structure has an exceptionally beneficial combination of strength and ductility. The formation of structure and mechanical properties of ADI was discussed in [30-33].

In [30-32] it has been proved that the temperature of austenitising affects the level of unnotched impact resistance of ADI. Raising this temperature reduces the impact resistance of ADI, which after austempering is higher than the impact resistance of ferritic ductile iron.

Austenitising is sometimes used in various other heat treatment operations preparing the cast iron matrix for other successive heat treatment steps, even for the treatment carried out at subcritical temperatures.

Examples of rationally heat treated high-duty ductile iron for responsible castings used as parts of machines are given in [4,28,33].

REFERENCES

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PODCZAS HARTOWANIA ŻELIWA ADI

STRESZCZENIE

Austenityzowanie osnowy żeliwa sferoidalnego podczas hartowania izotermicznego i innej obróbki cieplnej jest bardzo ważnym zagadnieniem, które decyduje o powodzeniu operacji cieplnej. W syntezie uwzględniono proces nawęglania osnowy metalowej, rozpuszczalność w niej węgla, wpływ temperatury i czasu wygrzewania oraz rolę wydzieleń grafitu kulkowego. Syntezę oparto o literaturę naukową z różnego okresu czasu i badania własne.

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