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MANUFACTURE OF TOOTHED ELEMENTS IN NANOAUSFERRITIC DUCTILE IRON

KOŁA ZĘBATE Z ŻELIWA SFEROIDALNEGO O OSNOWIE NANOAUSFERRYTU

The technology currently used for the fabrication of toothed wheels, gear couplings and chain drums involves the induction hardening process or hardening and tempering after carburising. All these processes take a long time and cause adverse changes in the dimensions and surface quality of products, requiring post-treatment machining to remove the resulting cavities. The paper proposes the implementation of gear elements made of ductile iron with nanoausferritic matrix obtained by a new appropriate heat treatment process. The new material offers good performance characteristics and nearly no need for the application of other technological processes commonly used in the manufacture of gears.

Keywords: austempered ductile iron, nanoausferritic matrix, austempering, toothed elements

Obecnie stosowany proces projektowania kół zębatych zakłada hartowanie indukcyjne uzębienia po procesach ulepszania cieplnego lub hartowanie i odpuszczanie po nawęglaniu. Procesy te są długotrwałe i powodują niekorzystne zmiany wymiarów wyrobu oraz zmiany powierzchniowe, które muszą być usunięte poprzez obróbkę skrawaniem. W artykule zaproponowano wykonanie kół zębatych z żeliwa o osnowie nanoausferrytu uzyskaną w wyniku odpowiednich procesów cieplnych. Nowy materiał oferuje dobre właściwości użytkowe oraz możliwości w ograniczeniu procesów technologicznych wykonywanych przy wytwarzaniu kół zębatych.

1. Introduction

The use of austempered ductile iron (ADI) for gears is a well-known and long applied technological solution [1-3]. Compared to steel, ADI is characterised by lower manufacturing cost, a 10% lower density, comparable toughness and yield strength, and comparable or superior resistance to abrasive wear. It is quite obvious, therefore, that ADI is gaining so much popularity in the automotive, railway, agricultural and mining applications. Operating in these sectors of industry, the gear components should offer very high resistance to dynamic loads. The ADI ratings are certainly not the best in respect to toughness properties. Studies have proved that its bending strength is by half lower than the bending strength of e.g. carburised SCr420H alloy steel [3]. One of the ways to improve these ADI properties is by increasing the fatigue strength through the strain hardening of product surface, e.g. by shot peening [3, 4], or refining the grain size within the entire product volume [5].

The strain hardening effect of ADI (TRIP effect – Transformation Induced Plasticity) has been described since 1989 [6-10]. Detailed analysis of the transformation of austenite to martensite under the stress and strain effect, e.g. during shot peening, can reveal its significant impact on most of the ADI unique properties, to mention only strengthening of the surface exposed to abrasion, increase of fatigue strength, and beneficial effect on the strength/toughness combination comparable to different grades of steel [2].

Strengthening through high-degree refinement of the ausferritic structure can be described with a yield stress – strain relationship (Hollomon model (equation 1) [11]). This dependence can be plotted in the $\ln\sigma - \ln\varepsilon$ system as a set of straight lines whose slope will be represented by the exponent n

$$\sigma = K \cdot \varepsilon^n \tag{1}$$

where: the parameters K and n are determined by approximation of the tensile test results in the form of a true stress – true strain function.

As a result of the studies of ausferritic ductile iron it was found that the exponent n changes its value linearly with the increasing temperature of austempering (Fig. 1). Based on this conclusion, it was determined that n reaches its maximum under the conditions of high austenite content, coarse ferrite and high temperature of isothermal transformation, while the minimum occurs when the austenite content is low and ferrite assumes a very fine form. This confirms the relationship derived by Häyrynen and co-authors, which allows determining the yield strength from the size of ferrite plates and austenite

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content (equation 2) [5]. The relationship shows that the size of the ferrite plates is the main factor governing the value of elastic stresses in ausferritic ductile iron. The finer are ferrite plates, the higher is the yield strength of the examined material:

$$\sigma = AL^{-1/2} + BX_\gamma + C \tag{2}$$

where: σ – the proof stress, L – the size of ferrite plates, X_γ – the austenite content, A, B, C – constants.

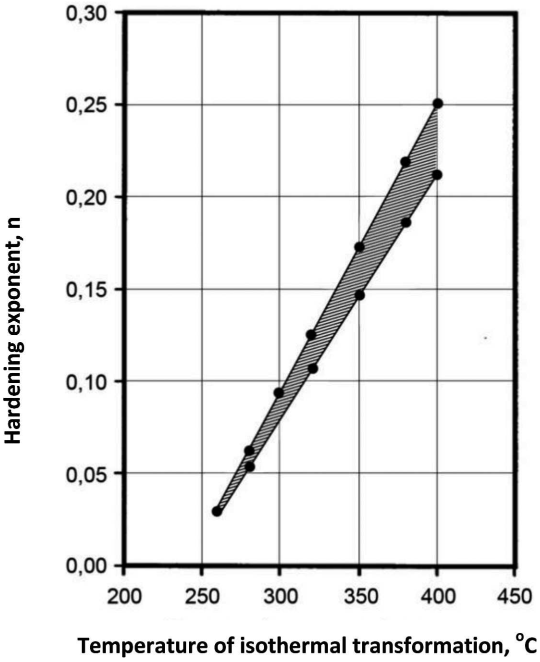


Fig. 1. The dependence of exponent n on the austempering temperature of ausferritic ductile iron [5]

ADI is a casting material which means that its metallurgical quality has a significant impact on the mechanical properties. Characteristics such as the non-homogeneous chemical composition in microregions, graphite morphology and wall thickness exert a significant effect also on the heat treatment process.Therefore, it is difficult to obtain submicron structures with characteristics similar to nanobainitic steels [12, 13, 14]. However, properly adjusted chemical composition of the alloy, strict control of the casting process or application of the preliminary heat treatment can produce the ductile iron with very fine grains in the matrix.

The article presents the results of studies carried out on four types of ADI (containing 0.24% Mo) from which the gear components have been cast for the mining industry. A heat treatment cycle was also proposed to produce submicron-sized or nanometric grains in a mixture of ferrite and austenite present in such structures.

2. Research methodology

Studies were carried out on ductile iron with the chemical composition shown in Table 1. Castings of gear components for the mining industry were made by Odlewnie Polskie SA in a configuration shown in Figure 2. Castings were heat treated in a salt bath at the temperature of 240°C, 270°C, 310°C and 360°C in time below 2h. From these castings, specimens were next cut out for the measurement of hardness HRC (measurement taken on the tooth cross- section – Figure 3), for the static tensile test (specimens with Ø8 mm diameter in the gauge section), and for the unnotched impact test (10×10 mm square section specimens). The investigation of static tensile test and impact test were carried on in accordance with PN-91/H-04310 and PN-69/H-04370 respectively. From every sample, cross-section polished surface were prepared for metallographic examinations by SEM. Additionally, from samples treated in the lower range of ausferritic transformation, thin films were cut out for TEM examinations in the bright and dark field. Microstructure was examined with HITACHI S3500N scanning electron microscope and JEOL transmission electron microscope.

TABLE 1
Chemical composition of the tested ductile iron [wt%]

Material	**C**	**Si**	**Mn**	**S**	**P**	**Mg**	**Cr**	**Mo**
ADI Mo	3.50	2.54	0.16	0.013	0.041	0.047	0.026	0.24

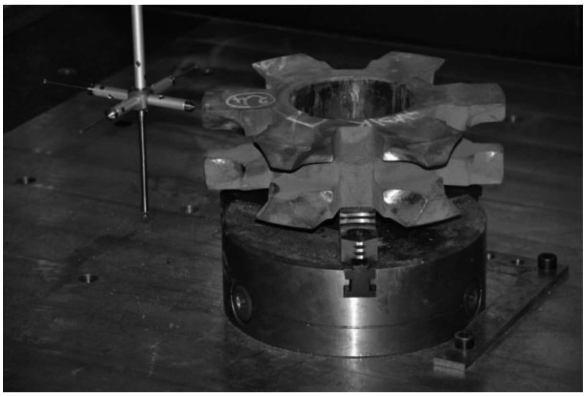


Fig. 2. Gear assembly used in mining applications cast for the research purposes

Fig. 3. Cross-section of a single tooth in the gear assembly

3. Results and discussion

Analysis of the microstructure and mechanical properties (Figs. 4 and 5) also confirmed the relationship derived by Häyrynen [5], making the temperature of austempering treatment responsible for the size of ferrite grains, although

Häyrynen's relationship does not allow for the very low temperatures of austempering ($M_S \div 250°C$). The authors of this study investigated for this ductile iron the short- and long-range process of austempering at 310°C and 240°C (Table 2). It was found that long time of isothermal transformation results in a significant refinement of the ferrite plates, leading even to a nanostructure (Figs. 6 and 7).

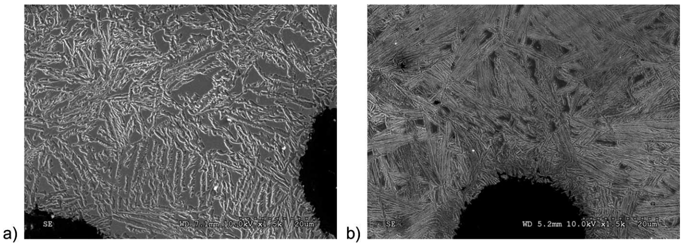


Fig. 4. SEM microstructure of specimens taken from castings heat treated at: a) 360°C – ferrite plates ⩾1 μm, b) 310°C – ferrite plates ⩽1 μm

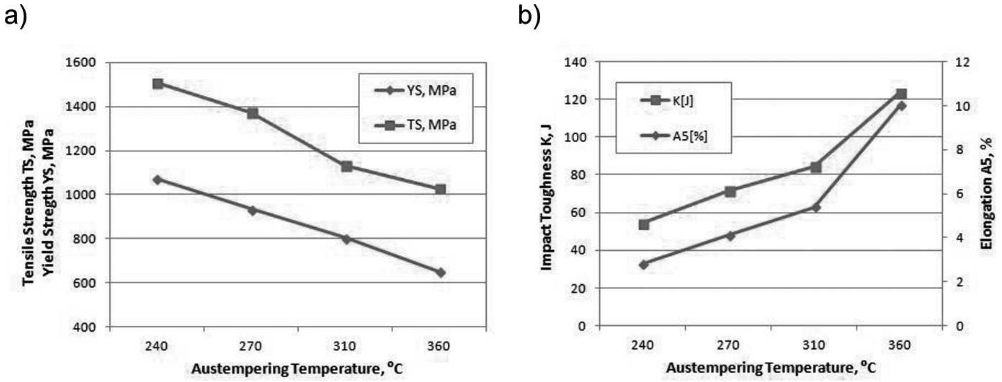
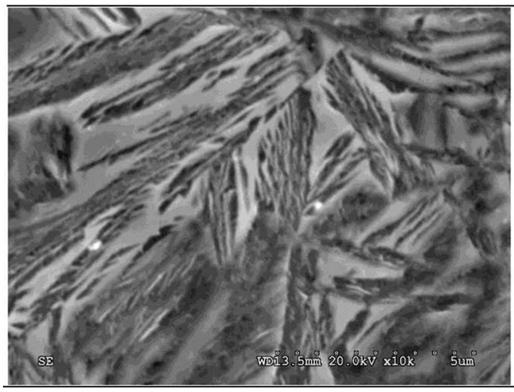
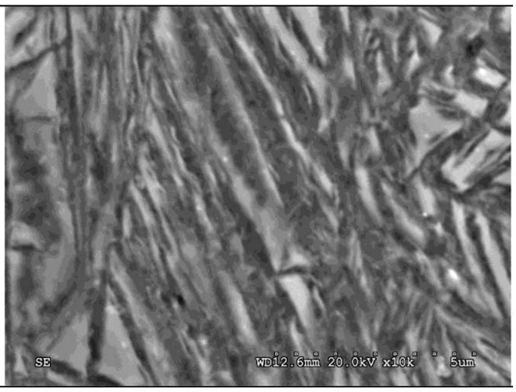
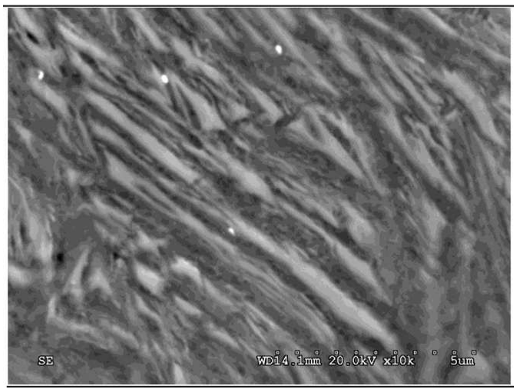
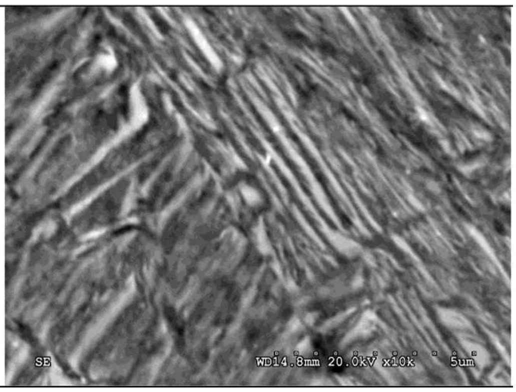


Fig. 5. Mechanical properties of ductile iron austempered at 240°C÷360°C: a) the tensile strength and yield strength of ADI, b) the elongation and impact toughess of ADI

TABLE 2

SEM microstructure of ADI matrix after different times of isothermal transformation

Temperature / Time of isothermal transformation	
a) 310ºC / 2h	b) 310ºC / 6h
	
c) 310ºC / 36h	d) 240ºC / 36h
	

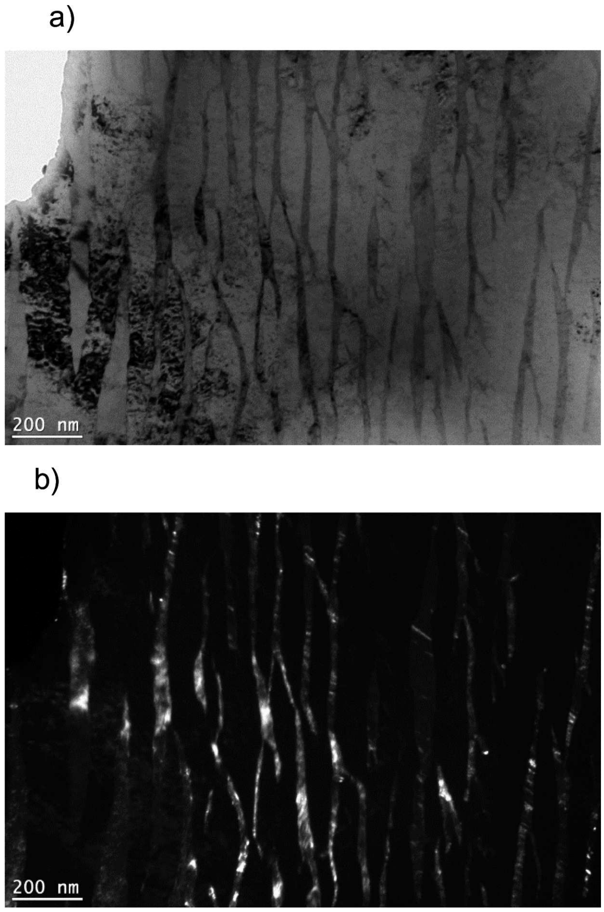


Fig. 6. ADI matrix structure obtained as a result of isothermal transformation carried out for 36 hours at 310°C; a) TEM-BF micrograph, b) TEM-DF micrograph (austenite reflexes)

Structure examinations show that even short-lasting isothermal transformation of ausferrite refines the ferrite plates (<100nm), which tend to form a typical feathery pattern indicating the direction of the plate growth (Table 2). The structure morphology after long-time transformation indicates austenite content reduced in favour of the ferrite content, and also change in the spatial arrangement of austenite between the fine ferrite plates of nanometric thickness (Fig. 6 and Fig. 7). The result is the ductile iron matrix after short time austempering assuming a completely ausferritic structure and containing austenite in two forms - austenite separating the plates of ferrite and blocks of austenite located between the ferritic-austenitic packages (Table 2.a). Longer time of transformation increases the ferrite fraction in the form of packages of plates separated by austenite (Table 2.b,c). Lower temperature of transformation means that ferrite plates are thinner (Table 2.d). Also, longer time of transformation gradually reduces austenite content in the microstructure of the cast iron matrix, increasing hardness (Fig. 8) and, consequently, improving the mechanical properties. In a mixture of ferrite and austenite of ductile iron matrix after proposed heat treatment is not observed the presence of carbides precipitates.

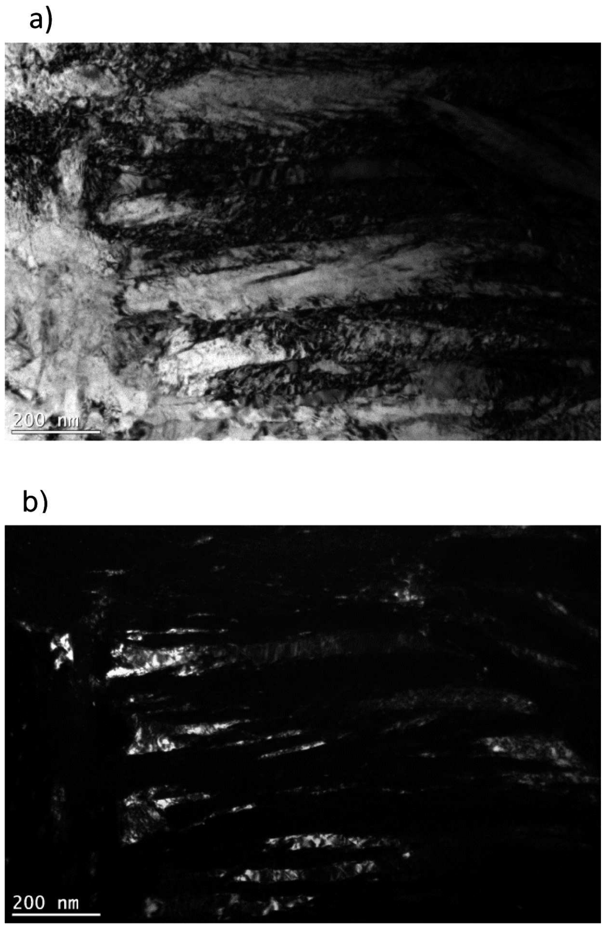


Fig. 7. ADI matrix structure obtained as a result of isothermal transformation carried out at 240°C; a) TEM-BF micrograph, b) TEM-DF micrograph (austenite reflexes)

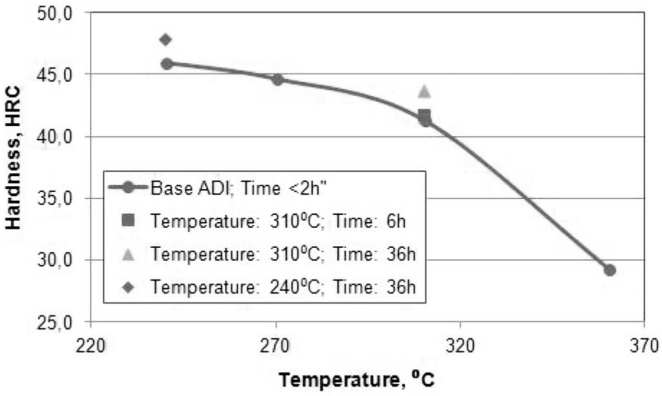


Fig. 8. Diagram of ADI hardness measurements results depending on temperature and time of austempering treatment

4. Summary

The work conditions in mining environment are particularly burdensome for machine gear elements. They must be resistant to the dynamically changing conditions, which means that they should offer resistance to dynamic deformation, high fracture toughness, wear resistance to the effect of various abrasive agents, etc. Ausferritic ductile iron meets some of these requirements, and this is the reason why now it is boldly entering the mining industry. Making responsible toothed elements from ausferritic ductile iron is due to the permanently growing knowledge about the potential hidden in this new structural material. The article shows that conducting special thermal processes leading to significant refinement of the ausferritic ductile iron matrix microstructure, even to the size of nano-scale, can contribute to the improvement of its properties. Particularly important is the fracture toughness, which so far has been identified with the presence of stable austenite in the cast iron structure. The authors prove that the presence of austenite in ultrafine grain cast iron matrix structure can be a critical factor in obtaining the satisfactory properties, corresponding to EU Standard, enabling the use of this cast iron for very responsible parts of machinery. Tests carried out on gear components for the mining industry have indicated that the material has potentially good abilities to carry loads under harsh operating conditions.

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