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AUSTENITE-MARTENSITE TRANSFORMATION IN AUSTEMPERED DUCTILE IRON

PRZEMIANA AUSTENITU W MARTENZYT W ŻELIWIE SFEROIDALNYM AUSFERRYTYCZNYM

Austempered ductile iron, commonly known as ADI, has already gained some renown among producers and users of castings made from this material. Though famous nowadays, its properties are being improved all the time and studies are continued to better know the mechanisms that govern obtaining the properties so unusual for a material like cast iron. From the research carried out by the author of this publication it follows that at least some of the properties result from the phenomenon that is called martensitic transformation and that accompanies the formation of ADI at different stages of its manufacture and during the additional technological operations. In ADI microstructure, martensite is always the product of austenite transformation, and for this reason mainly an attempt has been made in this paper to describe this phase in more detail as well as various consequences of its presence in cast iron under different conditions.

Keywords: Heat treatment, austempered ductile iron (ADI), austenite, martensite, cryogenic treatment, TRIP

Żeliwo ADI w dzisiejszych czasach ma już swoją renomę zarówno wśród producentów, jak i odbiorców odlewów wykonanych z tego materiału. Nadal jednak ulepszane są jego właściwości oraz poznawane są mechanizmy umożliwiające uzyskiwanie niezwykłych dla żeliwa właściwości. W świetle badań prowadzonych przez autora niniejszej publikacji wynika, że niezwykle istotny wpływ na część z nich ma przemiana martenzytyczna, która będzie towarzyszyć powstawaniu ADI w różnych fazach jego produkcji oraz innych, dodatkowych zabiegach technologicznych. Martenzyt jest zawsze wynikiem przemiany austenitu w mikrostrukturze ADI, stąd w artykule podjęto próbę opisu tej fazy i konsekwencji jej występowania w różnych stanach.

1. Introduction

The cast material named "Austempered Ductile Iron" (ADI) has not been as yet fully investigated and known to the designers and process engineers. Maybe for this reason new ideas are emerging all the time of how to improve this material and its, even at the present state of the art excellent, properties. This is of particular importance for varied applications of this material. It is enough to say that in year 2003 the world production of ADI reached the value of 220000 tons [1], and by 2010 it is expected to increase further and reach the level of 300000 tons [2]. Even these numbers prove the enormous popularity that ADI enjoys as a material used for parts of machines and equipment operating in automotive industry, railway engineering, agriculture, defense, etc. Nevertheless, ADI still hides many mysteries which fascinate scientists all over the world.

The phase particularly interesting in ADI microstructure is austenite, to the presence of which are usually ascribed the best properties typical of this material, i.e. high elongation, very good fatigue and impact resistance, etc. In view of this fact, it seems reasonable and advisable to better understand this phase and its features while present in cast iron, and an attempt at doing this has been the main objective of this article.

2. Austenite in ADI

The presence of austenite in ADI microstructure results from the heat treatment of castings made of unalloy or low-alloy ductile iron, usually enriched with small amounts of nickel, copper, or molybdenum. The treatment consists in the operations of austenitising and austempering (the treatment including isothermal transformation) of ductile iron (Fig. 1). As regards the presence of austenite at a temperature of isothermal transformation after preliminary cooling and at ambient temperature, most important will be the parameters of the

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austenitising treatment and, established during this treatment, carbon content in the matrix of ductile iron.

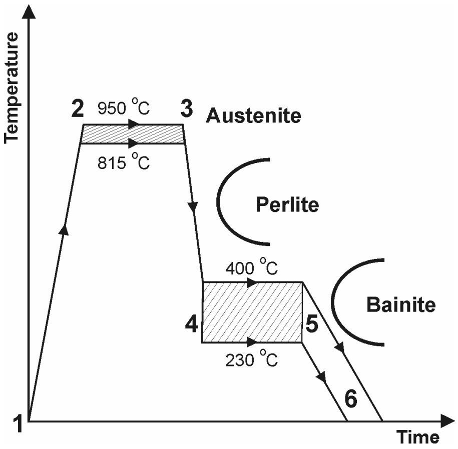

Fig. 1. Schematic representation of the austempering process of ductile iron

Both time and temperature of austenitising exert a very important influence on the kinetics of tranformation and on a final outcome of this process with its effect most significant, that is, the carbon content in the forming austenite. The temperature allows controlling the, possible to obtain, value of carbon equivalent in austenite, while time determines when (or if at all) the moment of achieving this state can take place. The higher is the temperature of austenitising, the quicker is the process of the austenite formation in matrix. The solubility of carbon originating from graphite precipitates increases, austenite becomes more homogeneous, and its grains are more prone to the growth. There is a well-known relationship m between the temperature of austenitising, the silicon content in cast iron, and carbon concentration in austenite [9]. The value of this parameter can be calculated for Fe-C-Si alloys from formula (1):

$$\mathrm{C}_{\gamma}^{\mathrm{A}} = \frac{\mathrm{T}_{\gamma}}{420} - 0,17(\%\mathrm{Si}) - 0,95[\%] \tag{1}$$

Basing on this formula, a diagram has been developed to illustrate the effect of temperature T_{γ} on carbon concentration in iron (Fig. 2), which is consistent with the experimental results. Possibly, some small inconsistencies may result from errors which occur when this parameter is measured [9].

Ensuring an appropriately long time of austenitising enables achieving the state of carbon equivalent in thus forming austenite, which will be characterised by a temperature M_{rmS}. From the research it follows that for the grades of cast iron which are used in fabrication of ADI, the temperature M_{rmS} will be at a level of about 150÷200°C [9, 13]. For transformations which occur during austempering this will be of really great importance.

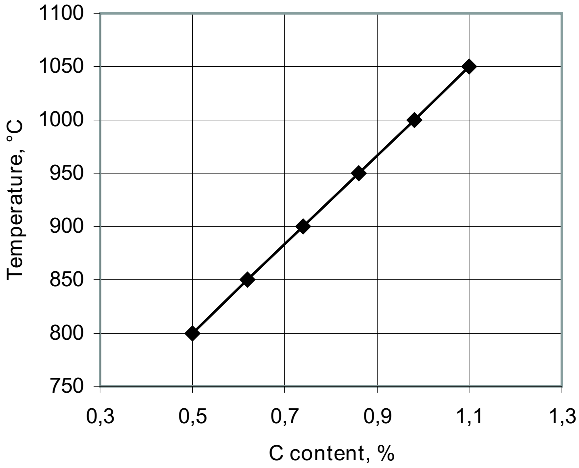

Fig. 2. Effect of austenitising temperature on carbon concentration in austenite – the values calculated from formula [9]

The effect of, determined in the process of austenitisation, carbon content in austenite on the kinetics of isothermal transformation can be explained by analysis of the individual stages of this transformation. The isothermal transformation starts after rapid cooling of casting from the temperature of austenitising to a temperature of 230÷400°C (Fig. 1). Figure 3, in correlation with figures 4, 5, 6, 7, shows schematically the formation of ductile iron matrix morphology during isothermal holding, compared with changes in temperature $\mathrm{M_S}$. At point A, when isothermal holding lasts for a short time only, the ductile iron will be characterised by an almost totally martensitic matrix, safe for a small amount of the lamellar precipitates of ferrite (Fig. 4). This is caused by complete transformation of the thermally unstable austenite. At point B, the ductile iron is already characterised by a matrix composed of the lamellar precipitates of ferrite and undercooled metastable austenite containing 1,0÷1,6%C, which is formed due to the saturation with carbon of regions of the growing ferrite (Fig. 5). At point C, austenite is already saturated with carbon to a level above 1,6%C which ensures its stability, and as such it will be called stable undercooled austenite. Further course of transformation will start the precipitation process of excess carbon in the form of carbides and, as a result of this process, the formation at point D of a bainitic matrix in ductile iron. In reality, the above described states of microstructure differ in character and, because of microsegregations in cast iron, may occur jointly at practically all stages of the isothermal transformation, cause as a result the differences of phase morphology in a matrix called ausferritic, i.e. composed of a mixture of the ferrite plates and high-carbon austenite. Therefore, also in regions of the elevated manganese and molybdenum content, the unreacted austenite may appear. It will be stabilised with these elements and as such will not undergo transformations at ambient temperature.

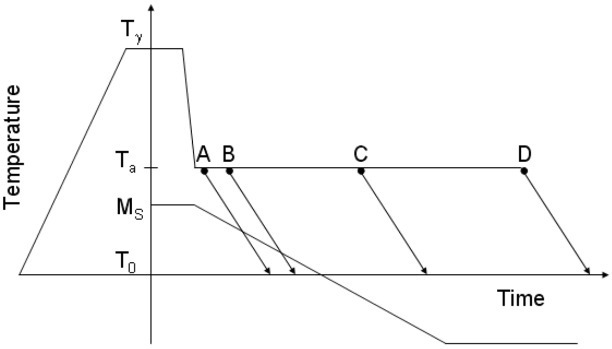

Fig. 3. Schema of the formation of DI matrix during austempering, compared with changes in temperature M_S

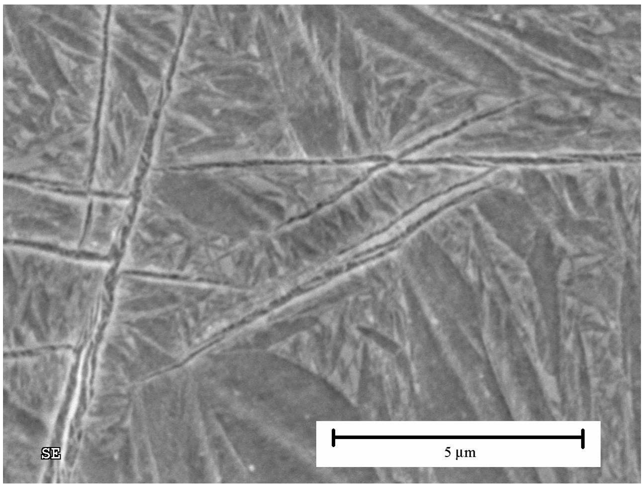

Fig. 4. Almost totally martensitic matrix with small amount of the plates of ferrite short time austempered ductile iron. State A – fig. 3. SEM

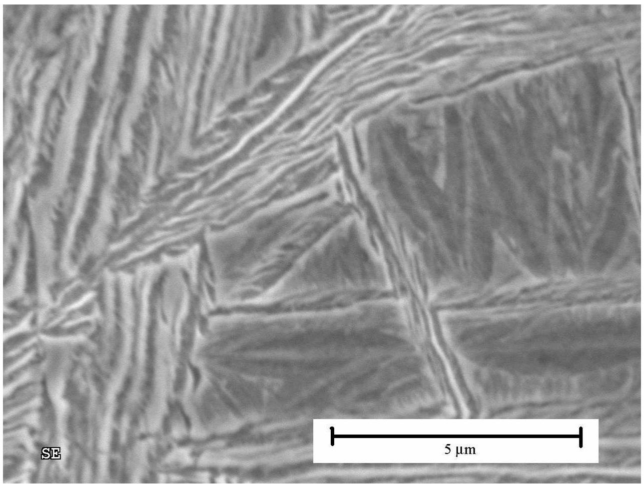

Fig. 5. Matrix of ADI composed of the lamellar plates of ferrite and martensite formed from undercooled metastable austenite. State B – fig. 3. SEM

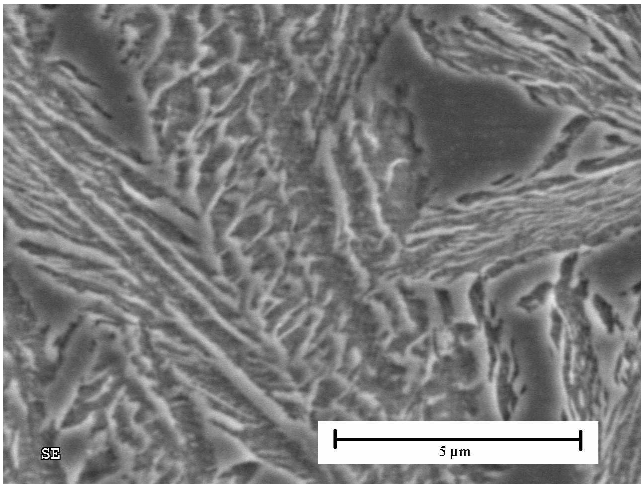

Fig. 6. Matrix of ADI including ferrite plates and austenite supersaturated with carbon. State C – fig. 3. SEM

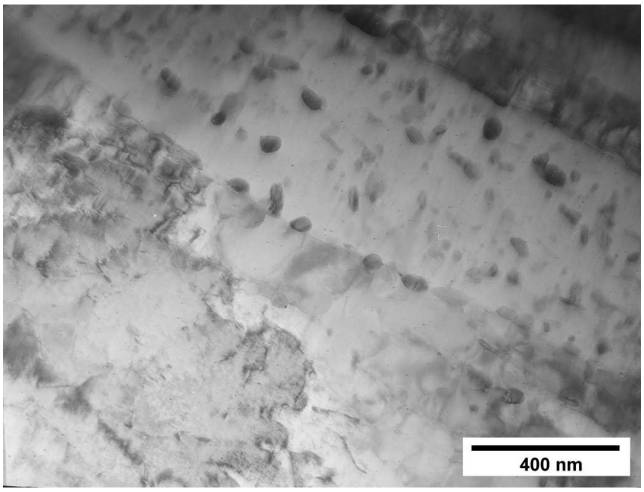

Fig. 7. Effect of austenitising temperature on carbon. State D – fig. 4. TEM

3. Cryogenic treatment of ADI

Because of the presence of austenite in austempered ductile iron whose temperature M_S is only slightly lower than ambient temperature, it is possible to have its transformation into martensite due to freezing [11]. Very interesting observations have been made by application of electron microscopy in microregions of the, frozen in liquid nitrogen, metallographic sections of ausferritic ductile iron austempered at 260, 300 and 360°C. On specimens of ADI, autempered at 360°C, and subsequently subjected to cryogenic treatment, one can observe fields of austenite partially transformed to martensite, which is not seen in the ADI matrix that is not cryogenically treated (Figs. 8 and 9). The observed phase is martensite can be inferred from the morphology of lens-like platelets arranged in characteristic shape “zigzags” (Fig. 9) [5], known from earlier investigations [11]. Noticeable also is the absence of transformation of austenite into martensite in regions between the ferrite platelets. Such a character of phenomena suggests that in these regions there occurs saturation with carbon, sufficient to lower the MS temperature of austenite to below -196°C. Subjected to martensitic transformation, stemming from cryogenic treatment in liquid nitrogen are bigger fields of austenite, where carbon saturation is less.

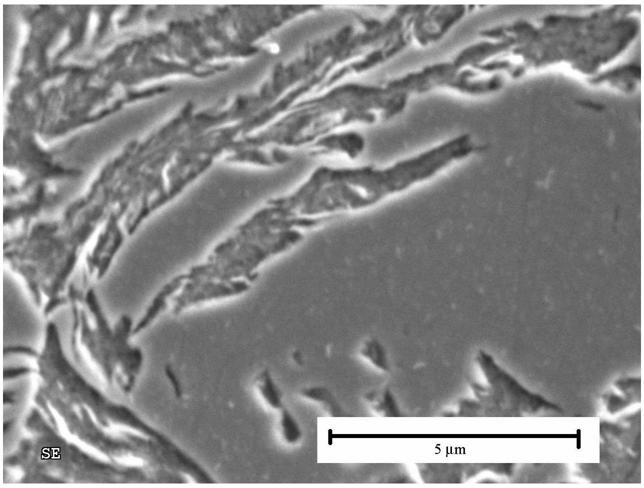

Fig. 8. Matrix of conventional ADI. SEM

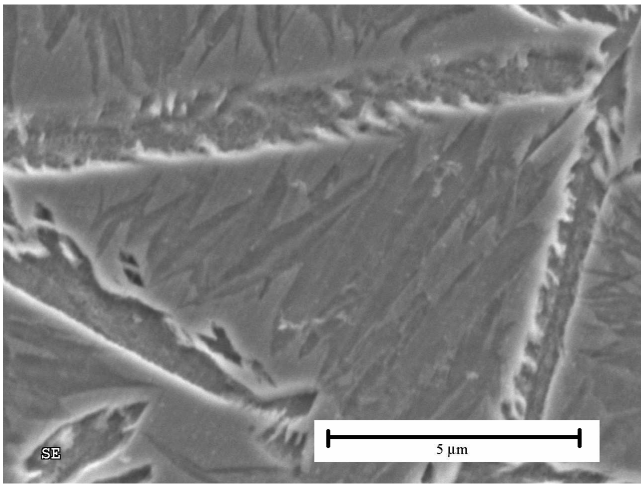

Fig. 9. Matrix of ADI after cryogenic treatment. SEM

A more intense character of martensitic transformation in ADI, obtained at a higher temperature of isothermal quenching was also determined by the DM-test method. The results of these measurements are presented in Fig. 10. From their analysis it follows that at the isothermal quench temperatures of 260 and 300°C for all specimens a small amount martensite (⩽1%) is obtained following cryogenic treatment. On the other hand, when ADI is austempered at 360°C, the amount of this phase is clearly greater. There is also a difference between the amount of martensite measured on specimens of austempered ductile iron that was isothermally quenched for 60 and 120 minutes. In the case of 60 minutes of isothermal transformation, the martensite content is generally greater than in the case of 120 minutes. This is consistent with the theory of thermal stabilization of austenite by carbon during isothermal transformation, which causes the gradual lowering of the MS temperature of austenite. Based on this premise, a conclusion may be drawn that the extension of the time of isothermal transformation from 60 to 120 minutes for ADI at 360°C causes thermal stabilization of approx. 2% of austenite.

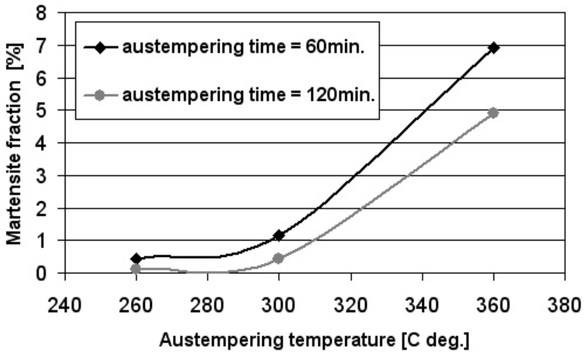

Fig. 10. Dependence of martensite fraction after cryogenic treatment on the temperature of austempering

4. TRIP effect in ADI

TRIP is often recorded to occur in ADI as a negative effect during machining. It is considered negative mainly because it results in premature wear of the cutting tools [7]. On the other hand, the occurrence of TRIP may also give some positive results. It is mainly the effect of surface shot blasting which raises the fatigue resistance of castings to a degree such that it can easily be compared with nitrided or carburised steel [4]. Due to shot blasting, rolling, or through direct contact of the mate surfaces, also the abrasion wear resistance is increasing, resulting finally in the possibility of having ADI applied on rotor blades in shot-blasting machines [8]. Yet, it has to be remembered that TRIP effect is related with the presence of austenite within the entire volume of ausferritic ductile iron, and not only in the surface layer of products made from this material, and as such it will also affect the ADI tensile strength during the tensile test. Probably, also due to this reason, just after the tensile test, the presence of martensite is observed on fractures, accompanied by austenite content much lower than the one observed in metallographic sections [9]. Therefore, martensite also appears in ADI microstructure after deformation during hardness measurement (Figs. 11a, b).

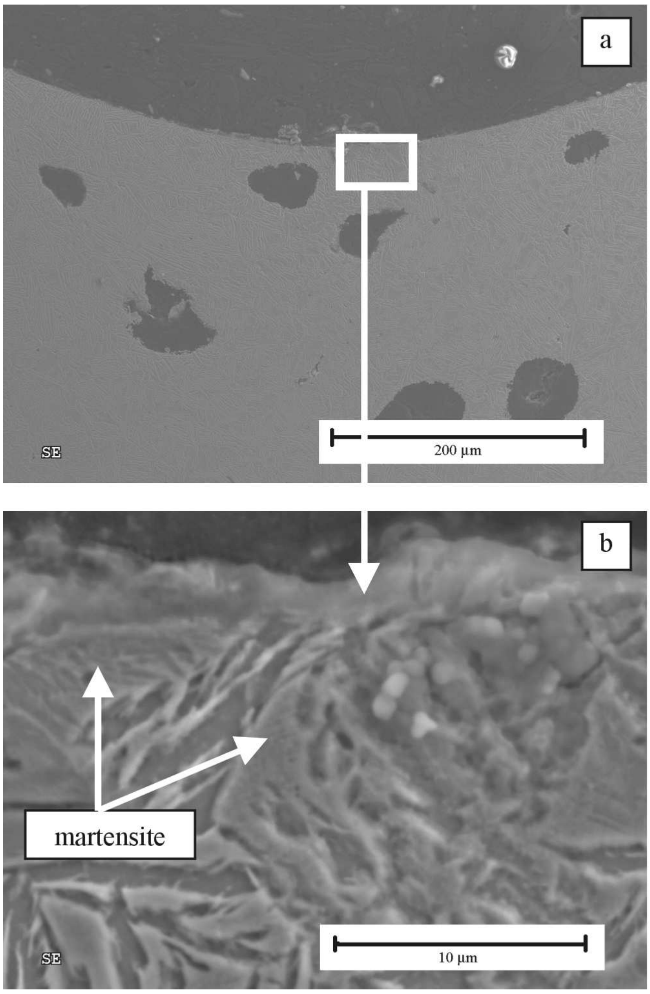

Fig. 11. a, b. Martensite in the matrix of ADI appeared after deformation by Brinell hardness tester. SEM

A key to the description of an effective influence of the martensitic transformation initiated by stresses in ADI on properties of this material is knowing the fraction of metastable austenite in the overall volume of austenite in ausferrite. This is a task very difficult but not impossible to be solved. Knowing properties of this phase and, first of all, its tendency to a deformation-related martensitic transformation, it is possible to carry out an experiment which consists in plastic deformation of ADI specimens, recording the content of martensite which appears after given deformation. Tests of this type were carried out and were published in [10]. Their result indicates that in ausferritic ductile iron due to 25% deformation of specimens it is possible to determine the content of the deformation-related martensite and stable austenite. For example, in ADI containing jointly 35,8% of stable and metastable austenite (with absence of martensite at ambient temperature), a 25% deformation results in the appearance of 24% martensite [10]. So, this result proves how important is the effect of metastable austenite on ADI properties, especially on the grades characterised by high ductility, containing large amounts of austenite. In a like manner, also the control of its fraction in phase structure of the ausferritic ductile iron will have an effect on the obtained values of not only elongation but also of other mechanical properties.

5. Conclusions

Basing on the observations disclosed above, the following conclusions can be drawn:

1. Ausferritic ductile iron is the developing engineering material of hidden potentials still not fully investigated by the scientific research, but offering various possibilities of application in automotive industry, railway engineering, agriculture, defense, etc.;
2. Austenite is the phase present in ADI in three basic forms, i.e. as metalstable undercooled austenite, stable undercooled austenite and unreacted austenite;
3. Freezing of ADI in liquid nitrogen results in the formation of martensite which is an outcome of austenite transformation at temperature MS, slightly below ambient temperature;
4. In ausferritic ductile iron the occurrence of TRIP (Transformation Induced Plasticity) effect takes place, due to which there is a mechanical transformation of metastable austenite into deformed martensite, thus contributing to changes in properties of this material.

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