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INFLUENCE OF THE SELECTED FACTORS ON THERMAL FATIGUE OF THE ADI IN AN ASPECT OF ITS SUITABILITY AS THE MATERIAL FOR METAL MOULDS

WPŁYW WYBRANYCH CZYNNIKÓW NA ZMĘCZENIE CIEPLNE ŻELIWA ADI W ASPEKCIE JEGO PRZYDATNOŚCI JAKO MATERIAŁU NA FORMY METALOWE

The investigation results of the thermal fatigue resistance of two ADI grades (EN-GJS-1200-2 and EN-GJS-800-8) are presented in the paper. Tests were performed on the author's research stand, by means of the resistance heating of samples acc. L.F. Coffin method. The thermal fatigue resistance is the basic criterion in assessing the material suitability for metal moulds. The maximal temperature (T_{max}) of thermal cycles influence on their number, which the sample can withstand before cracking, were estimated. Structure transformations, hardness and strength changes of the austempered ductile iron (ADI) were analysed. It was found, that at cyclic heating to T_{max} <500°C, the ADI retains its primary ausferritic structure, even after more than 10.000 thermal cycles. Such ADI behaviour predisposes it to be applied as a material for metal moulds used in the pressure die casting, it means mainly at casting Mg and Zn alloys as well as for small castings of Al alloys.

Keywords: ductile iron (ADI), thermal fatigue, metal moulds, pressure die casting

W pracy przedstawiono wyniki badań odporności na zmęczenie cieplne dwóch gatunków żeliwa ADI (EN-GJS-1200-2 i EN-GJS-800-8). Badania prowadzono na autorskim stanowisku badawczym stosując oporowe nagrzewanie próbek, wg metody L.F. Coffina. Odporność na zmęczenie cieplne jest podstawowym kryterium w ocenie przydatności tworzywa (materiału) na formy metalowe, które podlegają cyklicznemu nagrzewaniu. Oceniono wpływ maksymalnej temperatury (T_{max}) cykli cieplnych na ich liczbę do pęknięcia próbki, analizowano zmiany struktury żeliwa ADI, zmiany twardości i wytrzymałości. Stwierdzono, iż przy cyklicznym nagrzewaniu do T_{max} <500°C, żeliwo ADI zachowuje swoją pierwotną strukturę ausferrytu nawet po wykonaniu ponad 10.000 cykli cieplnych. Takie zachowanie żeliwa ADI predysponuje go jako materiał na formy metalowe stosowane w odlewnictwie ciśnieniowym, a więc przy odlewaniu głównie stopów Mg i Zn, ale również dla mniejszych odlewów wykonywanych ze stopów Al.

1. Introduction

The austempered ductile iron (ADI) is a relatively new structural material. Its macrostructure consists of ausferritic matrix and nodular graphite precipitates. Due to its mechanical properties it is finding wider and wider applications.

Generally, the ADI production is not a very complicated technological process. After producing a spheroidal cast iron of the chemical composition allowing to obtain final properties of the ADI, its heat treatment is performed. Austenitisation and isothermal quenching convert its initial (pearlitic) matrix structure into the ausferritic (ADI) one, [1,2,3]. Several research units are currently performing multidirectional research on assessing the ADI behaviour under operational conditions not tested thus far [1,4]. One of such potential (innovative) domains of the ADI applications can be metal moulds. Matrices and metal moulds are structures, which are utilised more and more intensely what sometimes causes that they operate at high and fast changing temperatures [5,6]. Production of

moulds for pressure die castings is usually expensive, since it requires the necessity of applying expensive alloyed steels, the most often after the multistage heat treatment. An influence of the selected factors on the ADI fatigue pathway, in the aspect of assessing its suitability for metal moulds, is described in the paper. The application of this new material will allow to lower production and usage costs without decreasing the service life.

2. Authors' own investigations

2.1. Metal moulds, pathways of temperature and stress changes

Metal moulds are classic examples of structures operating under thermal fatigue conditions. Specially large amount of metal moulds is utilised in the pressure die casting at producing castings of low-melting alloys – zinc, aluminium and magnesium. A heating degree of working surfaces of moulds

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is of a cyclic character and the highly heated inner surface obtains temperatures not higher than app. 500-550°C [7].

Pathways of thermal cycles of the tested ADI, which thermal fatigue was investigated, are very similar to the ones presented in the paper [7]. Their heating is fast, while cooling much slower. Temperature changes of the thermal cycle (T_{max} and T_{min}) can be kept at the 'arbitrary' range in the performed tests. Examples of thermal cycles realised in laboratory tests are shown in Figure 1.

Casting in metal moulds can be divided into two groups: casting at a low and at a high temperature. Castings of ferrous and copper alloys belong to the first group. Castings of non-ferrous metal alloys, e.g. zinc, magnesium and aluminium can be rated into the second group. In this second case the temperature of the mould working layer rarely exceeds 500°C. Such temperature provides the possibility of applying cheaper materials than steel or cast steel [8,9]. Thus, there is a possibility of substituting the presently used materials for metal moulds (steel, cast steel) – with a long-term heat treatment – by moulds of the ADI.
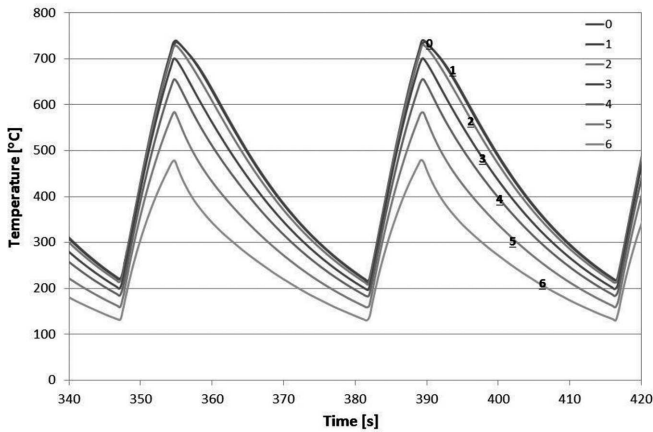

Fig. 1. Pathways of thermal cycles recorded in selected points (every 2 mm), along the sample length, cast iron EN-GJS-800-8, temperature range: T=200÷725°C [8,9]

2.2. Investigated material and methodology of thermal fatigue testing

The results of investigations of two different grades of the ADI, which according to binding standards are qualified as: EN-GJS-1200-2 and EN-GJS-800-8, are presented in the hereby paper. The initial ductile iron, of a composition shown in Table 1, was used for producing both materials, by means of heat treatment [10,11].

TABLE 1

Chemical composition of the initial spheroidal cast iron

Chemical composition of the obtained cast iron [%]									
C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Mg
3.56	0.20	2.4	0.039	0.014	0.02	1.4	0.31	0.6	0.04

In order to produce EN-GJS-800-8 and EN-GJS-1200-2 cast iron the austenitising and isothermal quenching procedures were applied. In case of EN-GJS-800-8 grade the

austenitising at 900°C was applied followed by the isothermal quenching at 380°. Both operations lasted 2 hours each. At producing EN-GJS-1200-2 grade similar operations were performed, but the isothermal quenching was carried out at 300°C. The results of the mechanical properties of the prepared ADI are listed in Table 2. Each value is the average of three measurements.

TABLE 2

Mechanical properties of ADI – EN-GJS-1200-2 and ADI – EN-GJS-800-8

		EN-GJS-1200-2	EN-GJS-800-8
Hardness	HB	388	311
Creep limit	$R_{p0,2}$ [MPa]	1111	772
Strength	R_m[MPa]	1361	1001
Elongation	A_5 [%]	4.6	7.9

The thermal fatigue term is generally used for wearing structure elements under an influence of multiple cyclic temperature changes causing the periodically variable stress field without additional external forces [12].
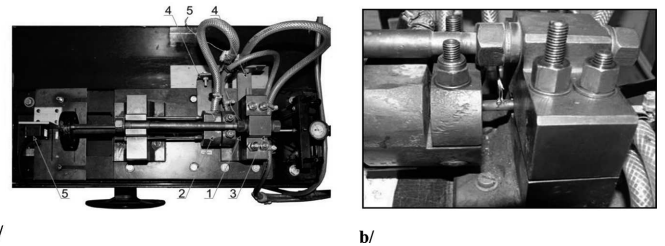

Fig. 2. System of fixing samples in the stand for testing thermal fatigue: a – View from above (1-sample, 2-mobile jaw, 3-master jaw, 4-feeders, 5-laser sensor of displacing, 6-thermo-couple; b - View of the fixed sample [5,8÷12,14÷16]

Investigations of the thermal fatigue were carried out on the special research stand in the Faculty of Foundry Engineering, UTS-AGH. The concept of investigations was based on the L. F. Coffin method [13], it means on resistance heating of samples. Therefore samples of a rod shape were applied. A high intensity current flowing through the sample causes its fast heating. The sample, fixed stiffly in the device holders, relatively well represents thermal-stress loads of the upper mould layer contacting with liquid metal. The research stand for testing the thermal fatigue is shown in Figure 2. The detailed description of the stand can be found in papers [5,8÷12, 14÷15,17].

2.3. Thermal fatigue, the influence of stresses

Thermal fatigue investigations were carried out within the range: T_{min} = 200°C; T_{max} = 650÷790°C. The range given above corresponds to moulds loads when they are poured with ferrous alloys. At casting of light metals alloys the temperature does not exceed app. 550°C. However, at such temperature level materials applied for metal moulds withstand sometimes a few hundred thousands of cycles. Since this would prolong extremely the time of investigating of the thermal fatigue, such measurements are very seldom performed at T_{max}<650°C.
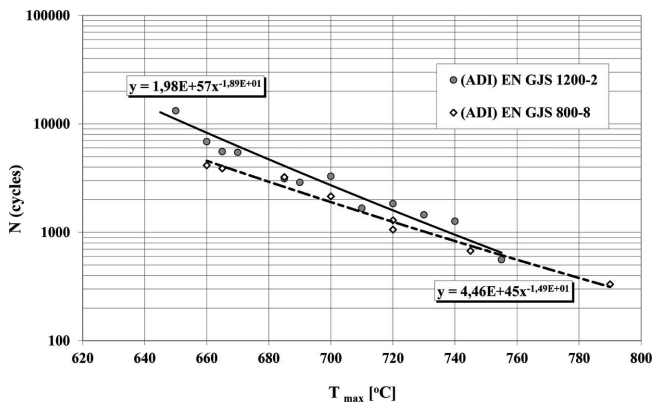
Fig. 3. Influence of the maximal temperature of the cycle on thermal fatigue of the investigated cast iron grades: EN-GJS-1200-2 and EN-GJS-800-8

The obtained results of the thermal fatigue depend not only on the thermal cycle range but also on the so-called degree of forcing of thermal deformations, stiffness of the measuring system. The results presented in the hereby paper were obtained at retaining the constant value of this parameter. Under actual conditions the degree of forcing thermal deformations depends on mould dimensions, its wall thickness, and other structural factors. The results of the influence of the maximal temperature of the cycle on the thermal fatigue of both investigated ADI grades are shown in Figure 3. The diagram was made in a semilogarithmic system and the pathway linear character means that the regression equation is exponential, which is confirmed by its diagram notation. Such influence of the maximal temperature is characteristic for materials used for metal moulds. Out of two tested grades significantly better resistance, especially at lower T_{max} values has EN GJS 1200 – 2 cast iron, characterised by a higher resistance R_m. At high T_{max} values the thermal fatigue resistances of both grades equalise.

Stresses play an important part in the thermal fatigue process. It results, from the previous investigations of the authors [8,10÷11,14,÷16], that stress influences are significant and decide on the thermal fatigue process – number of thermal cycles before a crack occurs.

2.4. Structure transformations of the ADI in the thermal fatigue process

The thermal cycles temperature constitutes one of the main factors responsible for transformations occurring in the investigated ADI grades. The higher is this temperature or when its influence time is longer the faster are these transformations. It was observed, during testing the thermal fatigue of test bars [5÷6,8÷12,14÷16,18], that the temperature distribution along the bars length is symmetrical and of a repeatable character - it is the same in every thermal cycle (Fig. 4). Apart from the central part of the sample, in the remaining cross-sections thermal cycles have different ranges. The stress level is the same in every place (cross-section) of the sample. Such heating of the sample allows to observe, in metallographic investigations of the same sample, the structure transformations caused by heating to various T_{max} values. Utilising this uneven distribution, investigations of the influence of the maximal cycle temperature were carried out in a

wide range of changes, especially lower than 650°C. From the previous investigations of the authors [8÷11,14÷16] it results, that the ausferritic matrix of the ADI was not transformed in these parts of samples in which T_{max} was not exceeding 500°C. Such information is very important in an aspect of applying this cast iron for metal moulds or matrices for pressure die castings. Thus, this means that at lower temperatures the moulds will retain – for a long usage period – high mechanical properties R_m and HB.
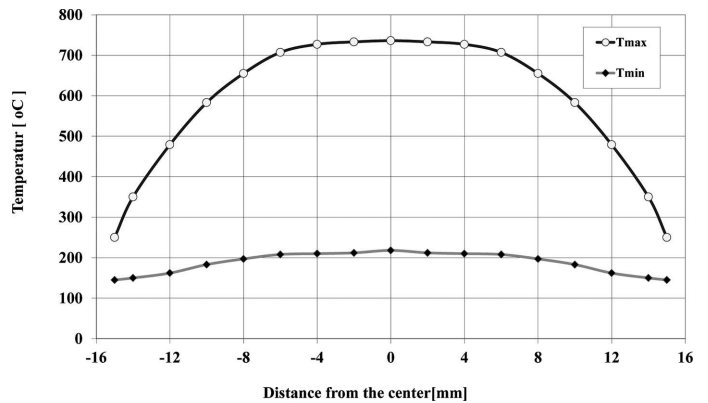

Fig. 4. Temperature distribution along the sample length of EN-GJS-800-8 cast iron, at the thermal cycle in the range: T – 200÷725°C
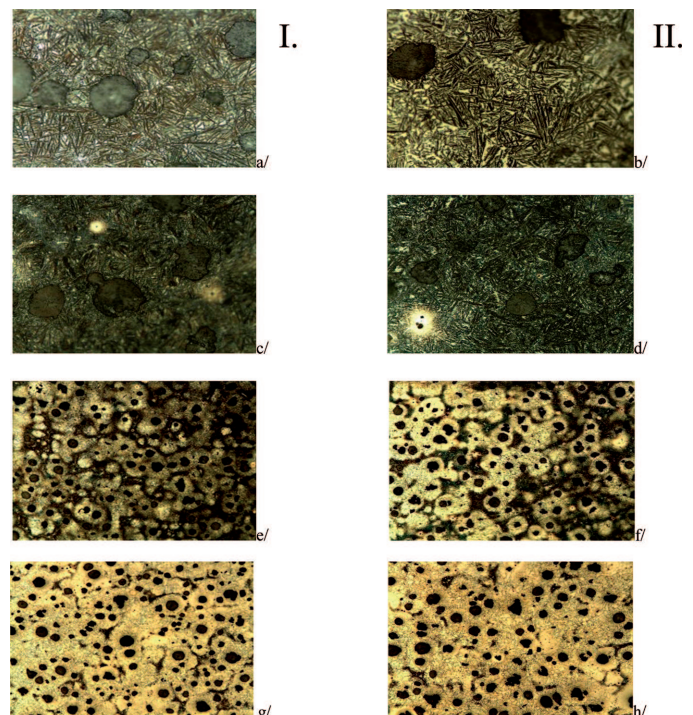

Fig. 5. Transformations of the metal matrix of EN-GJS-1200-2 and EN-GJS-800-8 cast iron: a, b, c, d – magnification 500x, e, f, g, h – magnification 100x, etched by nital, I – EN-GJS-1200-2, II – EN-GJS-800-8

Along with an increase of T_{max} of thermal cycles (above 500°C) a progressing transformation of the matrix of the investigated cast iron is observed. The ausferritic structure is the initial one for EN-GJS-1200-2 and EN-GJS-800-8 cast iron (Fig. 5 a, b). The thermal fatigue process unfavourably influences the ADI microstructure. Despite of application of

alloying additions (Cu, Ni, Mo), which are improving a general thermal fatigue resistance, the ausferritic matrix decomposition is not prevented, however it occurs slightly later. By increasing the maximal temperature or by prolonging its influence time a microstructure transformation can be accelerated. Such transformation, as it was earlier noticed, occurs in stages (Fig. 5). At first, precipitates of granular pearlite start occurring in the purely ausferritic matrix (Fig. 5 c, d). As the number of fatigue cycles increases the pearlite amount increases while austenite vanishes. At the second stage ferrite starts occurring in the microstructure (Fig. 5 e, f). As the number of thermal cycles increases the amount of granular pearlite decreases, while the ferrite fraction increases. The most often nearly purely ferritic structure can be seen in the crack range (the highest heating) of the sample, which cracked due to the thermal fatigue (Fig. 5. g, h). Thus, transformations lead to the matrix rebuilding from purely ausferritic to practically purely ferritic.

2.5. Recommended usage temperature of metal moulds of the ADI

Investigations of structure changes of samples subjected to fatigue, described in the previous part of the work, indicated that the maximal temperature at which the ausferritic structure was still stable equals ~500°C. In order to confirm this approximately determined temperature of the ADI structure stability and to verify this determination, additional investigations of the thermal fatigue were performed in the cycle range: T = 200÷500°C and T = 200÷475°C. Samples of EN-GJS-1200-2 cast iron were subjected to thermal fatigue, at the cycles number above 10.000. Samples were not worn, since – as can be determined from dependences given in Fig. 3 – they can withstand several dozen thousands of cycles. Then hardness measurements were performed along the sample length and the metal matrix form was estimated. The obtained HB results are presented in Fig. 6 (for T_{max} =500°C). The microstructures of the ADI – after 10.000 thermal cycles – are shown in Fig. 7.
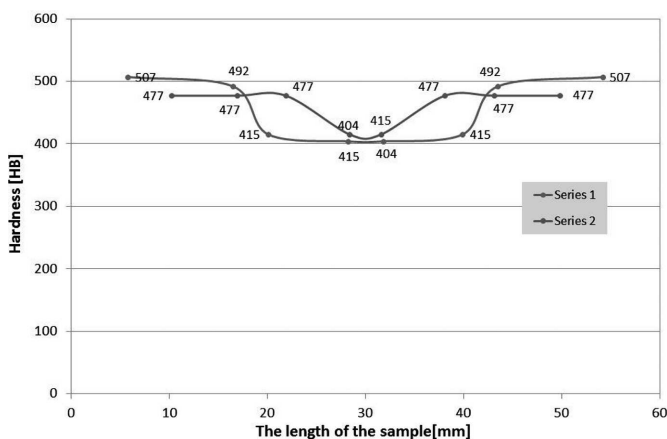

Fig. 6. Hardness distribution in the sample of ADI – EN-GJS-1200-2 , heated in the temperature range: 200÷500°C, number of cycles: N = 10400

a/ b/
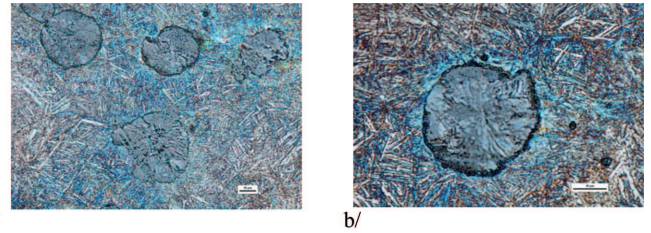
Fig. 7. Structure of ADI – EN-GJS-1200-2, after 10.400 thermal fatigue cycles, a – zone of heating to 500°C, b – zone of heating to 250÷300°C – magnification 500x, etched by nital

Metallographic tests confirmed that apart from more than 10000 thermal cycles the matrix form was not changed. It is very essential since, in combination with the hardness results, it allows to formulate an important conclusion that the ADI subjected to the thermal fatigueis structurally stable and retains its mechanical properties (mainly HB), if the cycle maximal temperature does not exceed 475÷500°C. This thesis concerns cast iron of the chemical composition given in Table 1. When a temperature exceeds 500°C the cast iron hardness decreases and its ausferritic structure is changing. These changes become faster as the thermal cycle maximal temperature is increased.

3. Conclusions

The performed investigations of the thermal fatigue resistance of two ADI grades allow to formulate the following conclusions:

- The thermal fatigue resistance of the ADI is higher than of unalloyed spheroidal cast iron;
- Favourable ausferritic structure of the ADI is not rebuilding during the cyclic loading of temperatures and stresses, however under condition that the maximal cycle temperature does not exceed 500°C;
- When the maximal thermal cycle temperature is maintained in the range: T_{max} <500°C even long-lasting cyclic heating does not cause transformation of ausferritic metal matrix, which allows to retain also a high hardness of this cast iron;
- On the basis of the obtained results and taking into account the heating degree of metal moulds, the ADI can be recommended as the material for metal moulds applied in die casting (at casting zinc and aluminium alloys).

REFERENCES

[1] D. M y s z k a, M. K a c z o r o w s k i, J. T y b u l c z u k, Publisher of Foundry Research Institute, Krakow (2003).

[2] The collective work, The technology development of ADI in Poland. Foundry Research Institute, Krakow 2009.

[3] E. G u z i k, Some selected problems concerning the process of cast iron improvement. Archives of Foundry Engineering, Monograph 1, Katowice 2001.

[4] J. T y b u l c z u k, A. K o w a l s k i, ADI. Foundry Research Institute, Krakow 2003.

[5] J. Z y c h, Archives of Metallurgy and Materials **58** (3), 757 (2013).

[6] A. W e r o ń s k i, Thermal fatigue of metals, WNT, Warszawa 1983.

[7] B. N o g o v i z i n, G. F r i e b e, Giessereiforschung **2**, 1 (2002).

[8] J. Z y c h, Metalurgia PAN, Katowice **38**, 107 (1988).

[9] J. Z y c h, D. J ę d r z e j c z y k, Przegląd Odlewnictwa **6**, 215 (1991).

[10] J. W r ó b e l, The resistance to thermal fatigue of ADI. PhD thesis. UST-AGH Krakow (2013).

[11] J. Z y c h, J. W r ó b e l, Przegląd Odlewnictwa **5**, 214 (2011).

[12] J. Z y c h, IX Symposium on the occasion of Foundryman Days, AGH Krakow (1983).

[13] L.F. C o f f i n, R.P. W e s l e y, Trans. of ASME **76**, 923 (1954).

[14] J. Z y c h, J. W r ó b e l, Giessereipraxis **10**, 476 (2011).

[15] J. Z y c h, J. W r ó b e l, Archives of Foundry Engineering **12**, 205 (2012).

[16] J. Z y c h, J. W r ó b e l, Archives of Foundry Engineering **10**, 2 (2010).

[17] J. Z y c h, Solidification of Metals and Alloys **24**, 135 (1995)

[18] A. W e r o ń s k i, T. H e j w o w s k i, The problem of sustainability components working at elevated temperatures. Publisher Lublin University of Technology, 1993.