A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 59 2014 Issue 3
DOI: 10.2478/amm-2014-0204

D. MYSZKA*, L. CYBULA**, A. WIECZOREK***

INFLUENCE OF HEAT TREATMENT CONDITIONS ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF AUSTEMPERED DUCTILE IRON AFTER DYNAMIC DEFORMATION TEST

WPŁYW OBRÓBKI CIEPLNEJ NA MIKROSTRUKTURĘ I WŁAŚCIWOŚCI ŻELIWA SFEROIDALNEGO AUSFERRYTYCZNEGO ODKSZTAŁCANEGO DYNAMICZNIE

In this article, an attempt was made to determine the effect of dynamic load on the austempered ductile iron resistance obtained under different conditions of heat treatment. Tests were carried out on six types of cylindrical ductile iron samples austempered at 320, 370 and 400°C for 30 and 180 minutes. For each type of material, two samples were collected. As a next step in the investigations, the samples were subjected to a Taylor impact test. The samples after striking a non-deformable, rigid target were deformed on their front face. After Taylor test, a series of material tests was performed on these samples, noting a significant increase of hardness in the deformed part. This was particularly well visible in the ductile iron isothermally quenched at higher temperatures of 370 and 400°C. In the zone of sample deformation, an increase in the content of ferromagnetic phase was also reported, thus indicating the occurrence of martensitic transformation in the microstructure containing mechanically unstable austenite. A significant amount of deformed graphite was also observed, which was a symptom of the deformation process taking place in samples. The ductile iron was characterized by high toughness and high resistance to the effect of dynamic loads, especially as regards the grade treated at a temperature of 370°C.

Keywords: austempered ductile iron, metastable austenite, dynamic deformation, Taylor test

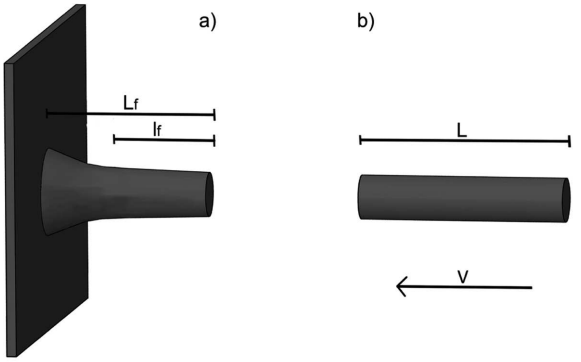
W artykule podjęto próbę określenia wpływu obciążeń dynamicznych na odporność żeliwa sferoidalnego ausferrytycznego otrzymanego w różnych warunkach obróbki cieplnej. Badania przeprowadzono dla 6 rodzajów próbek cylindrycznych wykonanych z żeliwa i poddanych hartowaniu izotermicznemu w temperaturze 320, 370 i 400°C w czasie 30 i 180 minut. Dla każdego rodzaju materiału pobrano po dwie próbki, a następnie poddano je uderzeniowemu testowi Taylor'a. Próbki te, po uderzeniu w nieodkształcalną, sztywną płytę zostały czołowo zdeformowane. Wykonano szereg badań materiałowych, stwierdzając znaczne zwiększenie twardości w części odkształconej materiału. Dotyczyło to zwłaszcza żeliwa hartowanego izotermicznie w temperaturach: 370 i 400°C. Wyznaczono również przyrost fazy ferromagnetycznej w strefie odkształconej próbki, co może świadczyć o zachodzeniu przemiany martenzytycznej w mikrostrukturze zawierającej niestabilny mechanicznie austenit. Stwierdzono również obecność znacznej ilości zdeformowanego grafitu, który był wyznacznikiem zachodzenia procesu deformacji próbek. Stwierdzono dużą plastyczność żeliwa oraz jego wysoką odporność na dynamiczne obciążenia, zwłaszcza dla gatunków hartowanych izotermicznie w temperaturze 370°C.

1. Introduction

The materials used for parts operating in the machinery and equipment for agricultural, mining and some other special applications face new demands, one of which is the resistance to dynamic loads. Due to the complexity of phenomena taking part in this type of interaction, the said materials are subjected to specific, non-static types of tests. They define the properties, which enable seeing the material already known in a new light and finding for this material a new field of applications. One of these special types of tests is Taylor impact test, which identifies the dynamic yield stress. The test is extremely useful offering the possibility of a wide comparison of the tested material with other materials, and the ability to translate the results obtained into potential applications.

Taylor test involves the dynamic deformation of a cylindrical sample that hits at a preset velocity a non-deformable target (Fig. 1). The impact parameters and the degree of sample deformation determined by geometric measurements are a measure of the dynamic properties of the examined material. Using impact parameters set out in the test and the degree of sample deformation in Taylor relationship (1) it becomes possible to determine the, so-called, dynamic yield stress. This, in turn, allows comparing the behaviour of different materials under the conditions of dynamic loads.

* WARSAW UNIVERSITY OF TECHNOLOGY, INSTITUTE OF MANUFACTURING TECHNOLOGY, WARSAW, POLAND
** WARSAW UNIVERSITY OF TECHNOLOGY, INSTITUTE OF MECHANICS AND PRINTING, WARSAW, POLAND
*** SILESIAN UNIVERSITY OF TECHNOLOGY, INSTITUTE OF MINING MECHANIZATION, GLIWICE, POLAND



$$R_d = \frac{\frac{1}{2}\rho V^2\left(1-\frac{l_f}{L}\right)}{\left(1-\frac{L_f}{L}\right)ln\left(\frac{L}{l_f}\right)} \quad (1)$$

Fig. 1. The basic principles of Taylor test: a) sample after deformation, b) sample before deformation; relationship (1): designations: R_d – dynamic yield stress, ρ – density of the tested material, V – sample impact velocity, L – sample length before impact, L_f – sample length after impact, l_f – the length of non-deformed part of the sample after impact [1]

Dynamic tests, including Taylor impact test, are conducted on a variety of materials, including those with very specific applications [1, 2]. This article describes studies conducted on a special type of the heat-treated cast iron. The said cast iron is known as "austempered ductile iron" (ADI). It has some specific features, which make it the material ideal for use in structures operating under the conditions of high dynamic loads. Special characteristics of this material are associated with the type of microstructure which is obtained by two-step heat treatment of the ductile iron, i.e. austenitising and austempering. Generally speaking, this microstructure is composed of the lamellae of ferrite and high-carbon austenite (called ausferrite). Under the conditions of dynamic loads, the phase particularly important in this material is austenite, with its hardenability resulting from the strain-induced martensitic transformation [8,9,10,11,12]. The transformation will be triggered by the action of stress or strain and will result in the excellent properties of the material, evident, e.g. in the Hadfield steel used for various impact structures. The elevated content of the high-carbon austenite in ADI (10 ÷40%) indicates the possibility of using this feature in a similar manner.

Through control of the heat treatment parameters it is possible to gain a whole range of the austempered ductile iron properties specified in the EU Standard [13]. Specific applications therefore require establishing new thermal conditions under which the desired microstructure and hence the relevant properties will be obtained. It is the fact well-known that the high or low temperature of the second heat treatment (austempering) and a short or long duration of this cycle can significantly affect both strength and toughness of ADI. Therefore a very rich literature is available on how to calculate the heat treatment parameters and material properties [14,15,16]. Yet, it would be very difficult to find publications dealing with the effect of dynamic loads on the properties of ADI, and therefore it was decided to investigate this aspect of this relatively new and prospective material.

2. Making samples

Tests were carried out on cylindrical Ø8×30 mm ductile iron samples of the chemical composition given in Table 1. Heat treatment of the samples was performed at the Department of Foundry Engineering, Warsaw University of Technology, using a Nabertherm chamber furnace and a fluidised bed based on SiC with the grain size of about 100 μm. The heat treatment parameters are shown in Table 2.

TABLE 1
Chemical composition of ductile iron castings [wt%]

C	Si	Mn	P	S	Ni	Mg	Cu	Mo
3.40	2.80	0.28	0.035	0.015	0.02	0.055	0.72	0.27

TABLE 2
Cycles of ductile iron heat treatment

Sample designation	Austenitising		Austempering	
	Temperature [°C]	Time [min.]	Temperature [°C]	Time [min.]
ADI_320_030	900	60	320	30
ADI_320_180				180
ADI_370_030			370	30
ADI_370_180				180
ADI_400_030			400	30
ADI_400_180				180

3. Taylor impact test

To determine the dynamic yield stress of austempered ductile iron by Taylor impact test, a test stand shown in Fig. 2 was used. The stand comprises a universal ballistic tool (UPB) – (1) on which is mounted a powder-driven propellant system – (2). In front part of the stand there is a sample capture system. The capture system consists of a pressure plate – (4), an "anvil" – (5) rigidly connected with the pressure plate and a casing pipe – (6). To measure the impact parameters, a set of photoelectric gates is used – (7) and a unit recording the velocity at which the sample is striking the "anvil" – (8). Changes in the pressure of powder gas in a propellant system are recorded by a piezoelectric pressure sensor – (9). The propellant system is designed to confer to a sample the required outlet velocity. The propellant system uses a 12,7 mm calibre ballistic barrel with a reduced length of the thread.

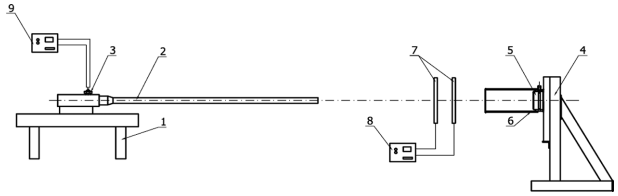


Fig. 2. Schematic drawing of a test stand to determine the dynamic yield stress: 1 – UPB bed, 2 – 12,7 mm calibre propellant system, 3 – piezoelectric pressure sensor, 4 – pressure plate to fix the „anvil", 5 – „anvil", 6 – casing pipe, 7 – a set of piezoelectric gates, 8 – velocity recording unit, 9 – powder gas pressure recording unit.

The study used specially designed, separately charged, cartridges. The cartridge was composed of a case and a blasting cap with the propelling charge placed inside and of a tested projectile. The tested projectile (Fig. 3) included sabot (2) made of plastic and sample (1) made of the tested material, located inside the sabot.

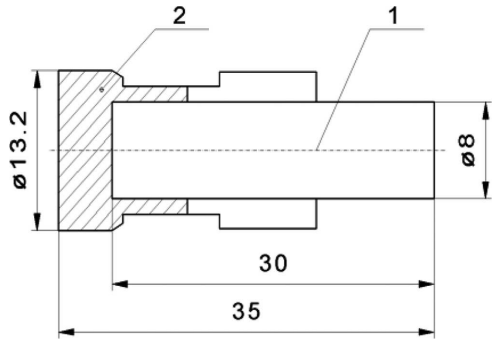


Fig. 3. The tested projectile, 1 – sample, 2 – sabot

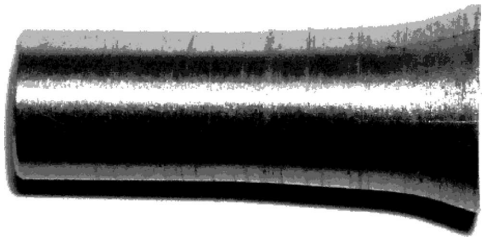


Fig. 4. Sample deformed in Taylor impact test

TABLE 3

Test results for samples deformed in the group of low impact velocities V = 177-205 [m/s]

Designation	Velocity	Static yield stress	Dynamic yield stress	Strength coefficient
	V [m/s]	Rp0.2 [MPa]	Rd [MPa]	$k=R_d/R_{p0.2}$
ADI_320_030	179	932	1261	1.35
ADI_320_180	205	1036	Failure of sample	
ADI_370_030	200	546	1075	1.97
ADI_370_180	191	673	1028	1.53
ADI_400_030	177	630	945	1.5
ADI_400_180	189	642	999	1.56

The object of studies consisted of a set of 12 samples made of the six types of ductile iron – 2 samples for each type. Tests were conducted on a test stand designed for the determination of dynamic yield stress by the Taylor impact test in accordance with the methodology developed by the IMiP WIP, Warsaw University of Technology. The test projectiles shown in Fig. 3 were used. In the studies, 12 rounds of shots were exercised with the measurement of sample velocity and powder gas pressure in the barrel. The test results are compiled in Tables 3 and 4. Due to the large number of results, they were divided into two groups: the results obtained at low impact velocities, i.e. V = 177÷205 [m/s] and the results obtained at high impact velocities, i.e. V = 224÷-249 [m/s]. The tables show only the measured velocity of sample striking the anvil, the static yield stress determined in static tests, and the calculated dynamic yield stress.The strength coefficient ”k”, defined as a ratio between the dynamic yield stress determined in Taylor test and the static yield stress determined in static tensile test, was also calculated.

TABLE 4

Test results for samples deformed in the group of high impact velocities V= 224-249 [m/s]

Designation	Velocity	Static yield stress	Dynamic yield stress	Strength coefficient
	V [m/s]	Rp0.2 [MPa]	Rd [MPa]	$k=R_d/R_{p0.2}$
ADI_320_030	236	932	1245	1.33
ADI_320_180	249	1036	1045	1.01
ADI_370_030	231	546	1026	1.88
ADI_370_180	225	673	1077	1.6
ADI_400_030	224	630	736	1.17
ADI_400_180	239	642	1163	1.81

The results of geometric measurements taken on ductile iron samples after striking the target and calculations made in Taylor test can also be grouped in other ways to enable more accurate analysis. Figures 5 and 6 graphically illustrate a relationship between the strength coefficient ”k” and the austempering time and temperature. The graphs indicate that for a shorter time of this treatment (30 minutes), the temperature of 370°C is an optimum to obtain the highest yield strength, i.e. the best dynamic-to-static yield stress ratio. It is easy to notice that longer time of austempering (180 minutes) gives values of ”k” lower than the time shorter (30 minutes), and this is true for each of the applied heat treatment temperatures (Figs.5b and 6b).

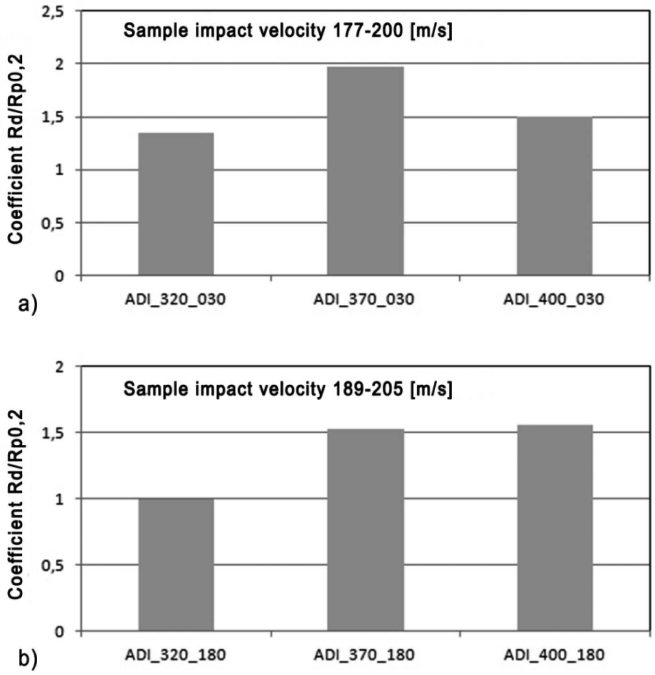


Fig. 5. The values of the strength coefficient “k” calculated for samples of ductile iron austempered at different temperatures for (a) 30 minutes, (b) 180 minutes deformed at low impact velocities

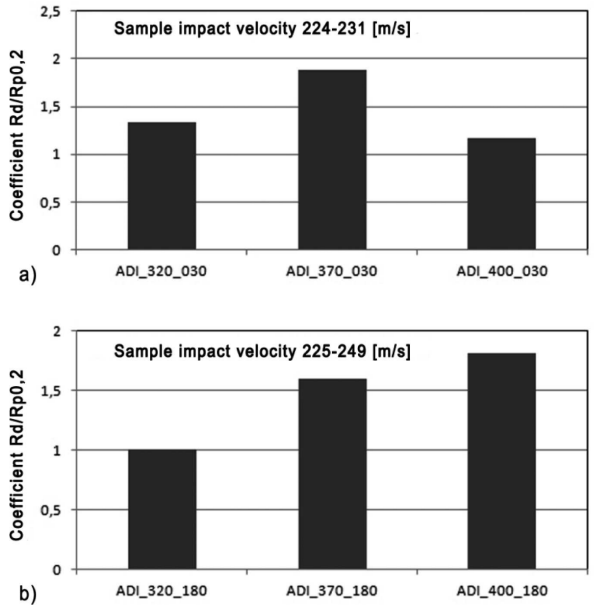


Fig. 6. The values of the strength coefficient "k" calculated for samples of ductile iron austempered at different temperatures for (a) 30 minutes, (b) 180 minutes deformed at high impact velocities

4. Evaluation of material properties

Samples deformed in Taylor test were next cut along the axis and on the cross-sections a series of material-related tests was performed, including hardness measurements, macro-and microscopic examinations, and magnetic measurements. The results of Vickers hardness measurements under a load of 100g were displayed as a distribution of values from the front face of the deformed sample in the direction of the undeformed sample fragment. Macroscopic evaluation was performed under a stereoscopic microscope studying the mode and the degree of deformation on the sample front face. Microscopic observations on metallographic sections unetched and etched with 3% Nital were made at magnifications of 200x and 1000x and identified the deformation of both matrix and graphite precipitates. Magnetic measurements were taken with a ferrite meter using the method of eddy currents, estimating the content of ferromagnetic phases at the four characteristic points of the sample designated as A, B, C and D (shown on the diagrams), with point A lying closest to the deformed edge.

TABLE 5

Material testing results for samples deformed in the group of low impact velocities V = 177÷205 [m/s]

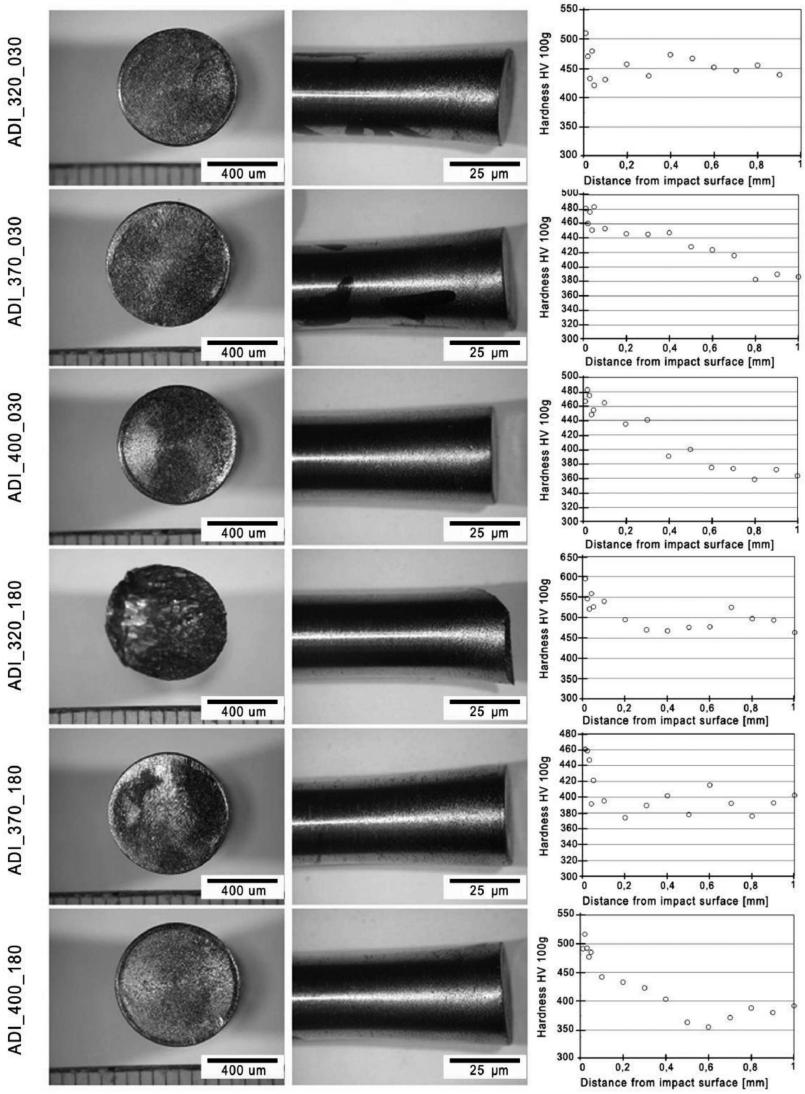


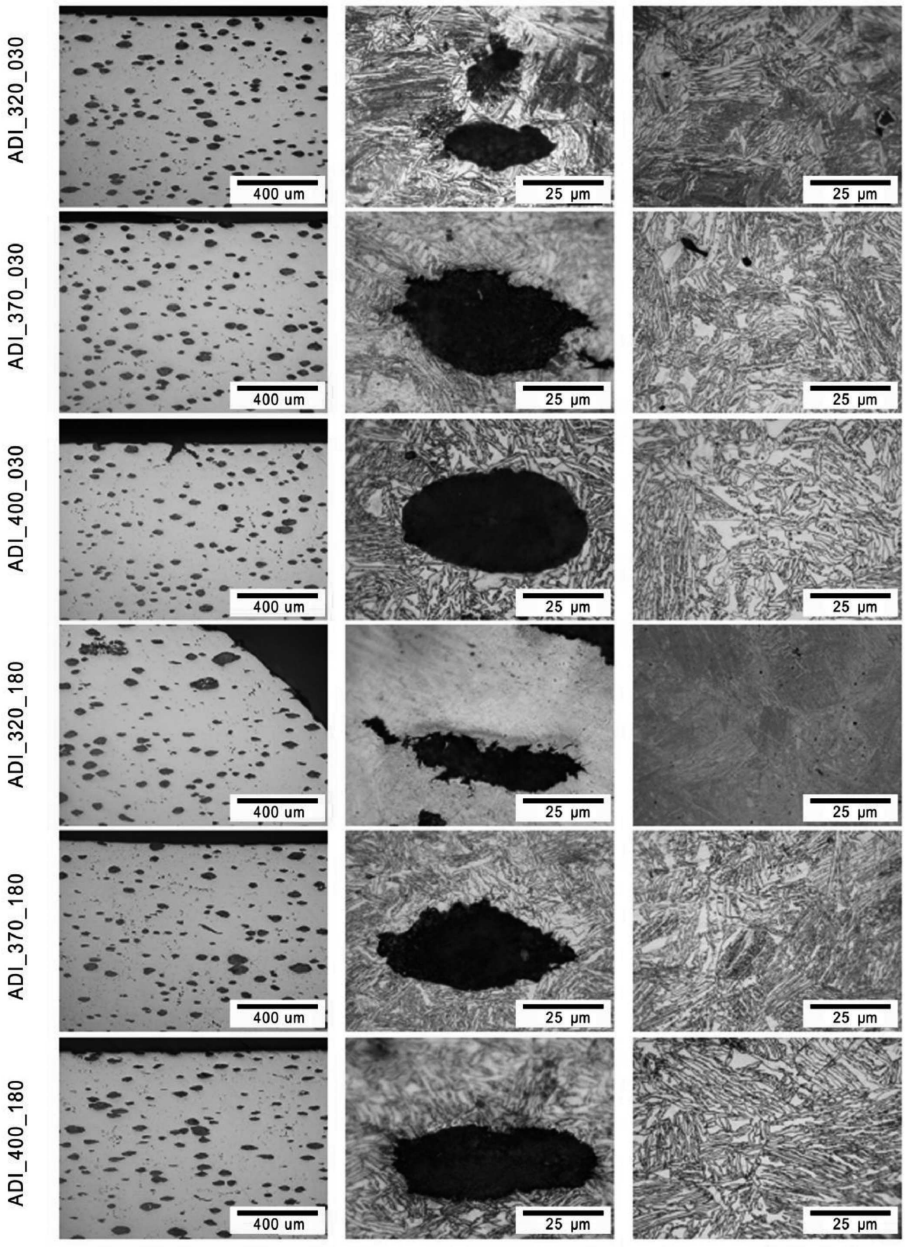
Table 5 shows photographs of a group of fractures and samples deformed at low velocities of striking the non-deformable plate. This table also contains collective results of the macroscopic evaluation and distribution of hardness values in samples from the front face of each of the deformed surfaces. Considerable increase of hardness values in samples designated as ADI_370_030, ADI_400_030 and ADI_400_180 was reported. Only one of the samples designated as ADI_320_180 failed, the other samples were characterized by high toughness and good resistance to the effect of dynamic deformations.

Table 6 gives cumulative results of microscopic examinations of the front face of each of the samples deformed at low impact velocities. High degree of graphite spheroids deformation within the sample deformation area penetrating to a depth of minimum 1mm was observed. This reflects the large range of deformation, but is not equivalent to the modification of matrix microstructure - changes in the ausferritic matrix can not be recognised at the applied magnification of 1000x and must be estimated by volume, using other techniques.

The content of ferromagnetic phases in samples deformed at low impact velocities was determined at the four characteristic points designated as A, B, C and D (Figs. 7 and 8). For most samples, with exception of the sample designated as ADI_400_180, the content of ferromagnetic phases was observed to increase in the direction towards the front face of the deformed sample. This increase was best seen in samples subjected to austempering at 370°C.

TABLE 6

The results of microscopic examinations of samples deformed in the group of low impact velocities V=177/205 [m/s]



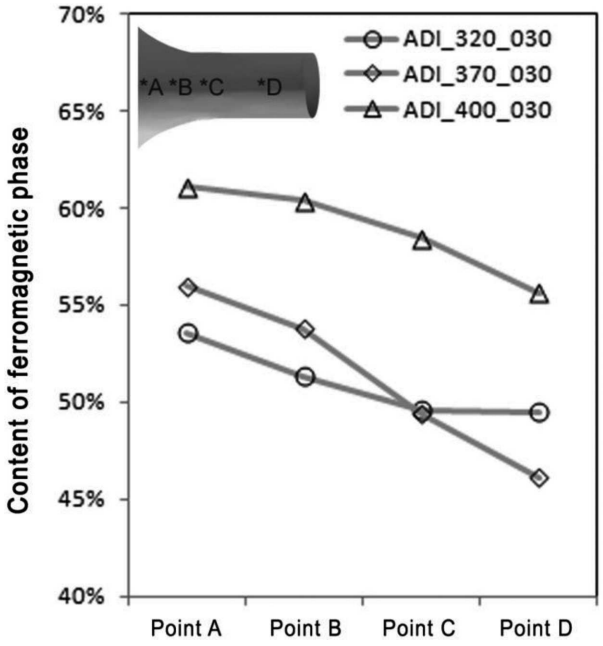


Fig. 7. The content of ferromagnetic phases in samples of ductile iron austempered at 320, 370 and 400°C for 30 minutes deformed at low impact velocities

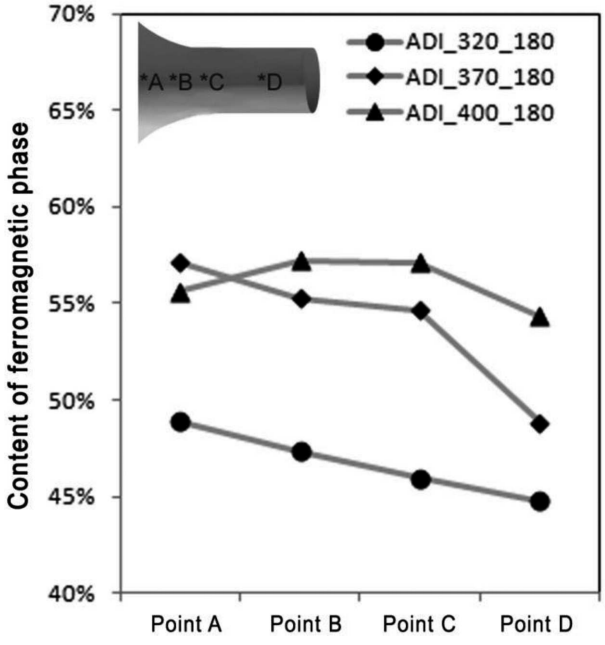


Fig. 8. The content of ferromagnetic phases in samples of ductile iron austempered at 320, 370 and 400°C for 180 minutes deformed at high impact velocities

Certain material-related features are reflected in a difference in the content of ferromagnetic phases in the sample microstructure at points A and D, i.e. those with the largest and smallest deformation. Figure 9 presents a graph showing that the largest increase in ferromagnetic phases has occurred in samples austempered at 370°C. In other cases, with longer duration of the treatment, the growth in the content of ferromagnetic phases has either been constant (samples ADI_320_x) or decreased (samples ADI_400_x).

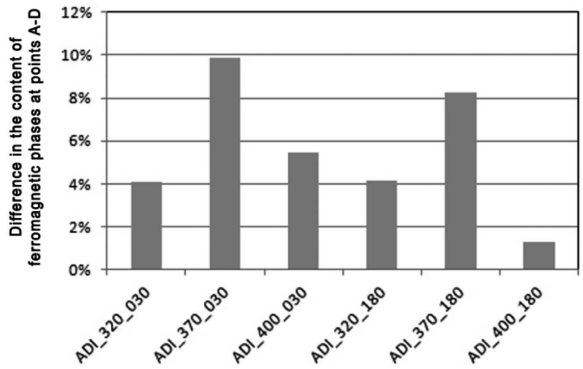


Fig. 9. Increase in the content of ferromagnetic phases in zone of the largest deformation in samples deformed at low impact velocities

Table 7 shows the group of samples deformed at high velocities of striking the target. This table also contains collective results of the macroscopic evaluation and distribution of hardness values in samples from the front face of each of the deformed surfaces. The increase of hardness was much more pronounced in samples tested at high impact velocities than it was in the samples tested at low impact velocities. In addition to samples designated as ADI_370_030 and ADI_370_180, all other samples suffered frontal damage. No surface cracks have been found in those samples, which indicates their good resistance to dynamic deformation.

Table 8 gives collective results of microscopic examinations of the front face of each of the samples deformed at high impact velocities. Just as in the case of lower velocities, a heavy changes in the shape of the graphite-matrix boundaries in the deformed area penetrating to a depth of minimum 1 mm was observed, but only in samples undamaged frontally during the test. The same features were also observed in the destroyed sample of ADI_400_180, but it seems that the damage might be caused by something else and not by the centred stroke in a non-deformable plate. Samples destroyed during the test showed in the microstructure the presence of undeformed graphite precipitates.

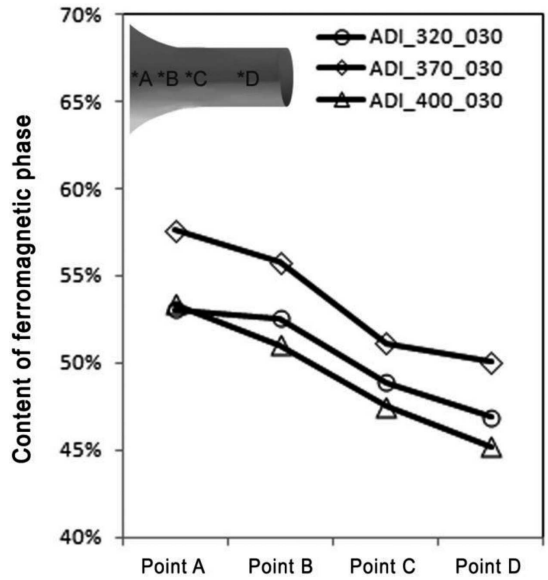


Fig. 10. The content of ferromagnetic phases in samples of ductile iron austempered at 320, 370 and 400°C for 30 minutes deformed at high impact velocities

The content of ferromagnetic phases in samples deformed at high impact velocities was determined at the four characteristic points designated as A, B, C and D (Figs. 10 and 11). For most samples, with exception of the one designated as ADI_320_180, the content of ferromagnetic phases was increasing in the direction towards the front face of the deformed sample. However, evidently higher content of ferromagnetic phases was observed in samples austempered for 180 minutes at 370 and 400°C.

TABLE 7

Material testing results for samples deformed in the group of high impact velocities V=224/249 [m/s]

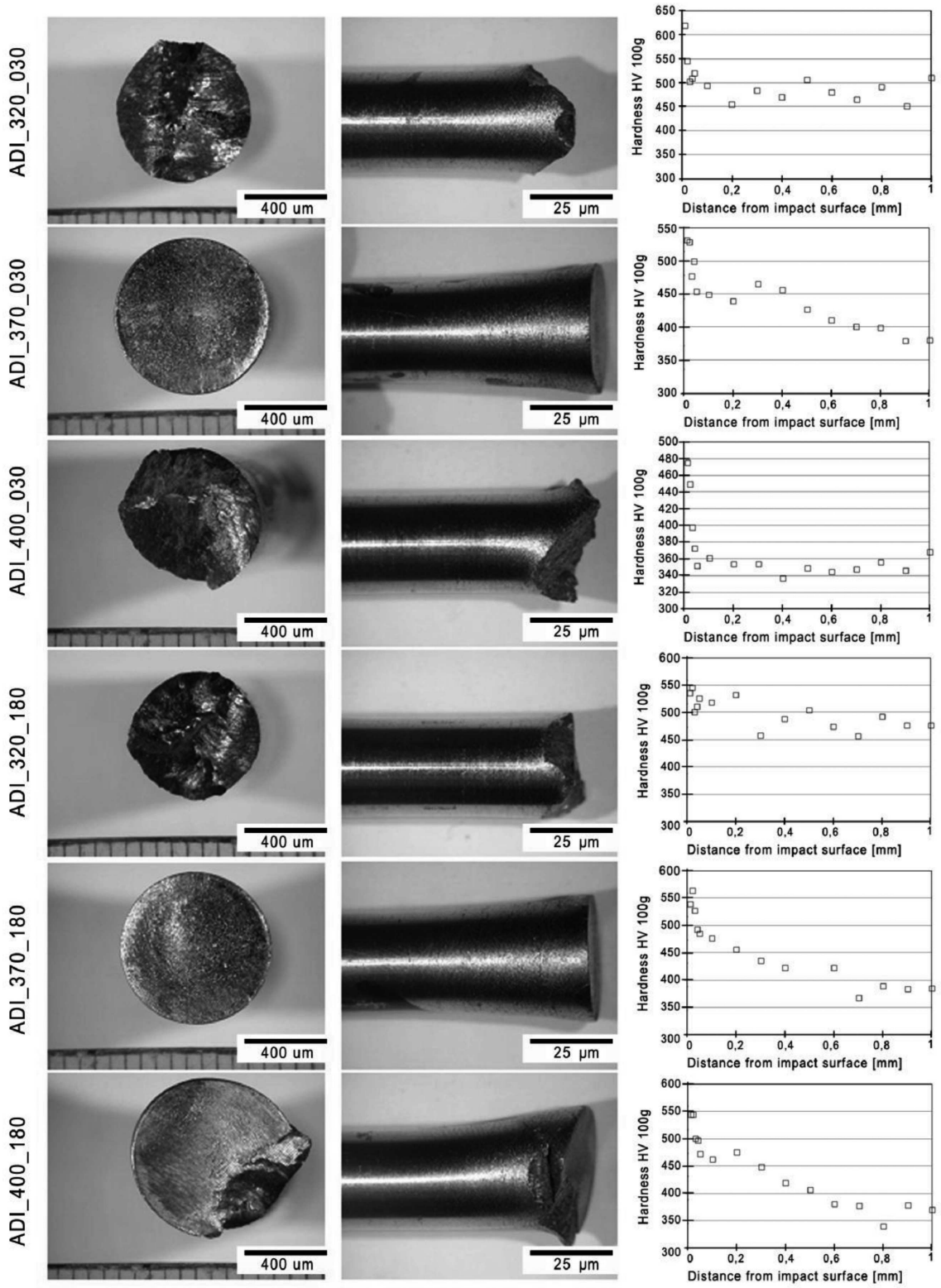
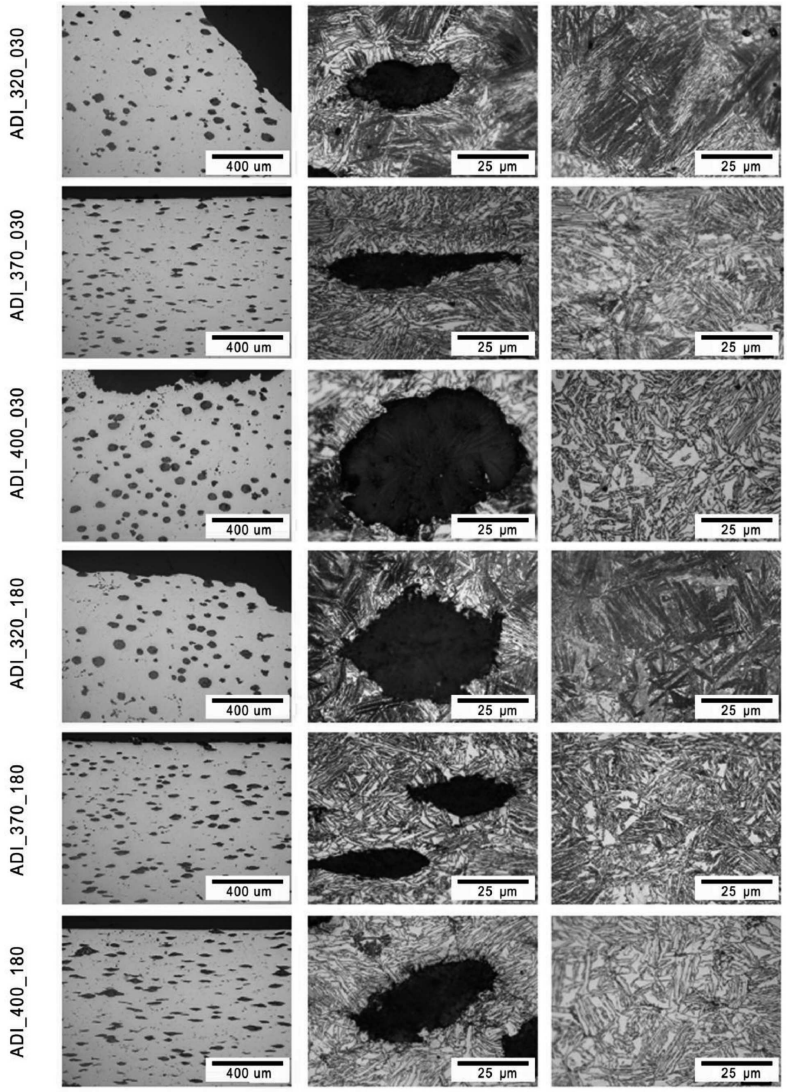


TABLE 8

The results of microscopic examinations of samples deformed in the group of high impact velocities V=224/249 [m/s]



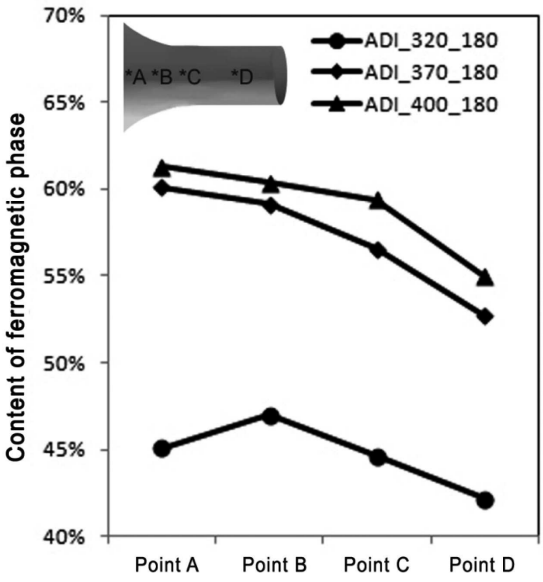


Fig. 11. The content of ferromagnetic phases in samples of ductile iron austempered at 320, 370 and 400°C for 180 minutes deformed at high impact velocities

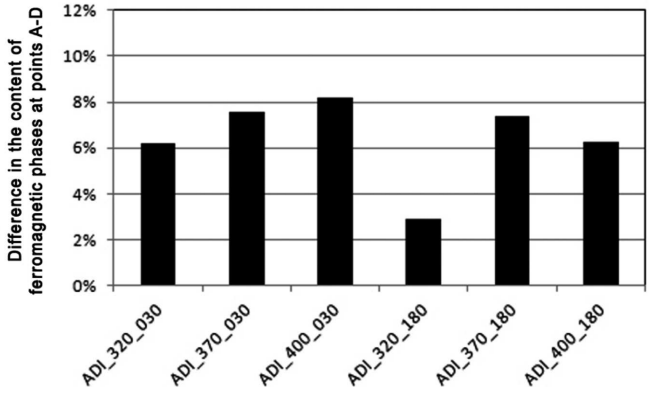


Fig. 12. Increase in the content of ferromagnetic phases in zone of the largest deformation in samples deformed at high impact velocities

The difference in the content of ferromagnetic phases at points A and D, i.e. those with the largest and smallest deformation (Fig. 12), shows that in all cases there is an obvious increase in the content of these phases as a result of deformation. Yet, in the case of austempering at 370°C, the duration of this treatment had virtually no impact on the increasing

content of ferromagnetic phases, while in all other cases, prolongation of the treatment time from 30 to 180 minutes gave less pronounced increase of ferromagnetic phases in the ductile iron microstructure.

5. Summary

This article deals with the problem of dynamic deformation in ductile iron samples. Cylindrical samples, distorted on the front face in Taylor test, show a high degree of work hardening, comparable to steel subjected to the same strain [17]. Calculations show that the observed high rate of hardening is not specific to one type of ductile iron. It is also difficult to determine if it is higher at the lower or higher impact velocities. The highest rate of hardening was observed in the ductile iron austempered at 370°C for 30 minutes, but it would be difficult to talk about the differences between this and other types of the ductile iron tested. All of the samples were surface-hardened; an obvious increase in hardness reaching 500HV was observed in the layer of 100 μm. The content of ferromagnetic phases also increases, as evidenced by a comparison of the sample portion deformed and undeformed, thus indicating the presence of a hard phase, i.e. martensite. The evaluation of the magnetic properties has proved that martensite appearing in the ductile iron matrix was due to the deformation and was a product of the strain-induced austenite transformation [18,19]. Taylor test allowed comparing different types of austempered ductile iron operating under the conditions of dynamic deformation. All of the tested types of ductile iron were hardened as a result of striking against the non-deformable "anvil". It was found that the mechanism of this hardening was in part only due to the cold work; its main cause was the strain-induced austenite-to-martensite transformation.

REFERENCES

[1] M. Grądzka, Numerical analysis of deformation of the cylindrical sample in a crash Taylor test, Postępy Nauki i Techniki **7**, 186-194 (2011).

[2] J. Janiszewski, J. Gacek, M. Burdek, J. Stępień, The study of dynamic properties of materials used for bodies, Works of Institute for Ferrous Metallurgy **1**, 118-123 (2010).

[3] G.I. Taylor, The use of flat-ended projectiles for determining dynamic yield stress I: theoretical considerations. Proc. Roy. Soc. London Series A, **194**, 289-300 (1948).

[4] R.F. Recht, Taylor ballistic impact modelling applied to deformation and mass loss determinations. Int. J. Engng Sci. **16**, 809-827 (1978).

[5] J.W. House, J.C. Lewis, P.P. Gillis, L.L. Wilson, Estimation of flow stress under high rate plastic deformation. Int. J. Impact Eng. **16**, 2, 189-200 (1995).

[6] J. Rżysko, The measurement of the yield stress dynamic loads, Work of the Department of Applied Mechanics, Zeszyt 2. Wyd. Kat. Mech. Tech. PW, Warszawa 1965.

[7] L. Cybula, The influence of strain rate on the characteristics of the material elements of the projectile – plate. Lab. Script, Warsaw University of Technology.

[8] D. Myszka, I. Pokorska, G. Mońka, The strengthening of the surface layer of austempered ductile iron castings subjected to shot peening, Inżynieria Materiałowa **4**(182), 616-619 (2011).

[9] J. Jeleńkowski, Shaping Fe-26Ni-2Ti steel structure of the using martensitic transformation, Oficyna Wydawnicza PW, Warszawa 2005.

[10] D. Myszka, Austenite-martensite trasformation in austempered ductile iron, Archives of Metallurgy and Materials **52**, 475-480 (2007).

[11] J.L. Garin, R.L. Mannheim, Strain-induced martensite In ADI alloys, Journal of Materials Processing Technology **143-144**, 347-351 (2003).

[12] M. Nili Ahmadabadi, Bainitic transformation in austempered ductile iron with reference to untransformed austenite volume phenomenon, Metall. Mater. Trans. A **28**, 10, 2159-2162 (1997).

[13] PN-EN 1564: 2012

[14] www.ductlie.org

[15] E. Guzik, Processing refinement of cast iron – selected issues, Archives of Foundry Engineering, Katowice 2001.

[16] D. Myszka, M. Kaczorowski, J. Tybulczuk, Ausferritic Ductile Iron – Direct Austempering, Wyd. Instytutu Odlewnictwa, Kraków 2003.

[17] D. Myszka, T. Cybula, The comparison of the microstructure and the mechanic characteristics of austempered ductile cast iron and steel subject to dynamic deformation in Taylor test, Transactions Of Foundry Research Institute, Kraków 2013.

[18] D. Myszka, A. Wieczorek, An assessment of the applicability of austempered ductile iron containing Mo and Ni for mining machines parts, Archives of Metallurgy and Materials **58**, 3, 967-970 (2013).

[19] D. Dziedzic, K. Muszka, J. Majta, Strain-induced austenitic structure in microalloyed steel, Archives of Metallurgy and Materials **58**, 3, 745-750 (2013).

Received: 20 March 2014.