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Microstructural Analysis of Austempered Ductile Iron Castings

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ABSTRACT

Austempered ductile iron (ADI) castings have a wide range of application areas in engineering designs due to their promising mechanical properties and lower cost. ADI has very good strength and toughness values at the same time its ductility is relatively high compared to most of the other cast irons. These promising mechanical properties originate from combination of specific graphite and matrix microstructure. The size, shape and fraction of graphite as well as the matrix microstructure influences the mechanical properties. In this paper the efforts regarding to a localization project of ADI is presented. In a more detailed manner, the first locally produced ADI which cannot satisfy the mechanical properties stated in ISO 17804 is compared with the original sample which is conform with the standard. The two pieces are inspected by mechanically and microstructurally by means of which necessary actions are detected for the local production. In other words the relation between the macro mechanical properties and the microstructural conditions are tried to be clarified.

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Key Words:
Austempered Ductile Iron; Mechanical properties; Microstructure; Graphite; Nodularity.

INTRODUCTION

Austempered ductile iron (ADI) is a specific type of spheroidal graphite cast iron (SGCI) grade which has attractive mechanical properties such as high tensile, fatigue strength, toughness and relatively good ductility. The grey cast iron, which is a widely-used engineering material, can have maximum 400 MPa ultimate tensile strength (UTS) values due to flake type of graphite. The flakes promote notch-effect and reduce ductility as well [1]. However if the graphite shape can be changed to a spheroidal or nodular form with some special casting techniques the UTS may reach to 800 MPa [2]. Further improvement of mechanical properties is possible by applying heat treatments, such as austempering, that change the matrix microstructure. The excellent mechanical properties of ADI, in particular the favorable combination of high tensile strength, wear resistance and ductility, predestine this material to act as a substitute for forged or case-hardened materials and Ductile Iron (DI) [2].

ADI also offers some technical advantages on engineering components such as, being weightless and damping vibrations. According to these facts, the usage of ADI, in especially automotive, earth moving machines and defense system industries has been developed in recent years. The important components in automotive which can be replaced with ADI are crank shaft, connecting rod, cam shaft, timing gear set, piston, suspension, etc. There are several automobile components, where ADI has been recommended for replacement of forged components [2-7].

The chemical composition of ADI is similar to that of conventional nodular or ductile cast iron. However, some alloying elements such as nickel, molybdenum, and copper are usually added to increase its heat treatability [8], i.e. to delay the onset of the decomposition of austenite into pearlite, and allowing room for austempering.

Proper heat treatment will avoid the formation of unwanted microstructural constituents such as pearlite, martensite, or carbide [9].

The microstructure and properties of ductile iron castings have been subject of intense research since its discovery in 1948 [10], including the size, shape and distribution of graphite particles [11] as well as the fraction and morphology of matrix phases [12], including retained austenite [13]. The matrices of those materials are controlled via heat treatments [14]. The effect of ADI microstructure on fatigue strength [15], rolling contact fatigue resistance [16], machinability [17], wear resistance [18], toughness [19] and fracture toughness [20] have been studied. However, the combined effect of both nodularity and matrix phase composition has not been fully exploited. Moreover, most of the referred studies rely on laboratory scale productions. In the present study, all the tests were conducted on industrial scale productions, including local productions.

The present study aims at performing quantitative metallographic analysis on ADI samples from 2 different lots showing different tensile behavior. The graphite nodularity and matrix phase composition of the samples were determined via optical and scanning electron microscopes as well as X-ray diffraction; and then those results were correlated to the mechanical behavior obtained from simple tension and hardness tests. After understanding the correlation between microstructure and mechanical properties, the newly produced lots of ADI components satisfy the requirements.

PRODUCTION STEPS OF ADI

The basic production steps of ADI are austenizing, austempering and final quench to room temperature. The production process involves a first austenizing as cast sample in the temperature range of 871–982 ˚C for sufficient time to get a fully austenite (γ) matrix and then quenching it to an intermediate temperature range of 260–400 °C. The casting is maintained at this temperature for 1–4 h [21]. The microstructure of ADI depends on austempering temperatures and times. Because of this reason, a wide range of mechanical properties can be obtained. Especially by determining a specific process window for the whole heat treatment operation the appropriate combination of high yield strength (YS) and high toughness could be provided [22].

An exemplar time temperature transformation diagram (TTT curve) and heat treatment process of ADI are illustrated in Figure 1.

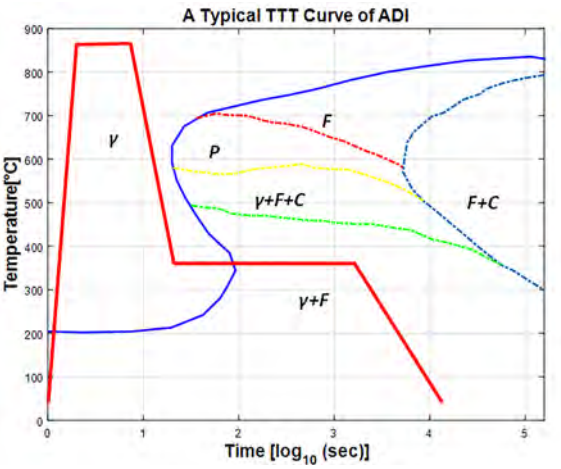

Figure 1. Schematic representation of TTT and a typical heat treatment cycle of ADI (adapted from [23])

MICRO STRUCTURAL CHARACTERIZATION STUDIES

In this study, two ADI samples exhibiting different mechanical properties were subjected to metallographic examination. As discussed, the mechanical properties of ADI are affected by the matrix composition and the characteristics of nodular graphites. The characteristics of graphite size, shape and distribution were investigated by quantitative analysis of optical micrographs taken with Nikon Eclipse LV 150 optical microscope using bright field illumination. The matrix microstructure was examined via Zeiss Evo LS 15 scanning electron microscope. For metallographic specimen preparation, firstly, the specimens were sectioned via Struers Secotom-10 precision cut-off machine and by electrical discharge machining (EDM) technique. Afterwards the specimens were subjected to 4 step grinding (240-400-600-1000 grit) with SiC papers and 3 step polishing (9μ-3μ-1μ) with diamond paste. The optical micrographs were taken from the as-polished state of specimens to understand the quantify shape clearly. Afterwards the specimens were etched with picral (4 gr. Picric acid and 100 mL ethanol) solution. Nodularity analysis was performed on at least 10 micrographs per specimen using imageJ and Clemex Vision software solutions. The results of the characterization studies of two specimens are shown in Figure 2-6. It should be noted that the original sample has conform mechanical properties (YS: 700 MPa, UTS: 1000 MPa, Total Elongation: %6) with respect to ISO 17804 whereas the locally produced one did not satisfy the requirements [24].

The nodularity analyses are preformed according to ASTM E2567 where [25]:

Table.1: Comparison of Nodularity Analysis of Two ADI Samples.

	Locally produced sample	*Original Sample*
Area Fraction of Graphite Particles	*8.72 %*	*7.39 %*
Area Fraction of Nodular Graphite Particles	*7.51 %*	*6.55 %*
% Nodularity by area	*86.13 %*	*89.72 %*
% Nodularity by number	*58.56 %*	*78.47 %*

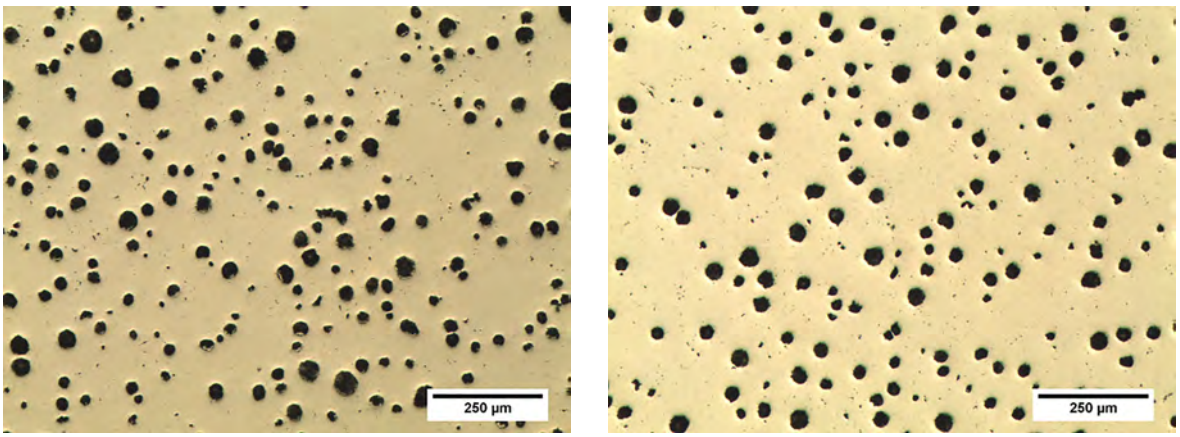

Figure 2. .a) Optical micrograph of as-polished locally produced ADI sample (x50), b) Optical micrograph of as-polished original ADI sample (x50)

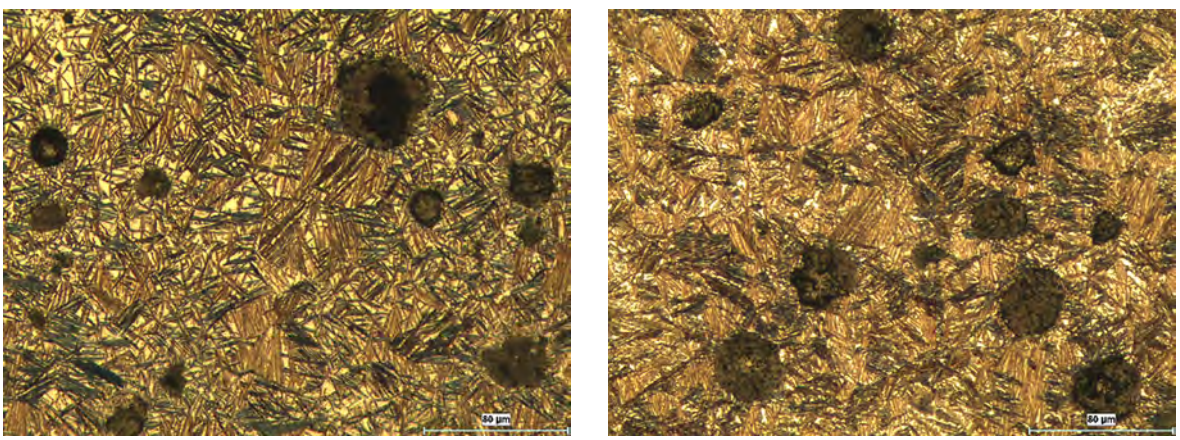

Figure 3. .a) Optical micrograph of etched locally produced sample (x200) (x50), b) Optical micrograph of etched original sample (x200)

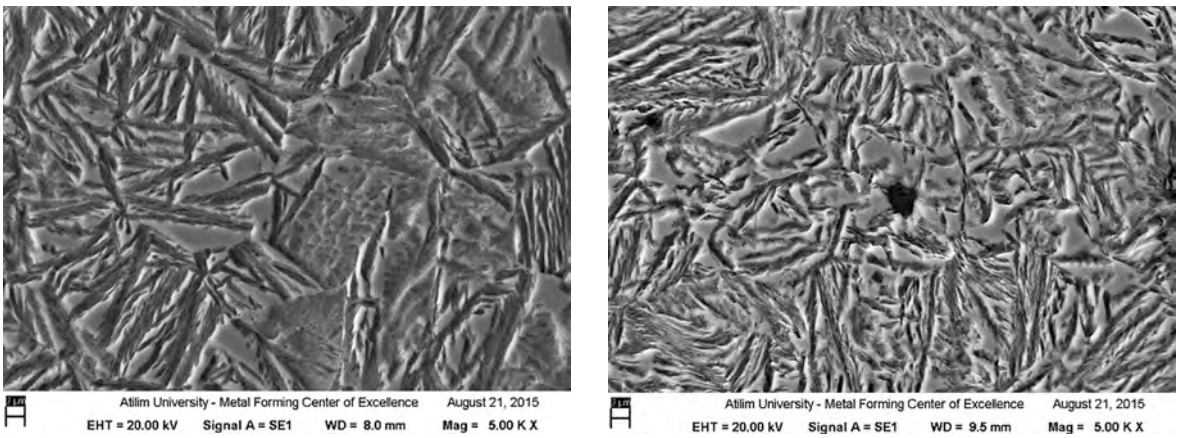

Figure 4. .a) SEM micrograph of etched locally produced sample, showing its matrix (x5000), b) SEM micrograph of etched original sample showing its matrix (x5000)

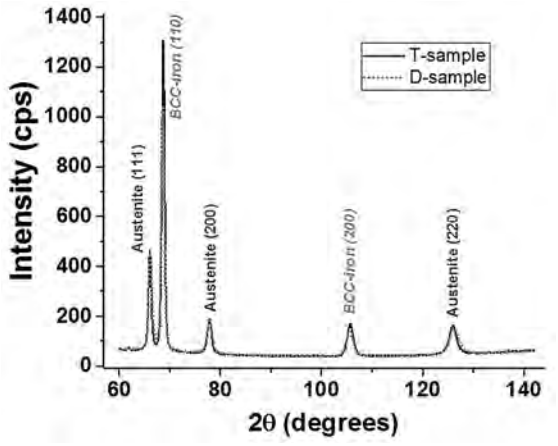

Figure 5. .XRD spectra of locally produced (D) and original (T) samples shown comparatively. The peaks for austenite and BCC-iron phases used for quantification of phase fraction is also shown.

Area of reference circle = π * (Max. Feret Diameter)^2/4

Shape Factor = Area of Graphite Particle / Area of Reference Particle

By the definition of ASTM E2567, the graphite particles whose shape factor are equal or greater than 0.60 is accepted as nodular. The others are treated as just graphite particle graphite unless their max. Particles having a ferret diameter lower than 10 mm are excluded from the analysis. Therefore the percentage nodularities are calculated as follows:

%Nodularity by area=100*(Area of Nodular Graphite Particles)/ Area of All Graphite Particles)

%Nodularity by number=100*(Quantity of Nodular Graphite Particles) / Quantity of All Graphite Particles)

The comparison of the two samples are illustrated in Table.1

The SEM micrographs in Figure 4 show different microstructures, indicating different matrix phase composition. In order to quantify the matrix phase compositions the amount of retained austenite in two samples were determined via X-Ray Diffraction analysis (XRD). XRD-analyses were performed with a GE-Seifert XRD 3003 PTS system, using Cr-K_α radiation. During the measurements χ-axis were oscillated and the Φ-axis were rotated in order to reduce the effects of crystallographic texture on results. The diffraction data was evaluated by the AutoQuan software. XRD analyses were illustrated in Figure 5. For each specimen an average hardness value was determined by measuring Vickers hardness at 10 different locations with Zwick / Roell ZHV 10 instrument using a load of 19.61 N applied at a speed of 25 mm/s.

The quantification of the XRD spectra shown in Figure 5 revealed phase fractions. It should be mentioned that, the BCC-iron peaks in the XRD spectra are mainly coming from martensite, bainite and presumably from ferrite phase or phase mixtures. It has been found that the original sample has 29.5 vol. % (+1.7;-1,4) retained austenite in comparison to the locally produced sample whose retained austenite content is %34,9 (+3.4;-2.5), as shown in Figure 6. The austenite content was calculated using the ratio of the integrated intensities of the corresponding peaks in Figure 6 and calculated R-values, in accordance with the ASTM-E975 standard [26]. The matrix hardness values are also shown and tabulated in Figure 6.

RESULTS and DISCUSSIONS

- It is observed that the quantity and the area based nodularity values of original sample is higher than locally produced one.
- When shape factor distribution is investigated it is stated that the original sample has a more stable (more likely to Gaussian normal distribution)

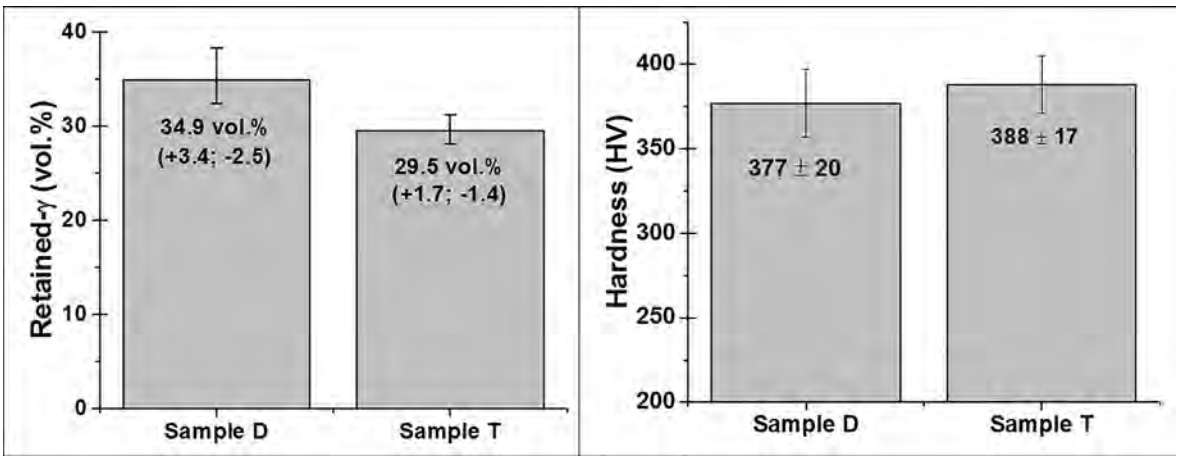

Figure 6. .Comparison of retained austenite volume fraction (vol. %) and the matrix hardness values (HV) of the locally produced (D) and original (T) samples.

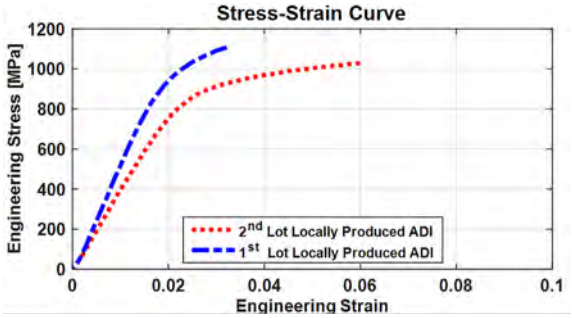

Figure 7. .Tensile test results of the First and Second Lots

dispersion compared to locally produced one.

- Both samples have relatively high nodularity values according to ASTM E 2567. It is concluded that the difference between the nodularity values is not sufficiently large to create reasonable changes in final mechanical properties.
- When the matrix structure is investigated individually, it is observed that the matrix is composed of nearly hundred percent of retained austenite and bainite for original sample. On the other hand the matrix structure of locally produced sample is composed of bainite, retained austenite and martensite. The retained austenite fraction is higher and it has a coarser microstructure for the locally produced sample.
- The hardness and strength of the original sample comes from the bainitic structure. The locally produced sample has a larger fraction of softer retained austenite, thus its strength and hardness comes from the martensite. As expected, the ductility of locally produced sample is lower due to martensite.
- The bainite structure of original sample is coarser than the locally produced sample.

In this study two ADI samples which are conform and unconform according to the mechanical properties designated in ISO 17804 are investigated microstructurally. As it is observed due to the bigger retained austenite and martensite content the locally produced sample has low ductility and uniform total elongation as expected. By performing detailed investigations and corrective actions especially on the heat treatment process (austempering temperature and duration) of locally produced one, a 2nd lot production is completed. In the second trial the locally produced sample could also satisfy the required mechanical properties. The tensile test results of the first and second lot of locally produced ADI material are shown in Figure 7. The second lot of the samples hardness drops slightly to 350 ± 14. This shows that the 2nd sample has slightly softer and more ductile matrix. During deformation it can exhibit some degree of strain hardening and conform the tensile strength requirements.

CONCLUSION

The relation between microstructure and mechanical properties were studied in austempered ductile cast iron specimens. The fraction and nodularity of graphite particles were determined; the original sample has slightly better nodularity; however, the differences among the specimens were too small to explain the difference in tensile behavior. The matrix phase fractions and morphologies were determined by SEM and XRD studies. The locally produced sample has more retained austenite and martensite in its microstructure. Moreover the retained austenite and bainite structure appears coarser than the original sample. After taking measures in heat treatment process to decrease the amount of martensite and retained austenite the tensile properties of the 2nd lot of locally produced sample showed significant improvement for the uniform elongation while maintaining the required higher strength.

REFERENCES

1. ASM Handbook Volume 15: Casting, 2008, Materials Park, Ohio, USA
2. Cast Metals Development Ltd. Austempered Ductile–Iron Castings – Advantages, Production, Properties and Specifications. Materials & Design 13 5 (1992) 285–297.
3. F. Kolcke, Arft M, Lung D. Material–Related Aspects of the Machinability of Austempered Ductile Iron. Springer. 4 (2010) 433–411.
4. Putatunda S.K, Kesani S, Tackett R, Lawes G. Development of Austenite Free ADI (Austempered Ductile Cast Iron). Materials Science and Engineering A 435-436 (2006) 112-122.
5. Zimba J, Simbi D.J, Navara E. Austempered Ductile Iron: An Alternative Material for Earth Moving Components. Cement & Concrete Composites 25 (2003) 643-649.
6. Dhanasekaran S, Vadiraj A, Balachandran G, Kamaraj M. Mechanical Behaviour of an Austempered Ductile Iron. 63 5 (2010) 779–785.
7. Guo X.L, Su H.Q, WU B.Y, LIU Z.G. Characterization of Microstructural Morphology of ADI by Electron Microscopy. Microscopy Research and Technique 40 (1998) 336–340.
8. Janowak J.F., Norton P.A. A Guide To Mechanical Properties Possible By Austempering, 1.5% Ni, 0.3% Mo Iron. AFS Trans. 88 (1985) 123-135.
9. Putatunda S.K. Development of Austempered Ductile Cast Iron (ADI) With Simultaneous High Yield Strength And Fracture Toughness By A Novel Two–Step Austempering Process. Materials Science and Engineering A 315 (2001) 70-80
10. Trudel A., Gagné M., "Effect of Composition and Heat Treatment Characteristics of Austempered Ductile Irons", Canadian Metallurgical Quarterly: The Canadian Journal of Metallurgy and Materials Science 36 (1997) 289 - 298
11. ASM Speciality Handbook: Cast Irons, Edited by Joseph R. Davis, ASM International 1996, Materials Park, Ohio, USA

12. Bahmani M., Elliott R., Varahram N., "The Austempering Kinetics and Mechanical Properties of an Austempered Cu–Ni–Mo–Mn alloyed Ductile Iron", Journal of Materials Science 32 (1997) 4783 – 4791
13. Aranzabal J., Gutierrez I., Rodriguez–Ibabe J.M., Urcola J.J., "Influence of the Amount and Morphology of Retained Austenite on the Mechanical Properties of an Austempered Ductile Iron", Metallurgical and Materials Transactions A 28A (1997) 1143–1156
14. Aranzabal J., Gutierrez I., Urcola J.J, "Influence of Heat Treatments on Microstructure of Austempered Ductile Iron", Materials Science and Technology 10 (1994) 728 – 737
15. Shanmugam P., Rao P.P., Udupa K.R., Venkataraman N., "Effect of Microstructure on the Fatigue Strength of an Austempered Ductile Iron", Journal of Materials Science 29 (1994) 4933 – 4940
16. Dommarco R.C., Bastias P.C., Dall'O H.A., Hahn G.T., Rubin C.A., "Rolling Contact Fatigue (RCF) Resistance of Austempered Ductile Iron", Wear 221 (1998) 69 – 74
17. Cakir C.C., Bayram A., Işık Y., Salar B., "The Effects of Austempering Temperature and Time on the Machinability of Austempered Ductile Iron", Materials Science and Engineering A 407 (2005) 147 – 153
18. Laino S., Sikora J.A., Dommarco R.C., "Development of Wear Resistant Carbidic Austempered Ductile Iron (CADI)", Wear 265 (2008) 1 – 7
19. Eric O., Sidjanin L., Miskovic Z., Zec S., Jovanovic M.T., "Microstructure and Toughness of CuNiMo Austempered Ductile Iron", Materials Letters 58 (2004) 2707 – 2711
20. Putatunda S.K., Gadicherla P.K., "Influence of Austenitizing Temperature on Fracture Toughness of a Low Manganese Austempered Ductile Iron (ADI) with Ferritic as Cast Structure", Materials Science and Engineering A 268 (1999) 15 – 31
21. Kruthiventi S., Basavakumar K.G., Nambala S., Subramanyacharyulu G. Influence of Heat Treatment on Microstructural and Mechanical Properties of Nodular Cast Iron. Journal of the Institution of Engineers: Series D 95 (2014) 75 – 79
22. Kuş H, Akdemir A, Yazman Ş. Östemperleme Isıl İşleminin Ferritik Küresel Grafitli Dökme Demirin Aşınma Özellikleri Üzerine Etkisinin İncelenmesi. 14th International Materials Symposium, Denizli, Türkiye, October 2012
23. Keough JR, hayrynen KL, Pioszak GL. Designing with Austempered Ductile Iron. Transactions of the American Foundry Society 118 (2010) 503–517
24. ISO 17804:2005, Founding Ausferritic Spheroidal Graphite Cast Irons, Classification, ISO, Switzerland, www.iso.org
25. ASTM E2567–14, Standard Test Method for Determining Nodularity and Nodule Count in ductile Iron Using Image Analysis, ASTM International, West Conshohocken, PA, 2014, www.astm.org.
26. ASTM E975 –13, Standard Practice for X–Ray Determination of Retained Austenite in Steel with Near Random Crystallographic Orientation, ASTM International, West Conshohocken, PA, 2013, www.astm.org