Vol. **135** (2019) *ACTA PHYSICA POLONICA A* No. 4

Special Issue of the 8th International Advances in Applied Physics and Materials Science Congress (APMAS 2018)

Influence of Cu and Ni Alloying on the Microstructure and Mechanical Properties of Austempered Ductile Iron Castings

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Austempered ductile cast iron (ADI) offers a good combination of high tensile and fatigue strength, good ductility, toughness, wear resistance and damping characteristics, lower density in an economical way. This excellent combination of properties is due to the specific microstructure of ADI; which is composed of spheroidal graphite particles on an ausferritic matrix. The ausferrite consists of acicular ferrite and high carbon retained austenite; which is produced via austempering heat treatment after casting. The alloying additions of Cu or Cu + Ni increases austemperability, which means completely ausferritic structures can be produced on larger cross-sections. In the present study the effect of the alloying additions of Cu and Cu + Ni on mechanical properties and microstructure of ADI was studied. For that purpose, Y-block specimens having a lean composition, 0.8% Cu and 0.8% Cu + 0.4% Ni alloying additions were cast. After austempering treatment, mechanical tests, fractographic and metallographic examinations were performed. The results show that the Cu + Ni alloyed specimen has higher strength and elongation. The lean alloy on the other hand, has the highest nodularity and matrix hardness but the lowest strength and ductility. Those differences in mechanical properties were attributed to the fraction and morphology of the retained austenite regions of the matrix.

DOI: 10.12693/APhysPolA.135.829

PACS/topics: austempering, ductile cast iron, microstructure, mechanical properties, alloying

1. Introduction

Austempered ductile iron (ADI) is a special type of ductile cast iron produced by a heat treatment process called "austempering". By austempering process, ductile iron shows great improvement in strength, ductility, and toughness [1]. The austempering process was developed in the 30's by Bain and Davenport [2], while they were studying on the isothermal transformation of steel. Flinn [3] used this heat treatment on gray iron in the early 40's. Since, there was not sufficient knowledge and facility to produce ADI on an industrial scale, not any significant commercial production started until the mid-70's. Announcements were made in a very short period from Finland [4] that was followed by China [5] and USA [6], respectively that ductile iron castings could be austempered. The announcements of commercial production resulted in a worldwide explosion in research in terms of its strength and ductility [6–8], hardness [6–9], wear resistance [6–10], impact energy [6–11], fracture toughness [12, 13], machinability [6, 14, 15], transformation kinetics [6, 15, 16], and electrical and thermal behaviors [13], which provided a solid background for expanding the production of this material in many industrialized countries since the 90's [17].

The effect of chemical composition and austempering heat treatment parameters on microstructure and hence mechanical properties have been subject of intense research. Shelton and Bonner [12] have worked on the effect of Cu addition on the mechanical properties of ADI. Padan [18] and Peng et. al [19], both have made a similar study showing the effects of Ni, V, Nb and Mo additions. Mattar et al. [7], showed individual effects of Cu, Ni and Mo alloying additions on austemperability of ADI. Zimba et al. [10], and Kim et al. [20], have studied the effect of austempering temperature. Sharma and Gupta [21], changed the austempering temperature and time together, to improve the wear resistance of ADI.

The mechanical properties of ADI, on the other hand, depend also on nodularity and nodule count, which has not been exploited in full detail in those referred studies. The present study aims at closing this gap by studying the combined effect of both nodularity and ausferritic matrix on mechanical properties. For that purpose 3 different alloys having different amounts of Cu and Ni alloying elements were cast, austempered, mechanically tested and finally a metallographic examination was conducted. The Cu and Ni are frequently added in order to improve the austemperability of the alloys. Therefore, the present study will also help to understand the influence of Cu and Ni alloying on microstructure and hence the mechanical properties of ADI.

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2. Experimental procedure

The material used in this study was first cast as Y-blocks, having 3 different chemical compositions: (i) lean alloy composed of carbon, silicon and manganese only; (ii) lean alloy + Cu; (iii) lean alloy + Cu + Ni. From each Y-block at least 3 cylindrical specimens having 6 mm diameter were machined. Those specimens were then austenitized between 850–950 °C for 60–90 minutes until a homogenous austenitic matrix was obtained. Austenitizing process was followed by austempering between 250–400 °C for 90–180 minutes, and then tension tests were performed. Both the heat treatment processes and tensile tests were repeated 3 times to ensure repeatability using DSI-Gleeble 3800 thermomechanical simulator. The same austenitizing and austempering temperatures and durations were used for all specimens.

The fracture surface of one tension specimen from each alloy were examined under Zeiss EVO scanning electron microscope. Afterwards, one specimen from each alloy was prepared for metallographic examination. For nodularity analysis, 30 images from each as-polished specimen were taken at 50× magnification via Nikon Eclipse LV 150 optical microscope, under bright field illumination in order to differentiate graphite particles. The nodularity, nodule count and nodule size of graphite particles were determined in accordance with the ASTM E2567 [22] by using Clemex Vision-Pro image analysis software. Before EBSD analysis, a final polishing with 0.05 mm colloidal silica particles was performed on the specimens. EBSD analysis was done using Zeiss Merlin field emission gun (FEG) scanning electron microscope (SEM), equipped with EDAX/TSL EBSD system with Hikari camera. The average hardness of the matrix of the specimens was determined by taking 10 Vickers micro-hardness measurements from randomly selected regions of the as-polished surfaces of the specimens. For this purpose Zwick/Roell ZHV 10 micro-hardness tester was used with a load of 19.61 N at a test speed of 25 mm/min. Lastly, the polished surfaces of the specimens were etched by picral solution and then the matrix phases were analyzed under optical and scanning electron microscopes.

3. Results and discussion

The results of nodularity analysis are shown in Fig. 1 and listed in Table I. Results indicate that lean alloy has the largest and Cu + Ni added ADI has the smallest nodular graphite particles by size. On the other hand each alloy has almost the same nodularity; and all of the sample nodularity values are higher than 83%. The lean alloy has the lowest elongation, tensile and yield strength; whereas it has the highest nodularity. This indicates that for the smaller differences in nodularity values do not correlate with the mechanical properties. The fraction and morphology of matrix phases have a more pronounced effect on mechanical properties.

SEM images of lean alloy reveals martensite regions in the matrix along with retained austenite and ausferrite, as shown in Fig. 2a. Although each alloy contains martensite, the lean alloy has the highest fraction and coarser regions of martensite. Moreover, Table I shows that, the lean alloys has the highest hardness but lowest ductility. The strength of the lean alloy is mainly coming from the presence of coarser martensitic regions. Martensite has higher strength and hardness whereas it lowers ductility significantly.

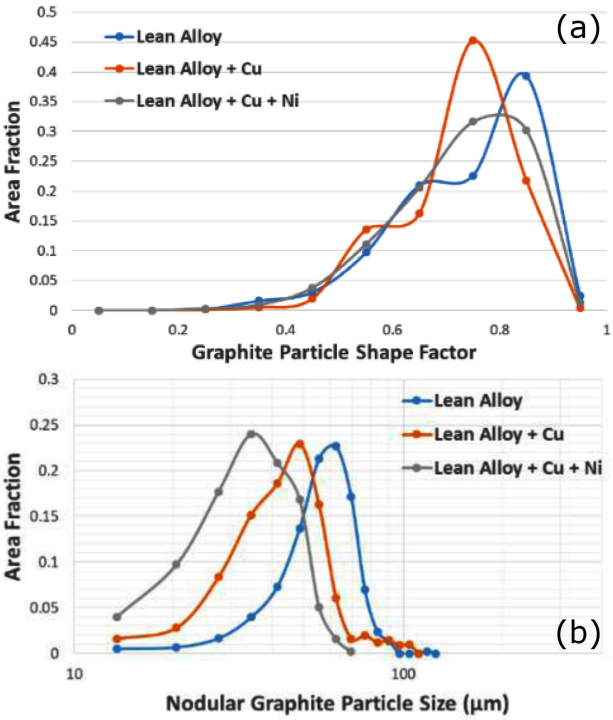

Fig. 1. (a) Graphite particle shape factor and (b) nodular graphite particle size distributions.

TABLE I

Nodularity, matrix hardness, mechanical properties and retained austenite of the alloys studied

	Nodularity by area [%]	Nodular graphite particle size [μm]	Vickers hardness [HV0.2]	Yield strength [MPa]	UTS [MPa]	Total elongation [%]	Ret-γ volume fraction [%]
lean alloy	89.27	47.5	462 ± 83	713 ± 14	1004.0 ± 28.1	4.2 ± 0.8	41.1
lean + Cu	86.36	35.1	458 ± 82	868.7 ± 23.0	1158.0 ± 4.3	9.0 ± 2.2	32.5
lean + Cu + Ni	83.74	27.9	437 ± 93	893.4 ± 8.0	1182.0 ± 14.7	10.5 ± 0.01	20.5

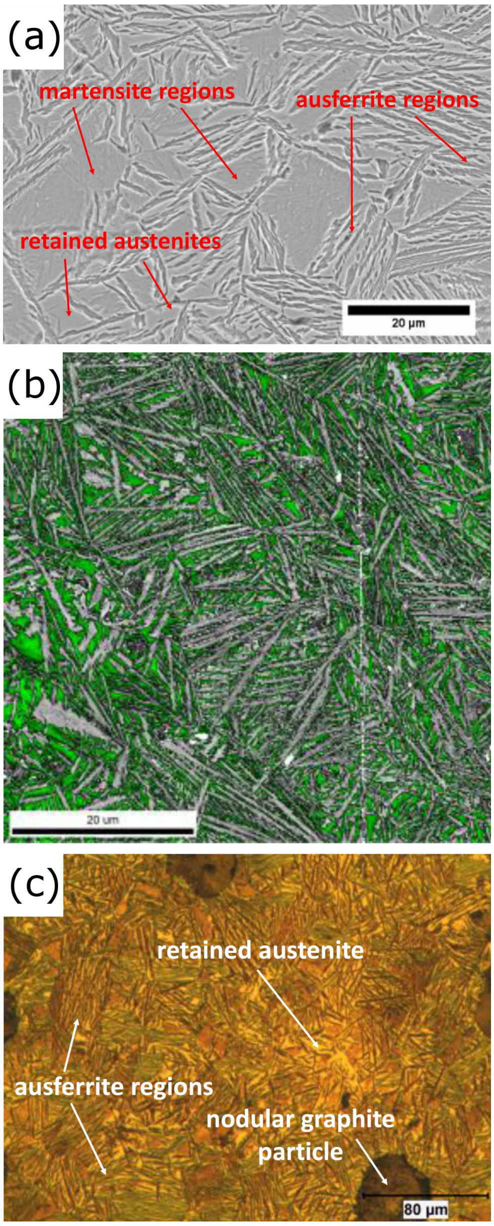

Fig. 2. (a) SEM secondary electron image taken at 5000×, (b) EBSD pattern quality and austenite (green) map, (c) optical microscope image of the lean alloy taken at 200×.

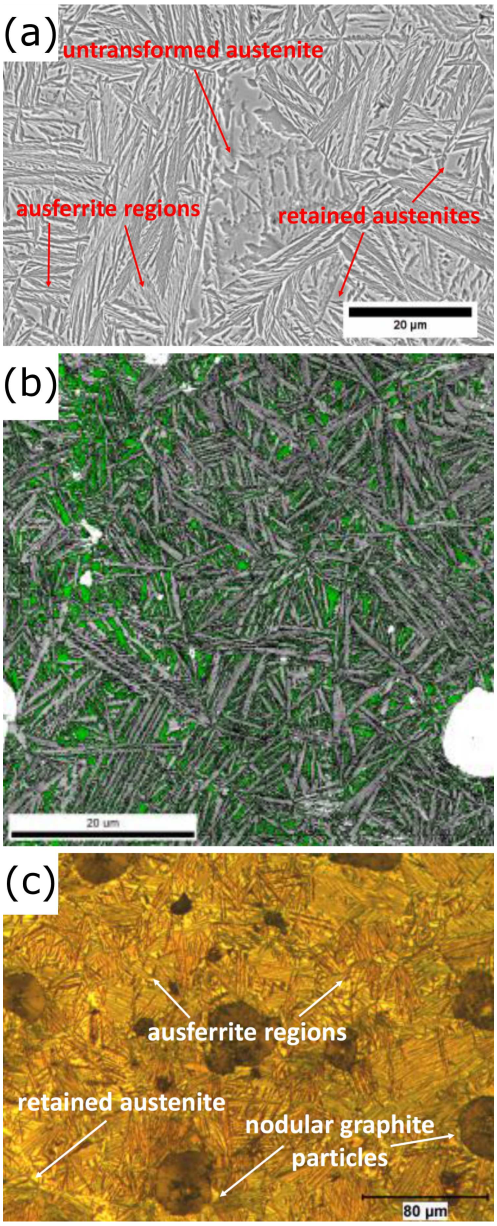

Fig. 3. (a) SEM secondary electron image taken at 5000×, (b) EBSD pattern quality and austenite (green) map, (c) optical microscope image taken at 200× of the alloy “lean + Cu”.

EBSD technique was employed to resolve carbon enriched austenite regions of the matrix of the specimens. Figs. 2b, 3b and 4b represent the EBSD pattern quality maps, and the overlaid green regions on those maps show the retained austenite regions. Figures indicate that both ausferrite and retained austenite become finer increasing alloying elements. Alloys with finer matrix phases exhibit higher elongation, tensile and yield strength. For the present studies alloys the differences in mechanical properties are mainly due to differences in fraction and morphology of the matrix phases.

The retained austenite volume fraction decreases with alloying as shown in Table I. This behavior can be attributed to 2 main reasons. One of those reasons is the ausferrite transformation kinetics. The second reason can be the transformation induced plasticity (TRIP) effect; which causes transformation of metastable retained austenite to martensite during tension testing. Further analyses are needed to fully understand those cases.

The fracture surfaces of the specimens are shown in Fig. 5, which reveals that all specimens have both brittle and ductile fracture zones indicating a mixed mode of fracture. The presence of martensite, specifically in the lean alloy promotes brittle fracture; whereas specimens with finer ausferrite matrix exhibit more ductile

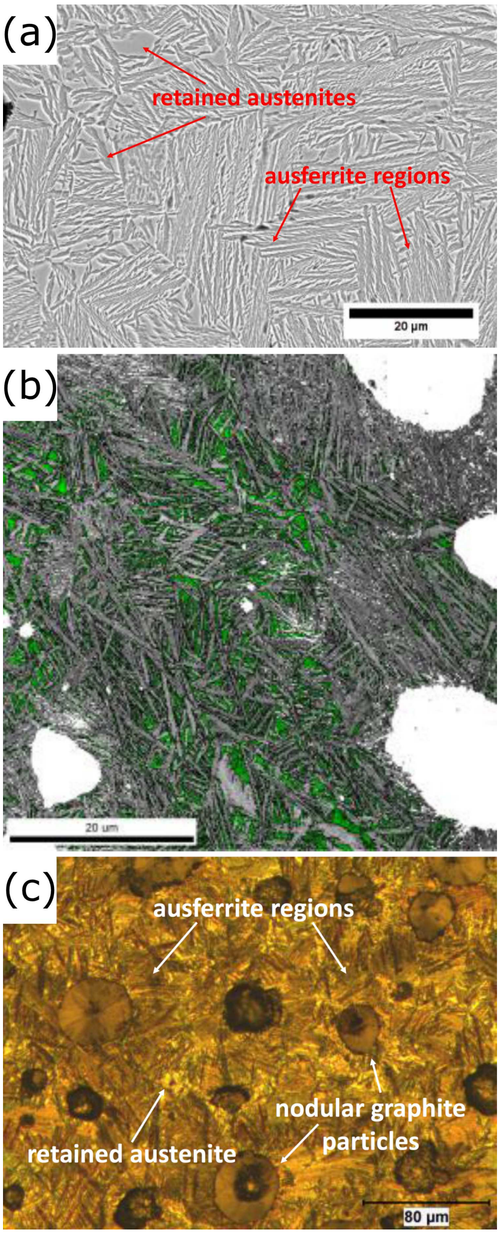

Fig. 4. (a) SEM secondary electron image taken at 5000×, (b) EBSD pattern quality and austenite (green) map, (c) optical microscope image taken at 200× of the alloy "lean + Cu + Ni".

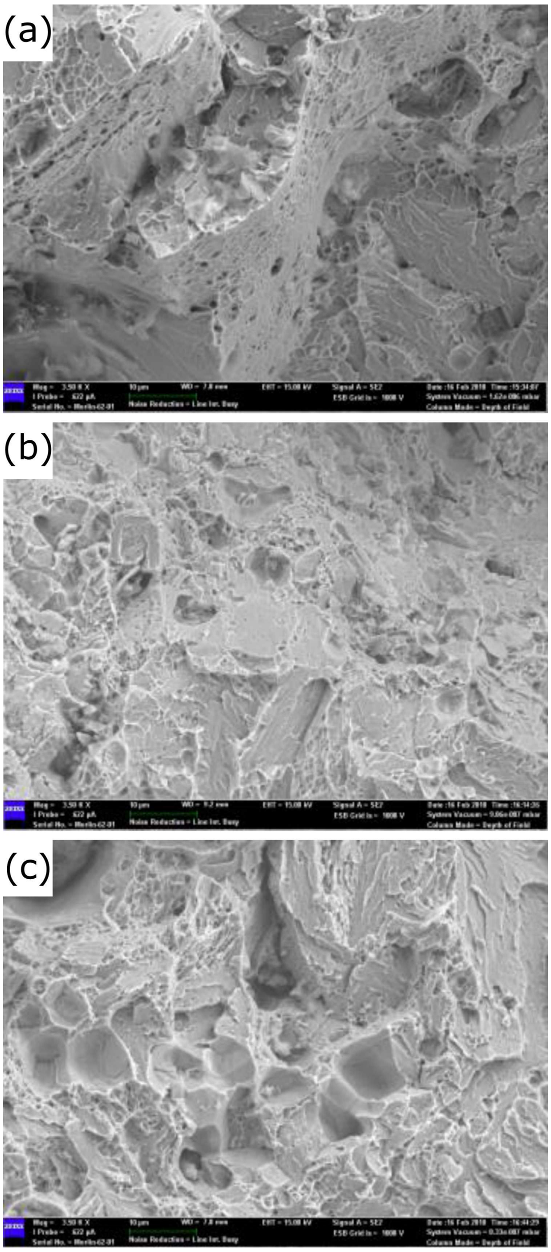

Fig. 5. Fractographs of the tension test specimens; (a) lean alloy, (b) lean alloy + Cu, (c) lean alloy + Cu + Ni.

behavior. The results of this fractograhic examination agree well with the ductility (percent elongation) values listed in Table I.

It should be noted that the results of the present study are identical, if not better than the previously reported results of similar ADI alloys. Eric et al. (2004) [23] and Shelton et al. [12] studied on alloys identical to "Lean + Cu + Ni alloy" presented in this study. Shelton et al. [12] reported 650–780 MPa UTS values. In the present study those strength levels are reached with a cheaper, virtually un-alloyed "Lean alloy". The present "Lean + Cu + Ni" alloy has higher strength and ductility compared to Shelton et al. [12]. On the other hand, Eric et al. [23] study reported higher yield and tensile strength, whereas much lower ductility. Similarly, Swain et al. [24] work indicates UTS and YS values nearly the same as present "Lean + Cu + Ni" alloy but the present alloy has almost 3 times higher ductility. The present "lean + Cu" alloy has lower alloying but also exhibits better strength compared to Chinella et al. [25] study at identical ductility levels. The enhanced ductility of present alloys can be attributed to the higher retained austenite fraction, which is 10 to 15 times higher than the previously mentioned studies.

4. Conclusions

The influence of Cu and Ni alloying on the microstructure and mechanical properties of ADI has been studied. The graphite nodularity of all 3 samples is almost the same. Beyond 83%, increasing nodularity does not influence the overall mechanical properties. On the other hand, increasing alloying additions make graphite particles smaller.

For the present case, the morphology and fraction of matrix phases have a more pronounced effect on mechanical properties. Alloying additions refine the ausferrite matrix and the retained austenite grains, which in turn increases strength and ductility at the same time. The matrix hardness of the specimens does not correlate well with the strength and ductility. Specifically for the lean alloy, the higher hardness is due to the presence of coarser martensitic regions, which also decreases ductility significantly. The samples with higher alloying additions contain less retained austenite after tensile testing. Moreover; those samples exhibit higher uniform elongations, which can be attributed to the TRIP effect.

The present strength and ductility values are identical, if not better than the results of similar alloys in literature. In addition, Cu and Cu + Ni alloyed samples conform the mechanical requirements of ISO-17804 grade JS-1050-6.

The present study shows the relative importance of graphite nodularity, morphology and fraction of matrix phases for improving mechanical properties. Those findings could also be used to develop newer grades and also further improve the existing grades of ductile iron castings.

Acknowledgments

The financial support of the Managerial Board of FNSS Defense Systems Co. Inc. is gratefully acknowledged. The authors also thank the Metal Forming Center of Excellence in Atilim University for their help with the characterization studies and with Gleeble Thermo-Physical simulations. Lastly, Akpınar Foundry Co. in Ankara is specifically acknowledged for casting of trial Y-blocks.

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