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Effect of Copper Addition on Microstructure and Mechanical Properties of Ductile Cast Iron

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Abstract

This work aims to investigate the influence of Cu addition on the microstructure and mechanical properties of ductile cast iron (DCI). A step-like mold was used to study the evolved microstructures at different cooling rates. It was observed that adding Cu to DCI increased the pearlite content and refined significantly the lamellar structure. This effect was more pronounced at the thicker sections (slower cooling rates). Tensile strength improved obviously with the increase in pearlite content from 550 MPa at 27 % pearlite (0.02 wt.% Cu) to 875 MPa at 83 % pearlite (2.47 wt.% Cu). However, the elongation decreased from 19 to 5 % upon increasing Cu content from 0.02 to 2.47 wt.% at 20 mm thickness. The impact toughness was affected negatively by Cu addition, where the value of toughness decreased from 65 J at 0.02 wt.% Cu to ~17 J at 2.47 wt.% Cu at 20 mm.

Keywords: Ductile iron, Copper, microstructure, tensile strength, Impact toughness.

1. Introduction

Ductile cast iron (DCI) is an excellent engineering material that combines cost and superior characteristics. DCI has good castability, high toughness, and high strength. [1,2]. The wide use of DCI includes components of construction machinery and automobiles such as crankshafts, camshafts, and steering knuckles. DCI can replace steels in many applications; however, its strength-to-impact toughness ratio is lower. The impact toughness of cast irons depends on the matrix microstructure [2,3]. If the percentage of pearlite is increased to enhance the strength, the impact fracture energy is decreased. On the other hand, to achieve high-impact energy, a ferritic matrix with 80 % nodularity is favoured. Several research works [1.2] aimed at resolving this problem. Though the assumption of combining high strength and high toughness has been challenging, the recent types of DCI made it possible. The recent grades of high-toughness iron have been introduced, where nickel, manganese, tin, etc. were added to improve the strength/toughness ratio.

Copper was also suggested as an alloying additive to enhance the mechanical properties of DCI [4, 5]. Cu is a pearlite promoter and stabilizer and is present in ~2.5 mass % for ductile cast irons. It has been reported that Cu is soluble up to 1.9 mass % in the Fe-Cu system. Therefore, the addition of Cu can increase the perlite content and hence improve strength. However, the influence of Cu on the mechanical properties of DCI is not well covered. In the current investigation, Cu was added to ductile cast iron in different percentages to study in detail its effect on the microstructure and hence the mechanical properties of as-cast DCI. Since the cooling rate plays a crucial role in the microstructure control, casting was done using a step-like mold hence the influence of Cu was observed at different cooling rates. The evolved microstructures at different conditions were investigated. Tensile properties and impact toughness were tested at 20 mm thickness and the results were compared for the different Cu percentages.

2. Experimental work

In the current investigation, a wooden step-like pattern with 5-, 10-, 20- and 30-mm section thickness was prepared. The molds were sodium silicate-bonded sand and the melting was done in an induction furnace. Pure copper was added to the charge materials (sorel metal, steel scrap, Fe–Si alloy, and carburizer) in different amounts to obtain ductile irons with different Cu contents. Pouring was done at 1520°C. Based on Cu addition (up to ~2.5 wt.%), four groups of ductile cast irons were produced. The chemical analysis of the samples was carried out using a spectrometer and is presented in Table 1. Mg treatment to obtain nodular graphite was performed using the sandwich method. In this method, Fe-Si-Mg is inserted at the bottom of the ladle and the molten iron is poured onto it.

Specimens for metallographic observation were cut from each section of the produced step-like cast. The samples were then ground with 120–1200 paper, polished, and finally etched with a solution of 2 vol.-% Nital. The optical micrographs were used to observe the changes in the constituting phases with the addition of Cu at different section thicknesses. A Scanning Electron Microscope (SEM) combined with EDX was used for characterization. Samples for tensile testing and impact toughness were cut from 20 mm section according to ASTM E8 and ASTM-E23 respectively.

Table 1 Chemical compositions of ductile cast iron containing different copper

No.	Chemical Composition, %							
	C	Si	Mn	S	P	Mg	Cu	Fe
1	3.57	2.73	0.315	0.015	0.037	0.054	0.022	Bal.
2	3.52	2.66	0.309	0.013	0.036	0.051	1.49	-
3	3.51	2.65	0.310	0.011	0.035	0.053	2.25	-
4	3.50	2.74	0.310	0.015	0.035	0.052	2.47	-

3. Results and Discussion

3.1 Microstructure investigation

Optical micrographs of Figs. 1 to 4 show the influence of section thickness (cooling rate) and Cu addition on the microstructure details of the cast ductile iron samples. As known, decreasing the cooling rate by pouring in thicker sections lowers the amount of pearlite, increases ferrite content and decreases the nodule count (No. of nodules/mm^2). The amount of pearlite decreased from ~ 45% at 5 mm to 23 % at 30 mm thickness.

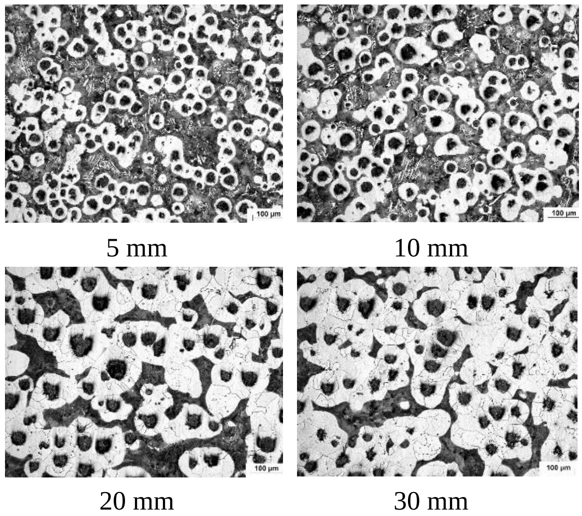

Fig. 1 Microstructure of 0.02 wt.% group.

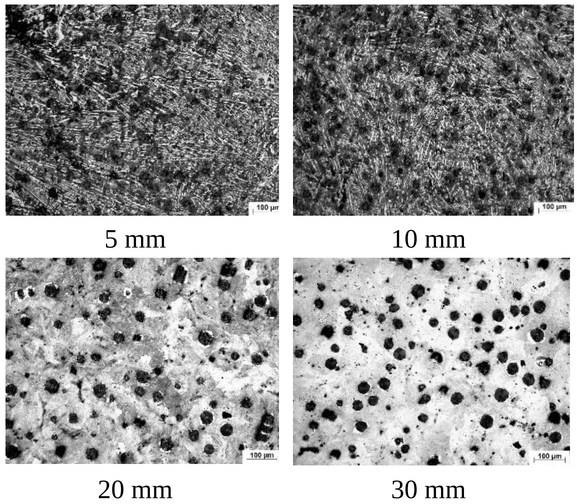

Fig. 2 Microstructure of 1.5 wt.% group.

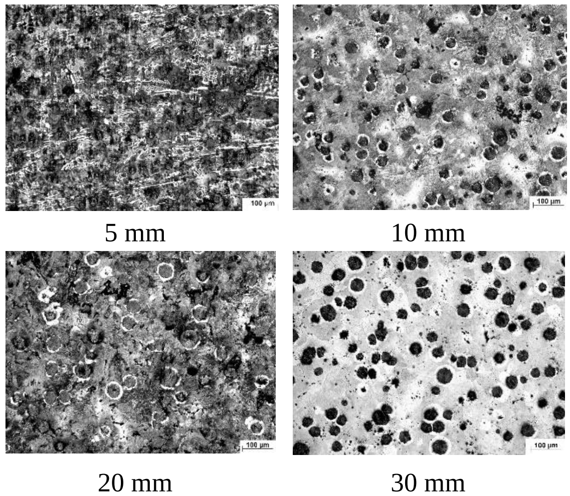

Fig. 3 Microstructure of 2.25 wt.% group.

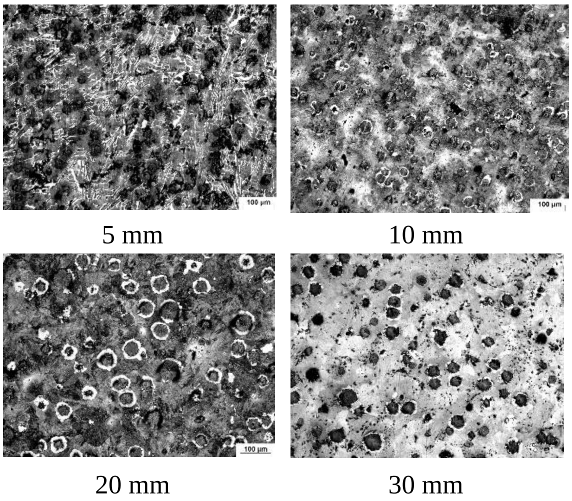

Fig. 4 Microstructure of 2.47 wt.% group.

Table 2 Pearlite % of the different cast samples.

Thick., mm	Cu, wt.%	Pearlite %
5	0.022	44.8
	1.49	79.1
	2.25	80.3
	2.47	81
10	0.022	45
	1.49	74.2
	2.25	81.5
	2.47	82.4
20	0.022	27.3
	1.49	82
	2.25	82.5
	2.47	83.4
30	0.022	23.5
	1.49	83.3
	2.25	80.6
	2.47	84.1

Concerning the effect of Cu, at the same section thickness, it is obvious from Table 2 that increasing the amount of Cu promoted pearlite formation and hence increased pearlite content. The effect was more significant in the thicker sections where pearlite % increased from ~ 23 to 84 upon increasing Cu content from ~0.02 to 2.47 wt.%. This agrees with the reported data [6] about the role of Cu as pearlite former and stabilizer. By adding copper to ductile iron, carbon diffusion increased in austenite, and as a result, more pearlite can be formed compared to ferrite [7]. Moreover, Cu has been reported to refine the shape of pearlite, which can be observed in Fig. 6. These changes in the pearlite content and refinement due to Cu addition are expected to influence the mechanical properties of the investigated samples. Figure 7 shows element mapping and line scan of Cu in 2.47 wt.% Cu sample. It was observed that the Cu-rich regions were embedded in a pearlite matrix.

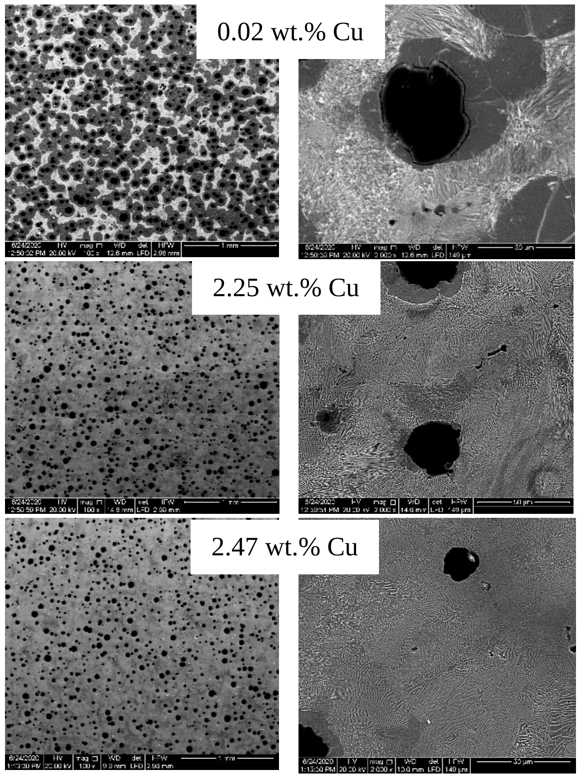

Fig. 5 SEM micrographs at different wt.% of Cu.

3.2 Mechanical Properties

Figure 8 shows the tensile properties of the samples with different Cu content (at 20 mm thickness). The contribution of the Cu to the strength of ductile iron increases with increasing wt.% Cu. This is by the microstructure changes with Cu addition, where the percentage of pearlite increased significantly with 1.49 wt.%Cu from ~ 27 to 83% at 20 mm thickness, Table 2. Also, it is well known that the addition of copper leads to solid solution strengthening [7] and prevents crack growth in low levels of applied stress [8]. Therefore, Cu addition improves ultimate tensile strength, yield strength, and hardness [9].

Figure 9 presents the impact toughness of Cu alloyed DCI. The increase in pearlite content with addition of Cu which was considered as a positive effect in terms of strength, negatively affected the impact toughness. This is due to the significant decrease in the ferrite phase which plays a crucial role in enhancing the toughness of DCI [10].

Based on the obtained results, future work is needed to investigate the same samples in the heat-treated condition.

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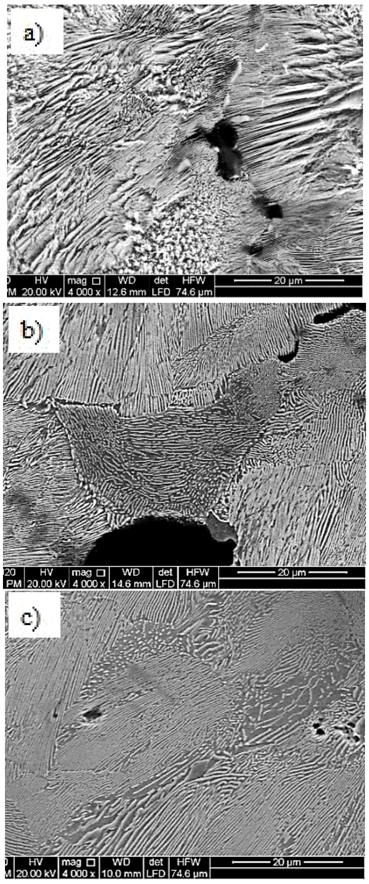

Fig. 6 Magnified SEM micrographs emphasizing pearlite phase at a) 0.02, b) 2.25 and c) 2.47 wt.% Cu.

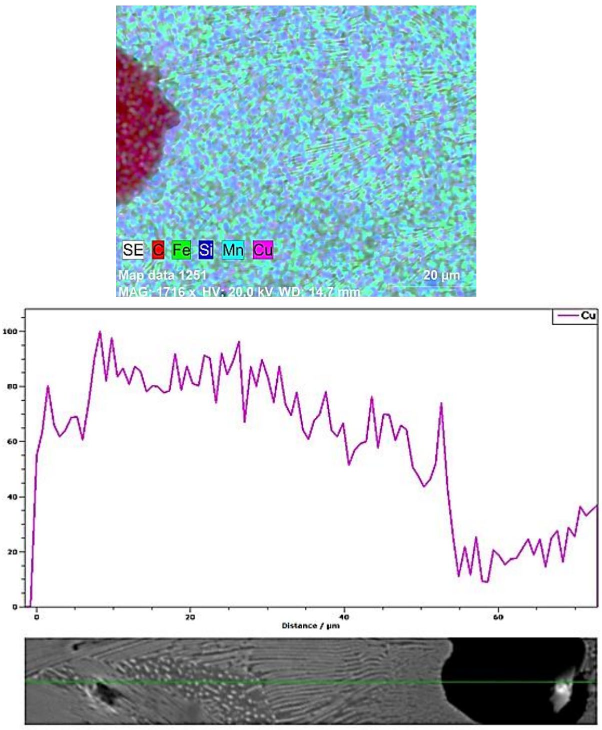

Fig. 7 EDX complex map and line scan of Cu along the constituting phases in 2.47 wt.% Cu sample.

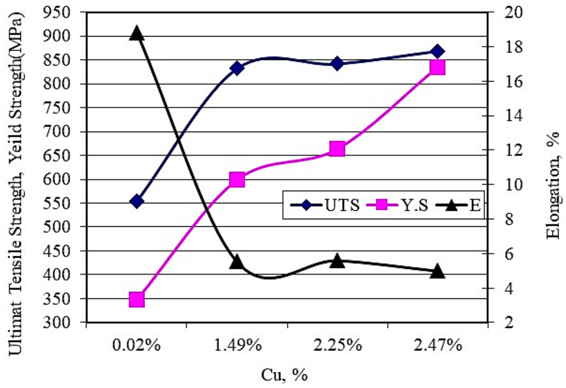

Fig. 8 Tensile properties of the different samples.

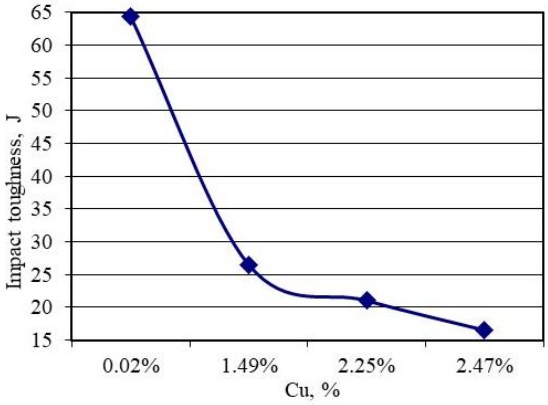

Fig. 9 Impact toughness of the different samples.

4. Conclusions

In the current research, the influence of Cu addition to the microstructure and mechanical properties of ductile cast iron was investigated and the following conclusions were driven:

1. Adding Cu to DCI increased the pearlite content and refined significantly the lamellar structure. This effect was more pronounced at the thicker sections (slower cooling rates).
2. Tensile strength improved obviously with the increase in pearlite content from 550 MPa at 27 % pearlite (0.02 wt.% Cu) to 875 MPa at 83 % pearlite (2.47 wt.% Cu). However, the elongation decreased from 19 to 5 % upon increasing Cu content from 0.02 to 2.47 wt.% at 20 mm thickness.
3. The impact toughness was affected negatively by Cu addition, where the value of toughness decreased from 65 J at 0.02 wt.% Cu to ~17 J at 2.47 wt.% Cu at 20 mm.

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