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Characterization of microstructural and mechanical properties of high-pressure die-cast en ac 46000 alloy

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The present research focuses on the characterization of microstructural and mechanical properties of real castings produced by HPDC using EN AC 46000 alloy. The Cu content of the alloy was varied inside the limits prescribed by the standard for EN AC 46000 alloy to investigate the influence of Cu on the material performance and to provide results useful for industrial applications. Castings with Cu content of 2 wt.% and 4 wt.% were industrially produced using a 2500-ton HPDC machine. Two areas of the casting with different cooling rates were selected to obtain samples for microstructural and mechanical characterization. In particular, area fraction, number density and equivalent diameter of intermetallic compounds were investigated, and the size distribution of these particles were statistically evaluated. Finally, hardness measurements and tensile tests were performed and the results were correlated to microstructural features and solidification conditions to deeply understand the alloy behavior.

KEYWORDS: HIGH PRESSURE DIE CASTING, MICROSTRUCTURE, INTERMETALLICS, TENSILE PROPERTIES

INTRODUCTION

Al-Si-Cu alloys are widely used for high-pressure die-casting (HPDC) processes. In particular, AlSi9Cu3 alloy (EN AC 46000) is frequently applied for the production of various components by HPDC, especially for the automotive industry. In fact, nowadays it offers many advantages, such as high productivity rate, low cost, possibility to obtain castings with complex shapes, thin walls and smooth surfaces, while the fast solidification ensures good microstructural properties. Nevertheless, the formation of porosities is a typical problem, which is emphasized in HPDC by the rapid filling able to create turbulences in the liquid metal flow. Another critical aspect from the microstructural point of view is the presence of high amounts of intermetallic particles containing Fe [1]. On the other hand, Fe has also beneficial effects in die-casting since it plays the important role of reducing the phenomenon of die soldering of the casting [2]. Several researchers deeply investigated the effect of Fe, Mn and Cr on intermetallics morphology and formation [3], while few studies examined the effect of Cu on the properties of a die-casting alloy [4,5]. In fact, the effect of Cu addition to casting alloys has mainly been studied for primary Al alloys with low Fe content [6,7] where Cu is ad-

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ded to improve mechanical properties (especially for high temperature applications [8]),applied in other processes, as such as gravity or low pressure die casting.
Regarding the effect of Cu to a secondary AlSi9Cu3 die casting alloy, Fabrizi et al. [4] observed a high porosity level for the alloy with the highest Cu content, which is expected to be detrimental for material performance, as discussed also by other researchers [9]. Instead, Outmani at el. [5] found that, despite the high porosity, the alloy with the highest Cu content (approximately 3 wt.%) showed enhanced tensile strength. Similar effect of Cu was documented also by Lumley et al. [10]. It has to be mentioned that in these studies several parameters were changed, as the content of other alloying elements, injection temperature and pressure [5,10] and therefore it is difficult to clearly identify the role of Cu. For these reasons, it is believed that further studies on this topic are necessary to exploit the alloy performance from both a scientific and industrial point of view. Therefore, the present research focuses on the commercial alloy EN AC 46000, whose Cu content was modified inside the range prescribed by the alloy standard (i.e. from 2 up to 4 wt.%). Furthermore, samples were taken from an actual casting of significant size and not from castings obtained at laboratory scale, as usually described in scientific literature [4,9,11] to make this study as close as possible to the industrial field. The aim is to quantify the influence of Cu content on microstructural features (especially intermetallic phases and porosity level) and mechanical properties.

EXPERIMENTAL PROCEDURE

The present study was carried out on castings obtained by HPDC process with EN AC 46000 alloy (often indicated as AlSi9CuFe alloy). Five castings with the minimum (i.e. approximately 2 wt. %) and maximum Cu content (i.e. approximately 4 wt. %) allowed for EN AC 46000 alloy were produced. The chemical composition of the final castings is shown in Table 1, as obtained from measurements by optical emission spectrometer.

Tab.1 - Mean chemical composition of the final castings.

Alloy	Si	Cu	Fe	Mn	Mg	Cr	Ni	Zn	Pb	Al
Cu2	8.025	2.097	1.097	0.296	0.125	0.094	0.095	0.918	0.058	Bal.
Cu4	8.298	4.104	1.033	0.231	0.149	0.095	0.111	1.031	0.089	Bal.

The sludge factor was calculated for both the alloys [12], as well as the critical temperature for sludge formation [12]. In addition, the area fraction of sludge that can form in the holding furnace was evaluated [13]. Samples for microstructural and mechanical characterization were taken from two different positions in the casting (indicated in Fig. 1) in order to evaluate different cooling conditions for each alloy. In particular, the position A is located near the gate and corresponds to the warmer zone (i.e. which solidifies more slowly), while the position B is located opposite to the gate and corresponds to the coldest zone (i.e. which solidifies faster).

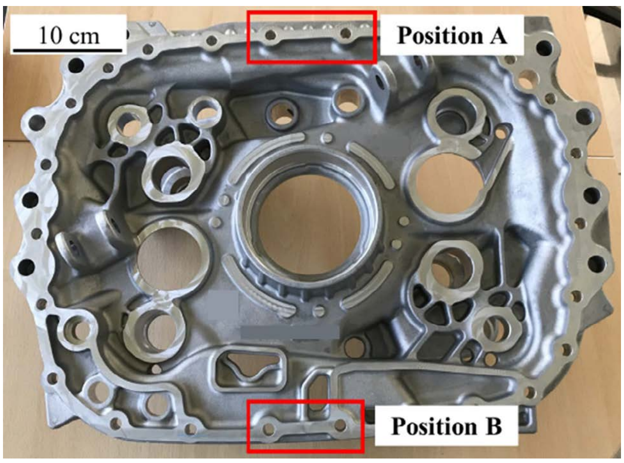

Fig.1 - Picture of the casting used for the present study with indication of the analyzed areas.

The microstructure of samples was observed by means of an optical microscope Leica DMI 5000 M, equipped with LAS image analyzer, on mirror polished samples. Average secondary dendrite arm spacing (SDAS) was calculated for each sample, according to the linear intercept method. Furthermore, porosity level was calculated by digital image analysis on a total area of 15 mm^2 for each sample.

The main phases and intermetallic compounds present in the samples were characterized by means of a scanning electron microscope (SEM), LEO EVO 40 equipped with an Energy Dispersive Spectroscopy (EDS) probe for elemental analysis. Digital image analysis was carried out on twenty SEM images (backscattering mode) for each alloy for both the positions considered in order to evaluate the area fraction, equivalent diameter, and number density (number of particles per unit of area) of intermetallic particles. Results in terms of equivalent diameter of these particles were further statistically evaluated by means of JMP® software.

Finally, tensile specimens were machined to final shape according to UNI EN ISO 6892-1 standard (sample diameter of 4 mm and gauge length of 20 mm). Tensile tests were carried out with a Galdabini Quasar testing machine at room temperature. The elongation was measured using a knife-edge extensometer fixed to the gauge length of the specimens. The crosshead speed was set at 3 mm/min in the elastic field and at 9 mm/min in the plastic one. Three samples were tested for each condition and average and standard deviation were calculated for ultimate tensile strength (UTS), yield strength (YS) and elongation (El. %) values extrapolated from strain-stress curves. Based on tensile tests results, the Quality Index, frequently used in foundry, was calculated as indicated by Drouzy et al. [14].

RESULTS

First, the sludge factor was calculated for both the alloys and values in the range 1.8-2 were found. In addition, the temperature of the holding furnace (675 °C) was slightly below the critical temperature for sludge formation (687 °C for Cu2 alloy, 682 °C for Cu4 alloy), suggesting the likely formation of primary intermetallic particles in the furnace. This is consistent with the calculation of sludge area fraction in the casting, which is estimated to be approximately 1%. This represents a limited area fraction of primary intermetallic particles, which nevertheless has to be considered to thoroughly understand material performance. Finally, according to the charts reported by various authors [12,15], no sedimentation of sludge in holding furnace is expected.

Regarding microstructural properties, the SDAS values in position A are slightly higher than in position B for both the alloy compositions (Table 2). It follows that in the former case the solidification rate is lower than in the latter and, easily leading to different mechanical properties. In addition, in Table 2, porosity level is indicated as measured from digital image analysis. Interestingly, it was found that the average porosity of sample Cu4-A is only slightly higher than Cu2-A, despite the higher Cu content. On the other hand, Cu4-B samples is characterized by the highest porosity level (above 1 %), suggesting that in this case the formation of eutectic intermetallic phases due actually hindered liquid feeding leading to significant microporosity formation. The faster solidification, due to the colder zone, combined with the higher distance from the gate, hindered the effect of pressure in compensating shrinkage and filling the interdendritic regions, giving rise to high porosity.

Tab.2 - Average values of SDAS and porosity for the studied samples.

Sample	Cu2-A	Cu2-B	Cu4-A	Cu4-B
SDAS (μm)	19 ± 2	13 ± 3	20 ± 1	16 ± 1
Porosity (%)	0.55 ± 0.10	0.20 ± 0.05	0.65 ± 0.20	1.25 ± 0.30

For each sample, various intermetallic particles were also identified and analyzed using SEM-EDS (Fig. 2).

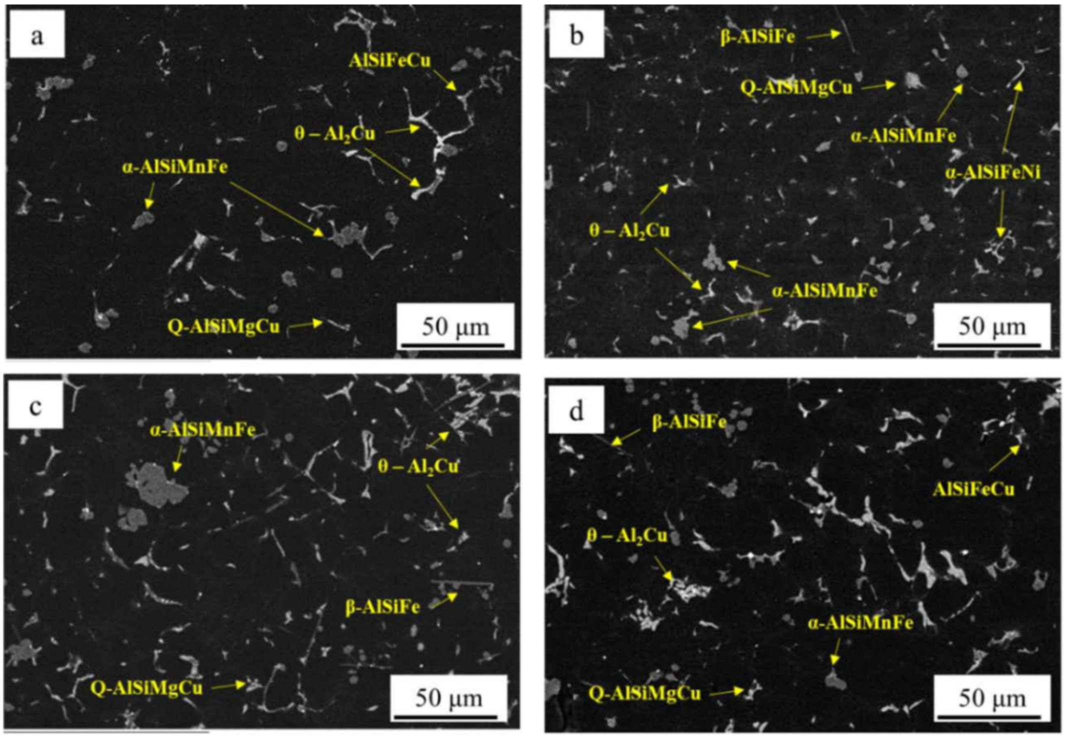

Fig.2 -SEM images and intermetallics identification for a) Cu2-A, b) Cu2-B, c) Cu4-A and d) Cu4-B samples.

Results from digital image analysis shown in Table 3, in terms of area fraction and number density of intermetallic particles, supported the evaluation of the presence of intermetallic particles.

Tab.3 - Analysis of intermetallic particles in the studied samples.

Sample	Cu2-A	Cu2-B	Cu4-A	Cu4-B
Area fraction (%)	4.1	4.6	8.2	6.0
Particles density (particles/mm^2)	$2.8 \cdot 10^3$	$2.9 \cdot 10^3$	$4.9 \cdot 10^3$	$3.5 \cdot 10^3$

For Cu2 alloy, the different cooling conditions between position A and B do not significantly affect the total amount of intermetallic particles since area fraction and particles density are comparable. On the other hand, the increase in Cu content leads to a higher area fraction of intermetallics than for alloy Cu2, especially in position A where the area fraction is the double in comparison with samples Cu2-A. Interestingly, for sample Cu4-B the area fraction of intermetallic particle is reduced. This can be ascribed to the different cooling conditions of the analyzed samples. In position A, based on SDAS measurements, it is expected to have a lower solidification rate, and this allows intermetallic particles to grow, resulting in the observed high area fraction. Further evaluation of the size of intermetallic particles was carried out in terms of equivalent diameter of the particles. In this regard, it is reported that that the size of intermetallic particles follows a two-parameters lognormal distribution [16]. This was verified also in the present study, as shown in Fig. 3, where the lognormal probability density function was used to fit experimental data of equivalent diameter obtained by digital image analysis. The shape parameter μ and the scale parameter σ, estimated from lognormal distribution are also indicated.

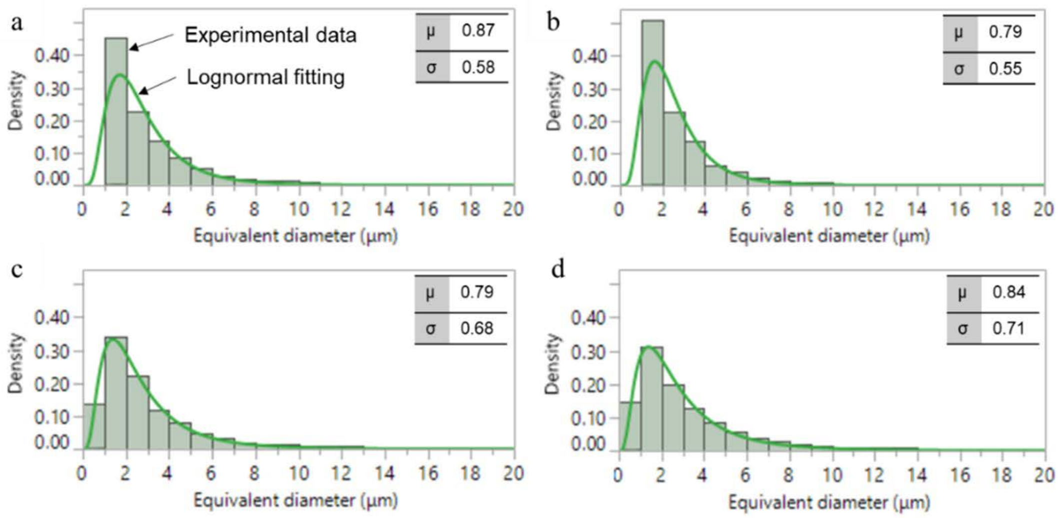

Fig.3 - Experimental data and relative lognormal fitting for intermetallic particles in the studied samples as a function of equivalent diameter: a) Cu2-A, b) Cu2-B, c) Cu4-A and d) Cu4-B samples.

It can be observed that particles size distribution is quite similar for all the investigated conditions and that most particles have an equivalent diameter below 6 μm. According to [17], these can correspond to proeutectic intermetallic particles, as opposed to primary sludge particles, which are characterized by bigger size. This is not surprising since the studied alloys are characterized by a limited sludge factor (SF = 1.8-2). This is also consistent with the limited expected sludge area fraction (approximately 1 %, as above-mentioned), while the total area fraction of intermetallic particles ranges from 4 to 8% in the investigated samples (Tab. 3).

Tensile properties of the studied alloy are shown in Fig. 4.

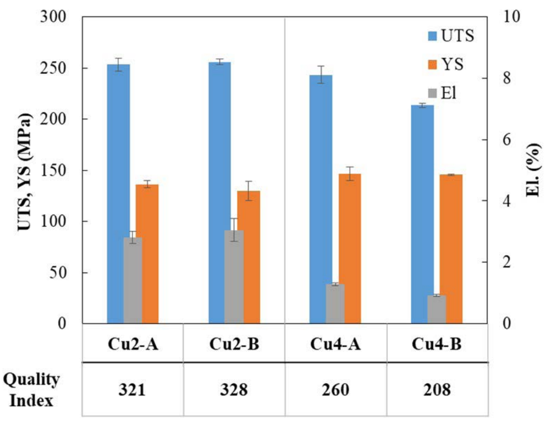

Fig.4 - Tensile properties of studied samples.

Samples with low Cu content exhibit quite similar values of tensile strength. This is consistent with the similar content of intermetallic particles, while the minimum amount of porosity for sample Cu2-B may be responsible for its slightly higher elongation. When Cu4 alloy is considered, it appears that ductility is significantly reduced and that also UTS is decreased, even if not so strongly. On the other hand, an increase in YS can be appreciated. The loss in UTS and elongation for Cu4-A sample can be explained considering that this sample is characterized by the highest area fraction of intermetallic particles, which have a brittle behavior and easily detach from the Al matrix during tensile testing. The poor performance of Cu4-B samples, despite the lower number of intermetallic particles, is instead related to the high porosity level, which diminishes the load bearing area of the samples, resulting in reduced UTS and ductility of the material. Regarding YS, it has to be mentioned that the castings are cooled in water after extraction from the die. This operation can act as an effective quenching, resulting in higher amount of Cu retained in solid solution for Cu4 alloy, due to excess of Cu in comparison with Cu2 alloy. This can lead to a higher amount of Cu in solid solution, which is effective in hindering dislocation motion during tensile testing. This results in the enhanced YS of Cu4 alloy. Tensile behavior of the studied samples is summarized by the quality index, which has the highest values for Cu2-A samples, while it is significantly reduced for Cu4 alloy.

CONCLUSIONS

The present study focuses on the characterization of microstructural and mechanical properties of real castings produced by HPDC using AlSi9Cu alloy. The Cu content of the alloy was changed from 2 wt.% to 4 wt. % in order to investigate the influence of Cu on the material performance and to provide results useful for industrial application. It was found that the increase in Cu content leads to a higher total area fraction of intermetallic particles, while their size distribution is not affected by Cu content and cooling rate. As a result, Cu4 alloy exhibits lower tensile strength and ductility, especially in position B, where the presence of intermetallic particles was coupled to high the porosity level. This is correlated to the cooling conditions of the considered position in the casting, as indicated by SDAS values. On the other hand, higher Cu content lead to improved yield strength likely because of higher Cu retained in solid solution.

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