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Microstructure and mechanical properties of AC AlSi9CuX alloys

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Materials

ABSTRACT

Purpose: In order to gain a better understanding of how to control the as-cast microstructure, it is important to understand the evaluation of microstructure during solidification and understanding how influence the changes of chemical concentration on this microstructure and mechanical properties. In this research, the effect of Cu content on the microstructure and mechanical properties of AC AlSi9CuX series alloys has been investigated.
Design/methodology/approach: The experimental alloy used in this investigation were prepared at the University of Windsor (Canada) in the Light Metals Casting Laboratory, by mixing the AC AlSi5Cu1(Mg) commercial alloys and two master alloys AlSi49 and AlCu55, in a 10 kg capacity ceramic crucible. Optical microscope, transition electron microscope and scanning electron microscope were used to characterize the microstructure and intermetallic phases. Secondary dendrite arm spacing measurements were carried out using an Leica Q-Win^{TM} image analyzer. Compression tests were conducted at room temperature using a Zwick universal testing machine. Rockwell F–scale hardness tests were conducted at room temperature using a Zwick HR hardness testing machine. Vickers microhardness tests were conducted using a DUH 202 microhardness testing machine.
Findings: It was found that the increase of Cu content to 2 wt% leads to change of the Al+Si eutectic morphology, resulting in a grate increase in the ultimate tensile strength and ductility values compared to the alloys include 1 and 4 wt % of Cu. Based on the X–ray phase analysis was found, that change of Cu content don't influences on the phases composition of investigated alloy.
Practical implications: The aim of this work is describe in detail the solidification process in a number of AC AlSi9CuX foundry alloys. In investigated alloys there were identified five phases, which can suggest together witch thermal analysis, that in these alloys occur four solidification reactions.
Originality/value: The carried out work confirmed the solidification reaction of AC AlSi9CuX foundry alloys and shown influence of Cu content on the microstructure and mechanical properties.
Keywords: Mechanical properties; Electron microscopy; X-ray phase analysis

1. Introduction

The AC AlSi9CuX series (Al-Si-Cu) casting alloys are widely used for automotive industry. The AC AlSi9CuX series alloys are used in the production of engine components such as cylinder blocks heads and several parts of car suspension. The use of aluminum alloy castings in this application is growing, replacing grey iron in many demanding applications [6].

A deeper understanding of the effect of the Cu content on the solidification process and mechanical properties has to come to understand in recently years [1, 4, 6, 7]. The effect of Cu content on the structural feature and mechanical properties of Al-Si-Cu alloys has been investigated by many authors [1-10, 12-15]. It is well known that Cu addition increases the strength of Al–Si–Cu alloys, which is due to the influence of Cu on the precipitation behavior of the alloys during the age-hardening treatment.

The investigated AC AlSi9CuX series alloys are hypoeutectic Al-Si alloys with two main solidification stages, formation of aluminum reach (α-Al) dendrites fallowed by development of two phase eutectic (α-Al+Si). However, the additional alloying elements like as: Cu and Mg, as well as impurities like as: Fe, Mn, leads to more complex solidification reaction. Therefore, the AC AlSiCuX as-cast microstructure presents many intermetallic phases. Bäckerud [13] identified five reactions in alloy AC AlSi6Cu3 (319.1).

The solidification reactions are listed in Table 1. For a similar alloy, Samule [9] proffered to indicate the new solid phases appearing at each characteristic temperature (Table 1).

The data presented in Table 1 show the two solidification sequence differ only slightly. After crystallization of Al-dendrites, Bäckerud identified the precipitation of phase $Al_{15}Mn_3Si_2$ probably together with Al_5FeSi, which wasn't detected by Samuel probably because of the smaller Mn content of the alloy used by the Samuel's. The eutectic Al+Si nucleation temperature for Samuel is significantly differs in these studies, 575 ºC for Bäckerud and 562 ºC for Samuel is agreement with the fact that this temperature is depressed by increasing the nominal Si content of the alloy. A slight thermal arrest at 554 ºC corresponding to the precipitation of $Al_6Mg_3FeSi_6$ and Mg_2Si could be detected by Samuel by comparison to their results on ACAlSi6Cu3 alloy with a high Mg concentration (0.5 wt.% [8] or according [13] 0,2 wt %) where this precipitations are easily observed.

Bäckerud recorded four phase $Al+Al_2Cu+Si+Al_5FeSi$ reaction at 525 ºC. This reaction relates to the start of Al_2Cu precipitation [13]. According to Samuel [9] this multi-phase compose should rather involve $Al_5Mg_8Cu_2Si_6$ together to Al_2Cu, somewhat in agreement with Backerud [13].The phase $Al_5Mg_8Cu_2Si_6$ appears in an invariant quaternary eutectic of Al-Cu-Mg-Si system which corresponds to the last reaction listed by Bäckerud (Table 1)

The Al_2Cu phase is observed such a bulk shape and in fine multi-phase eutectic-like deposits. These two shapes may be observed in castings cooled at very different cooling rates, with apparently a lower proportion of blocky precipitates as the cooling rate increased [7, 8, 10, 11].

2. Materials and experimental procedure

Three (AC AlSi7Cu, AC AlSi7Cu2, ACAlSi7Cu4) experimental AC AlSi9CuX alloys were produced at the University of Windsor (Canada) in the Light Metals Casting Laboratory, by melting the AC AlSi5Cu(Mg) base alloy and adding in proper proportion a AlCu55 and AlSi49 master alloys. The melted test samples were held for 12 hours in Lindberg^{TM} electric resistance furnace at 850±5 ºC under a protective argon gas atmosphere. Before casting the melts were homogenized and degassed with the aim to reduce the hydrogen level and the surface was carefully skimmed. A total of 24 samples of the AC AlSi9CuX alloys were cast into a 0.25 mm thick stainless steel crucible. Their chemical compositions were analyzed by Optical Emission Spectroscopy (OES) according to ASTM E1251 specification. The chemical compositions of these alloys are given in Table 2.

The samples were cut longitudinally and were prepared for metallographic analysis. An etching reagent a 0,5–2 % of HBF_4 acid has been used for disclose grain boundaries and to differentiate precisely the particular precipitations in AC AlSi9CuX alloys.

The observations of the investigated as-cast materials have been made on the light microscope LEICA MEF4A at magnification 500x, as well as on the electron scanning microscope Opton DSM-940 using a secondary electron detection. For comprehensive characterization of the Si structures a Leica Q-Win^{TM} and a Simagis Research^{TM} Image Analysis System were utilized.

The X-ray qualitative and quantitative microanalysis and the analysis of a surface distribution of elements in the examined AC AlSi9CuX cast alloy specimens have been made on the Opton DSM-940 scanning microscope with the Oxford EDS LINK ISIS dispersive radiation spectrometer at the accelerating voltage of 15 kV and on the JEOL JCXA 733 X-ray microanalizer. Observations of thin foils structure were carried out in the JEM 3010UHR firm JEOL transmission electron microscope using an accelerating voltage of 300 kV.

Samples for compression testing were machined from center of the thermal analyses specimen ingots. The machined samples were polished with fine sandpaper to remove any machining marks from the surface. Compression tests were conducted at room temperature using a Zwick universal testing machine. Prior to testing, a precision alignment device was used to minimize frame bending strains.

Rockwell F–scale hardness tests were conducted at room temperature using a Zwick HR hardness testing machine. Vickers microhardness tests were conducted using a DUH 202 microhardness testing machine. Load of indenter was set at 25 g.

Table 1.
Reactions occurring during the solidification of the same AC AlSi6Cu3, (319.1) alloys according to Bäckerud [13] and Samuel [9]

Bäckerud et al. [13]	Temperature, ºC	Samuel et al. [9]	Temperature, ºC
(Al) dendrite network	609	(Al) dendrite network	610
$L \rightarrow (Al)+Al_{15}Mn_3Si_2+(Al_5FeSi)$	590		
$L \rightarrow (Al)+Si+Al_5FeSi$	575	Precipitation of eutectic Si	562
		Precipitation of $Al_6Mg_3FeSi_6+Mg_2Si$	554
$L \rightarrow (Al)+Al_2Cu+Al_5FeSi$	525	Precipitation of Al_2Cu	510
$L \rightarrow (Al)+Al_2Cu+Si+Al_5Mg_8Cu_2Si_6$	507	Precipitation of $Al_5Mg_8Cu_2Si_6$	490

3. Results and discussion

As-cast microstructure of AC AlSi9Cu, AC AlSi9Cu2, AC AlSi9Cu4 alloys shows the typical solidification structure. Microstructure contains primary aluminum dendrites, eutectic silicon crystals, iron-based intermetallics and copper-based intermetallics are shown on Figure 1. The analyses of thin foils have validated the fact, that the structure of the investigating alloys consist of the solid solution α–Al (matrix) and an intermetallic secondary phase β–Si.

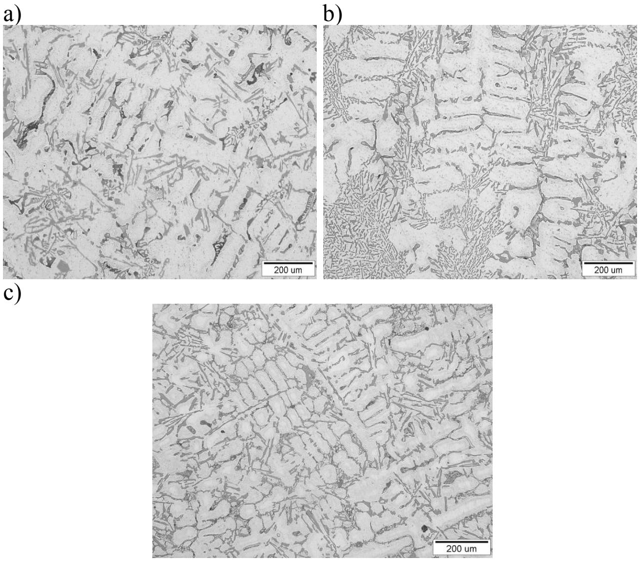

Fig. 1. Microstructure of the alloy containing: a) 1 % Cu. b) 2 % Cu. c) 4% Cu

The β – Si phase forms large flakes, needles and fibrous precipitations. depending on the Cu concentration. Moreover, the TEM examinations confirm the existence of intermetallic phases: $AlFe_5Si$ (Figure 2) and Al_2Cu and didn't confirm the existence of intermetallic phases $Al_{15}Mn_3Si_2$ and Mg_2Si. The Al_2Cu phases solidify in two forms, bulk precipitates Al_2Cu (Figure 1 (brown particles)) and the finer eutectic-like $Al+Al_2Cu$ (Figure 3). The Al_2Cu block phases fraction is depending on the Cu content. Increasing the Cu content from 1 to 4 wg % increased the total of Al_2Cu block phases. The chemical composition examinations with the use of the EDS dispersive radiation spectrometer as well as literature data, confirm, that in investigated alloy occurring $Al_8FeMg_3Si_6$ phase (Figure 3).

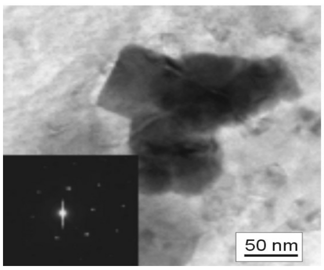

Fig. 2. TEM image of the AC AlSi9Cu4 alloy with selected area diffraction pattern

Additional result of the surface distribution of elements and the X-ray, quantitative micro analysis made using the EDS energy dispersive radiation spectrometer show the presence of single Si crystals inside the $Al+Al_2Cu$ eutectic. This phase forms multicomponent eutectic with α–Al, β–Si and Al_2Cu (Figure 4). The distribution of the intermetallic phase is rather homogeneous.

The mechanical properties of AC AlSi9CuX as a function of the Cu content are shown in Figure 4 and 5. In general, YS. hardness and microhardness increase with an increase the Cu contents.

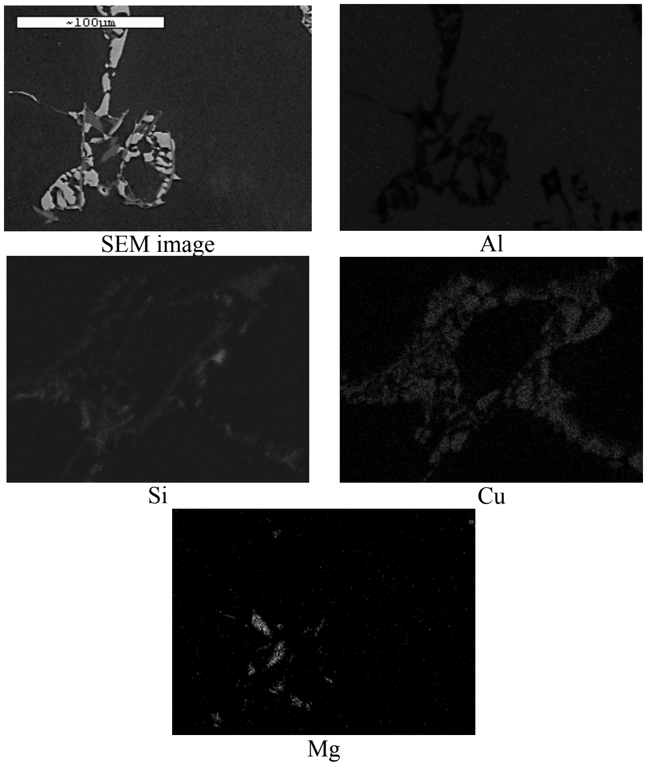

Fig. 3. The result of the surface distribution of the alloying elements of AC AlSi9Cu alloy

These properties depend on the supersaturation of the Al–α solid solution. An increase of Cu content in studied alloys affected on the increase of degree Al–α solid solution supersaturation. Moreover the degree Al–α solid solution supersaturation has negative effect on the shortness of AC AlSi9CuX alloys. The investigate alloys are more brittle.

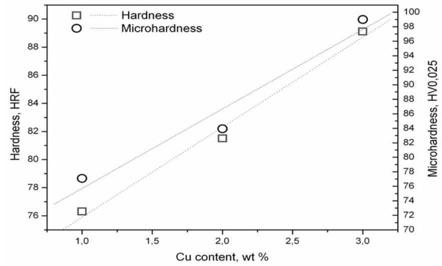

Fig. 4. Hardness and microhardness of the investigated alloys as function of Cu content

Table 2.
Average chemical composition of investigated alloys

Alloy label	Average chemical composition, wt %						
	Si	Fe	Cu	Mn	Mg	Zn	Ti
AC AlSi9Cu	9.094	0.179	1.049	0.360	0.268	0.140	0.073
AC AlSi9Cu2	9.033	0.187	2.248	0.090	0.195	0.451	0.095
AC AlSi9Cu4	9.268	0.338	4.640	0.014	0.284	0.048	0.089

The variation in UCS with composition can be explained in terms of the size and distribution of both intermetallics $AlFe_5Si$ and eutectic Si particles.

The change in the morphology of the eutectic Si particles (with increase a Cu content from 1 to 2 wt %) from a coarse, flake-like form to a fine fibrous one is also a parameter to consider in explaining why the UCS of AC AlSi9Cu2 alloy is higher than the UCS values obtained from the other alloys.

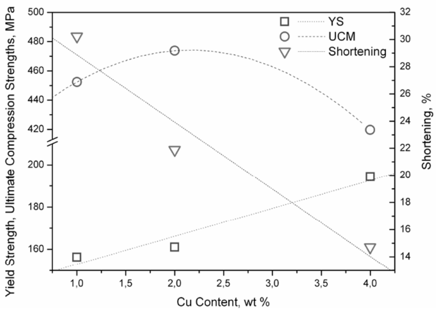

Fig. 5. YS, UCT, Shortness of the investigated alloys as function of Cu content

4. Conclusions

Understanding of metal quality is of superior importance for control and prediction of casting characteristics. The results are summarized as follows:

1. In investigated alloys there were identified five phases, which can suggest, that in these alloys occur four solidification reactions listed below:
   a) (Al) dendrite network
   b) $L \rightarrow (Al)+Si+Al_5FeSi$
   c) $L \rightarrow (Al)+Al_2Cu+Al_5FeSi$
   d) $L \rightarrow (Al)+Al_2Cu+Si+Al_5Mg_8Cu_2Si_6$
2. Mechanical properties, viz, YS, hardness, microhardness and increase with an increase the Cu content, regardless of alloy composition.
3. Increase of Cu content leads to a change in the morphology of the eutectic Si particles from a coarse flake-like form to a fine fibrous one. Thus, the alloys with 2% of Cu display much higher UCS values compared to the alloys included 1 and 4 wt% of Cu.

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