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The Effect of Cu on Feeding Characteristics of Aluminum Casting Alloys

Jae-Ik Cho[1], Chang-Yeol Jeong[2], Young-Chan Kim[1], Se-Weon Choi[1], Chang-Seog Kang[1]

[1]Korea Institute of Industrial Technology 1110-9 Oryong-Dong, Buk-Gu, Gwangju, Rep. of Korea

[2]Dongguk University, 707 Sekjang-Dong, Gyeongju, Gyeongsangbuk-Do, Rep. of Korea

The effect of copper on feeding characteristics and has been investigated in 3xx series Al-Si based casting alloys. It is well known that copper increases the strength, hardness and fatigue resistance of aluminum alloys but it generally responsible for the reduction of casting characteristics, especially feeding. The microstructures of directionally solidified alloy showed that the extents of eutectic mushy zone were significantly affected upon the content of copper, resulting from the late formation of copper-containing phases. By precipitation of copper-enriched phases within the last regions to solidify, the solidification temperature range was also greatly extended. Due to the appreciable effects on the solidification characteristics of the aluminum casting alloys by copper, influences on the development of micro-porosity are evident. From the analysis obtained by directional solidification, microstructure and the appreciable effects on the solidification characteristics, the effect of copper on the feeding characteristics were evaluated. The underlying mechanisms for the development of micro-porosity are also discussed in terms of compositional differences and microstructures developed during solidification.

Keywords: *Aluminum casting alloy, Copper, Feeding, Porosity*

1. Introduction

Demands for light weighted aluminum casting alloys have been increased for structural applications in automotive, marine and aerospace industries. Among aluminum alloys, the aluminum-silicon system is known to be one of the most important casting alloys due to its superior casting characteristics. Most of aluminum products are silicon-based aluminum alloys [1] and thus a considerable amount of research has been carried out to control the growth and morphology of the aluminum-silicon eutectic phases to improve the performance of the alloys. At the same time, since copper improves strength and hardness of aluminum alloys by precipitation hardening in both as-cast and heat treated condition, copper has also been used as one major alloying element in aluminum alloys [1].

However, it has been documented that copper is usually responsible for a reduction in corrosion resistance and hot tearing resistance [1,2,3,4]. Also, casting characteristics of the aluminum alloys are generally biased upon a cupper addition, because copper and its compounds nucleate and grow in the last stage of solidification and appear to interfere with feed metal transfer, resulting in the formation of an increased amount of shrinkage porosity and micro-porosity in the alloys [5,6]. Therefore, aluminum alloys containing silicon and/or copper as both a major and minor element limits a practical application in some conditions where soundness of castings is critical and/or the castings are in service in a severe corrosive environment.

Especially, the feeding and micro-porosity characteristics are of significant for fabrication of sound casting products, while there are few documents concerning the effect of copper on the solidification of aluminum alloys. It has been documented that the solidification / feeding behavior of aluminum-silicon alloys is affected by composition variation. [5,7], while the mechanism by which copper interferes with the feed metal transfer has not been fully understood.

Therefore, in this research, a special focus has been given to identify the underlying mechanism of the feeding and micro-porosity formation characteristics affected by the variation of copper content in Al-Si based casting alloys.

2. Experimental

Two different kinds of hypoeutectic aluminum-silicon alloys, A356 and 319 alloy and one hypereutectic alloy, 391 alloy, were prepared for the investigation. The compositions of each alloy are shown in Table 1. High purity alumina tubes, 3 mm in inner diameter, 4.5 mm in outer diameter and 355 mm in length, were prepared and they were lightly coated with Y_2O_3 before the experiment to minimize an interaction between the alloys and the alumina tube. Total weight of about 30g of alloy was vacuum induction melted and cast in an alumina crucible. Copper additions were made 0% and 0.5% for A356 and 391 alloy, and 0% and 1.0% for 319 alloy, resulting that total amounts of copper were 0.01% and 0.51% for A356, 3.36% and 4.36% for 319 alloy, and 0.02% and 0.52% for 391 alloy.

The directional solidification experiment was carried out because it allows for more effective control of cooling rates and microstructures than conventional casting technique. The vacuum cast samples were assembled with the sample holder and placed inside of the furnace of the directional solidification apparatus with temperature gradient of 45°C /sec through cooling jacket at the bottom of the furnace. After the alloy specimen was melted completely, the sample was pulled downward 50mm with 0.1mm/sec. When the sample had traveled 50mm down, the sampled holder was released and dropped into a water bucket for quenching.

To assess the influence of copper on the microstructure of aluminum castings, a series of heats was produced from A356, 319 and 391 alloy ingots as received and with added copper content. Melts of about 5 kg were prepared in a high frequency coreless induction furnace. Then the melt was poured into cylindrical graphite molds {12.7, 25.4, and 38.1 mm (0.5, 1.0, and 1.5 inches) in diameter and 152.4 mm (6 inches) long}.

Table 1 Compositions of the aluminum alloys (wt.%)

	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Sr
A356	7.21	0.10	<0.01	<0.01	0.40	<0.01	0.01	0.012	0.02
319	6.7553	0.5635	3.3646	0.2884	0.4522	0.0393	0.5290	0.0618	0.0000
391	18.030	0.1842	0.0238	0.0228	0.5865	0.0032	0.0156	0.0851	0.0059

3. Results and discussion

The directionally solidified alloys were sectioned longitudinally so as to examine their respective microstructures. Each sample was selected from a region containing some eutectic liquid at the time the sample was water quenched.

Examples of these microstructures of A356, 319 and 391 alloy are presented in Figure 1. These microstructures are presented to illustrate the segregation of elements, and the formation of complex compounds, during the final stages of solidification. With solidification progressing from right to left, the left side of each photomicrograph contains some quenched eutectic liquid. Solidification of the high Cu alloys was similar until the latter stages of solidification extending the solidification temperature range and developing pockets of entrapped liquid in the solidifying structure. Those quenched liquid islands are the potential sites for microshrinkage and/or microporosity in the real castings. The segregation of copper is well observed in these microstructures in the darker regions containing quenched liquid. Also it was found that the higher copper content alloy also caused a more irregular interface to develop between the eutectic liquid and solid rather than the flatter interface obtained in the low copper content alloys, especially in A356 and 391 alloy. This was accompanied by pockets of liquid which were entrapped as solidification progressed and an appreciable widening of the eutectic mushy zone.

In 319 alloy which already contains appreciably large amount of copper, 3.36%Cu, there was no significant influence of additional 1.0%Cu in the alloy except existence of a greater amount of entrapped liquid pools or pockets with the higher copper content alloy.

The solidification temperature range affected by copper has been reported in the literature [5,6,7]. Cárceres, et al., and Edwards, et al., reported that the solidification of Al-Si-Mg type casting alloys with copper was delayed by the ternary reaction, L → α-Al + Si + Al_2Cu, which occurs at the temperature below the Al-Si eutectic. Mackay, et al., reported that the solidification ranges for aluminum-silicon eutectic in both Al-7%Si and Al-9%Si alloys increased with a decrease in copper content from 4% to 1%.

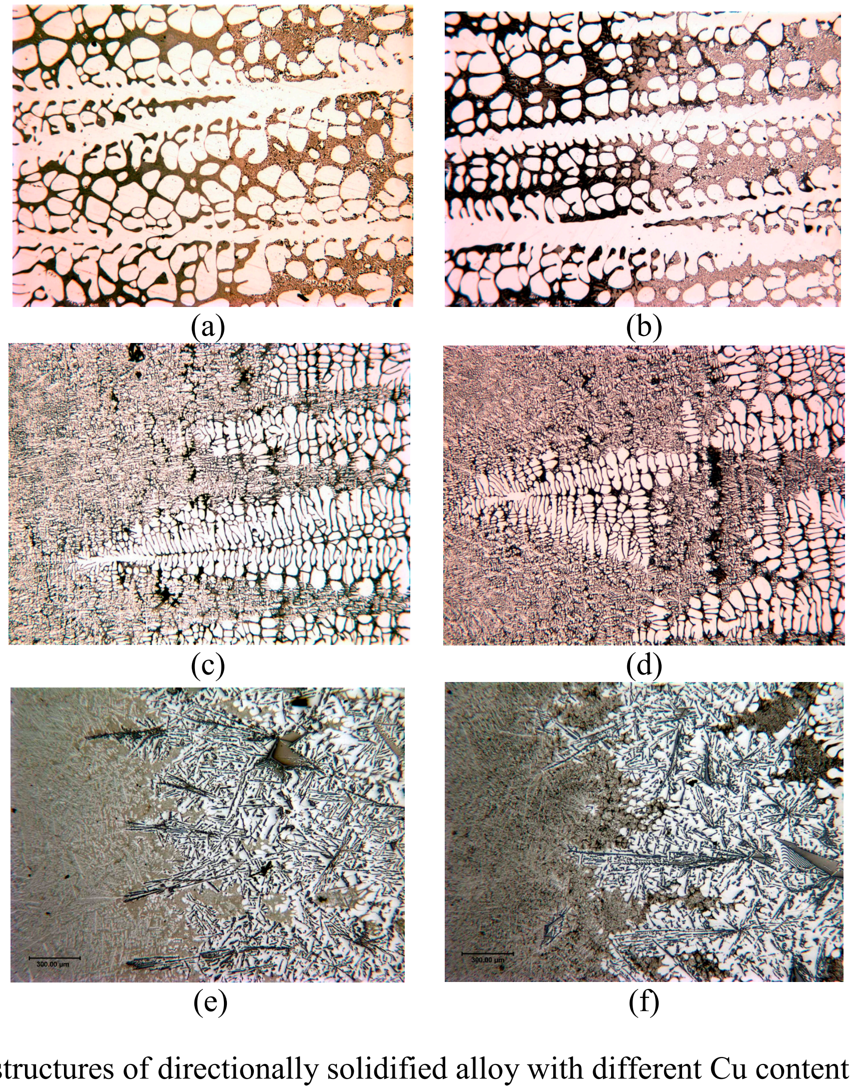

Fig. 1 Microstructures of directionally solidified alloy with different Cu content at growth rate of 0.1mm/sec; (a) A356 with 0.01%Cu, (b) A356 with 0.51%Cu, (c) 319 with 3.36%Cu, (d) 319 with 4.36%Cu, (e) 391 with 0.02%Cu, (f) 391 with 0.52%Cu.

This phenomenon had been confirmed in the solidification simulation by using Pandat software. It presented a significant increase in the solidification temperature range by the differences in amount of copper due to the late formation of copper enriched phases in A356 and 391 alloys, as shown in Table 2. The final solidification temperatures were substantially decreased in both A356 and 391 alloys as a result of the additional copper content, while the differences in the liquidus temperatures at which the solidification starts were about 2°C in A356 and 391alloys. Therefore, the higher content of copper extended the solidification temperature range or freezing range, as much as 48.4°C and 21.4°C in

A356 and 391 alloy, respectively. However, 319 alloy, which is the longest freezing range alloy among the alloys studied already contains an appreciable amount of copper (3.36%); therefore, the influence of the additional 1.0% of copper on the solidification or freezing range of the alloy was inconsiderable.

This extended solidification temperature range developed in A356 and 391 alloy due to the presence of higher content of copper is mainly because of the significantly delayed last stage of solidification due to the last formation of copper phases, such as $Al_5Cu_2Mg_8Si_6$ and Al_2Cu. Because of this extended solidification temperature range, the eutectic mushy zone can be greatly extended as well. The extended eutectic mushy zone caused by copper in aluminum casting alloy was also reported in the analysis of the alloys between Al-6%Si-0.26%Mg alloy and Al-6%Si-3%Cu alloy [8].

Table 2 Calculated liquidus and eutectic temperatures of A356, 319 and 391 alloys with different amounts of Cu content (°C).

	A356 alloy		319 alloy		391 alloy	
	0.01%Cu	0.51%Cu	3.36%Cu	4.36%Cu	0.024%Cu	0.524%Cu
Liquidus Temp.	613.5	611.8	602.4	599.0	654.8	656.6
Eutectic Temp.	573.5	572.2	561.6	559.4	573.7	572.8
Final Sol. Temp.	552.6	502.5	430.6	430.6	497.5	478.2

Typical microstructures obtained from the 38.1mm diameter bar castings of each alloy with low and high Cu are presented in Figure 2. In the eutectic solidification region, Al_5FeSi (needle, light gray), $Al_{15}(Fe,Mn)_3Si_2$ (script, light brown), $Al_8Mg_3FeSi_4$ (script, brown), and Mg_2Si (black, particle) phases were identified in both the high and low copper alloys. No copper containing phase was observed in the microstructures of the low copper A356 and 391 alloy because of the very low copper contents, 0.01%Cu and 0.024%, respectively, as shown in Figure 2 (a) and (e). However, with an increased amount of copper by 0.5%, the formation of copper enriched phases was clearly demonstrated, forming both $Al_5Cu_2Mg_8Si_6$ (bulk, dark brown) and Al_2Cu (particle, orange red) phases, as shown in Figure 2 (c) and (f). The microstructures obtained clearly illustrate the presence of an orange-red colored compound which would be characteristic of Al_2Cu. EPMA (Cameca SX-50) revealed the following composition in the copper concentrated region of the 0.524%Cu version of the 391 alloy: 1.27% Mg, 66.55% Al, 2.59% Si, 0.46% Fe, 29.08% Cu. Comparison of the microstructures of both 319 alloys with 3.36% Cu and 4.36% Cu showed no significant differences except for the formation of a larger volume of the Al_2Cu phase in the higher copper alloy.

The shrinkage porosity, or microporosity, measured from the microstructures of each alloy is shown in Figure 3. The percent microshrinkage porosity was measured from the microstructures of 38.1mm diameter bar castings by using image analysis techniques. The porosity is characteristic of interdendritic shrinkage as a result of volumetric shrinkage and insufficient feeding during the eutectic solidification. In a comparison of the microstructures obtained from the low and the high copper alloys, a larger amount of shrinkage porosity was apparent with an increased amount of copper content as shown in Figure 4. Because of volumetric shrinkage and insufficient feed metal transfer to the last region to solidify during solidification, shrinkage porosity resulted. It was evident that because of the higher concentration of copper and the consequent interference in the feeding characteristics, the shrinkage porosity observed in the 319 alloy was much larger amount than that of A356 and 391 alloys.

The literature agrees with the results of this investigation. It was reported that increased amount of copper content in strontium pre-modified A356 alloy showed a dramatic increase in the amount of microporosity with an increased amount of copper up to 1.0% [6]. Moreover, Al-(4.5% and

9.0%)Si-(0.1% and 0.5%)Mg-(0.2% and 0.5%)Fe alloys resulted in a modest increase in the volume fraction porosity with varying the copper amount from 1.0% to 4.0% [5].

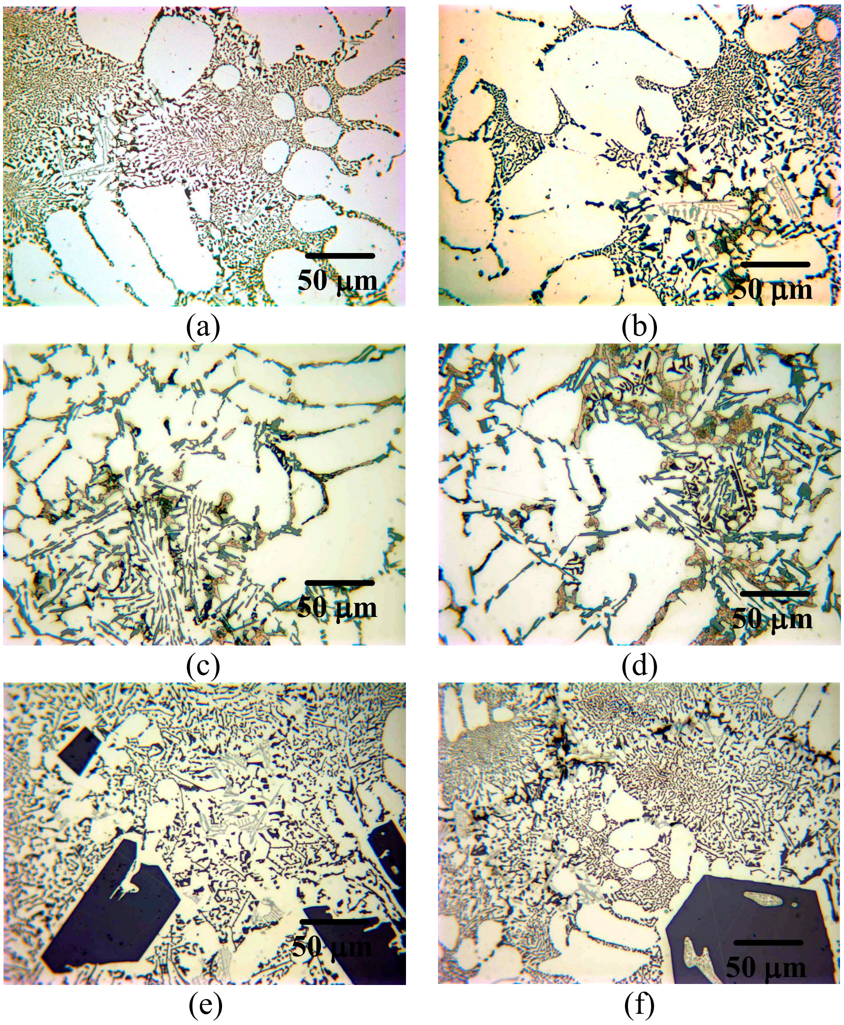

Fig. 2 Microstructures of 38.1mm diameter bar casting of each alloy with different Cu content; (a) and (b), A356 alloy; (c) and (d), 319alloy; (e) and (f), 391 alloy.

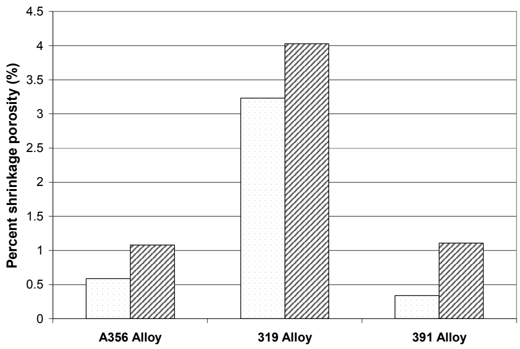

Fig. 3 Variation of percent shrinkage porosity in A356, 319 and 391 alloys (measured from the 38.1mm diameter bar castings)

4. Summary

The effects of copper on feeding characteristics of 3xx series aluminum casting alloys have been examined via directional solidification, microstructural analysis and solidification simulation. It is quite evident that copper segregates during solidification and it becomes more intense in the alloys with higher amount of copper and predominant as the solidification reaches its completion. As a result, the high copper A356 (0.51%Cu) and 391 (0.524%Cu) alloys showed the precipitation of copper-enriched phases, such as $Al_5Cu_2Mg_8Si_6$ and Al_2Cu phases, in the microstructure, while no copper containing phase identified in the low copper alloys (0.01%Cu in A356 and 0.024%Cu in 391 alloy). It was apparent from the microstructures that those copper phases are formed at the interdendritic area in A356 alloy and at the cell boundary in 391 alloy where are the last region to solidify.

Because of the influence on the solidification characteristics, the A356 and 391 alloys showed the extended solidification temperature range and eutectic mushy zone area. As a result of late formation of copper phases at the end of solidification in the high copper A356 and 391 alloys, freezing ranges may greatly extended. However, 319 alloy already contains appreciable amount of copper (3.36%Cu), therefore, the influence of copper on the solidification of 319 alloy was not significant.

Interference on the feeding characteristics of the alloys by copper and consequent formation of microshrinkage and/or microporosity are quite evident based upon the microstructural examinations. Due to the longer freezing time and the extended eutectic mushy zone by copper, feeding was greatly influenced and resulted in larger amount of microporosity in the microstructure.

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