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T-phase formation and its effect on mechanical properties of Al-Cu-Mn alloys

SobanMuddassir Dar[1], HengCheng Liao[1,a] and GuangJing Li[1]

[1]*School of Materials Science & Engineering, Southeast University, Jiangsu Key Laboratory for Advanced Metallic Materials, Nanjing 211189, China*

Abstract. Al-Cu-Mn alloys are used in components in automotive and aircraft industry which work at high temperature. Recent research is focused on Al-Cu-Mn alloys to enhance their performance by promoting the formation of thermally stable phase particles. In this study, the effect of Cu/Mn content on microstructure and mechanical properties of two Al-Cu-Mn alloys (Cu/Mn wt.% ratio = 5.56, 2.75) is investigated by optical microscopy, scanning electron microscopy, energy dispersive spectroscopy and tensile testing. Results reveal that as-cast microstructure of both the alloys consists of trunks of α-Al dendrites surrounded by Cu-rich interdendritic region. After solution treatment, a great amount of Al-Cu-Mn intermetallic compound particles are found to precipitate adjacent to this region. Alloy with low Cu/Mn content ratio exhibits high strength due to relatively high amount of Al-Cu-Mn (T-phase) particles.

1 Introduction

Al-Cu-Mn alloys are widely used in automotive and aircraft industry due to their high strength and light weight[1]. These alloys possess excellent strength because of high density of meta-stable θ′′/θ′ precipitates after solutionizing and aging treatment. However, the service temperature of these alloys is usually limited to 250°-300°C because of coarsening of these metastable precipitates[2, 3]. To improve the properties of these alloys, the effect of rare earth addition on the properties of these alloys is studied[4-6]. Recently, scientists have focused their attention in these alloys to completely avoid or suppress the formation of Al_2Cu (θ-phase) and to maximize the formation of Mn-rich phase (T-phase) [7, 8]. Some of these studies have been proved to be fruitful in terms of improved properties. However, no attention is paid to microstructure evolution during/safter solidification (as-cast) and its effect on the properties. Furthermore, the solidification reactions proposed by Mondolfo[9] long ago in Al-rich portion of Al-Cu-Mn ternary phase diagram are largely of hypothetical nature and have no physical significance[10]. So, in this study, the effect of Cu/Mn content on microstructure and mechanical property of two Al-Cu-Mn alloys is investigated.

2 Experimental procedures

Two alloys of varying Cu and Mn contents, as listed in Table 1, are produced from commercially pure aluminum, Al-20%Cu and Al-10%Mn master alloys. Cu/Mn content ratio in these alloys corresponds to 5.56(hereafter Alloy-1) and 2.75(hereafter Alloy-2), respectively. The alloys are prepared by melting at 760°C for 3 hrs in an electrical resistance heating furnace. After degassing by C_2Cl_6 at 720°C, the molten alloys are cast into a plate like cast-iron mold with a cavity of 170×150×20mm3 which was preheated at 250°C for at least 5h. The composition of the alloys is measured by MAXx LMF15 spark emission spectrometer. The as-cast alloys are solution treated at 530°C for 16 hrs, then water quenched and finally aged at 170°C for 6 hrs. Microstructure of alloys is characterized by using optical microscopy (OM) and scanning electron microscopy (SEM). For this purpose, samples are prepared by mechanical grinding, polishing and final etching with Keller's reagent. Phase constituents are determined by energy dispersive spectroscopy (EDS). Samples for tension test are cut from the central part of casting in accordance with GB/T228-2002 (a Chinese standard). Mechanical properties are determined at 25°C (room temperature) and 300°C on a universal testing machine (CMT4503) with a strain rate of 2 mm min-1. For each alloy, three samples are tested at every temperature and mechanical properties are reported as an average.

Table 1: Composition of the experimental alloy by MAXx LMF15 spark emission spectrometer

Alloy Name	Composition, wt.%			Cu/Mn, wt.% ratio
	Al	Cu	Mn	
Alloy-1	Bal.	1.67	0.29	5.57
Alloy-2	Bal.	2.27	0.77	2.75

[a] Corresponding author: hengchengliao@seu.edu.cn

Fe<0.15%, Si<=0.08%

3 Results and discussion

3.1 Microstructure

Optical micrographs of as-cast alloys (Alloy-1 and Alloy-2) are shown in Figure 1. There is no obvious difference between the microstructure of two alloys. The as-cast microstructure consists of trunks of α-Al dendrites surrounded by Cu-rich interdendritic region, as demonstrated in Figure 2(a), (b) for Alloy-1 and Alloy-2, respectively. Moreover, some black particles are also observed within the interdendritic region. SEM images and EDS analysis shows that these are particles of θ-Al_2Cu phase formed as a result of divorced eutectic reaction. In Alloy-1, the interdendritic region consists of α-Al + globular particles of Al_2Cu phase, as shown in Figure 2(a) and in Alloy-2, the interdendritic region consists of α-Al + broken network of Al_2Cu phase. Two morphologies of Al_2Cu phase i.e. globular particles and elongated particles are observed in Alloy-2, as shown in Figure 3(a). It is because of relatively high amount of Cu present in this alloy. SEM-EDS analysis shows that in addition to non-equilibrium θ-Al_2Cu phase, some Fe-rich and Si-rich intermetallics, formed during solidification, are also observed in the microstructure because of minor amounts of these elements present in these alloys. Distribution of alloying elements within the microstructure is studied by EDS analysis. Results reveal that most of Cu is present in the form of θ-Al_2Cu phase. No Mn-rich binary or ternary intermetallics are observed. It is worth noting that, in both the alloys, amount of Cu is low in Al matrix as compared to nominal composition of the alloy (Fig. 2(b) and Fig.3(b)). On the other hand, amount of Cu is higher in interdendritic regions (Fig.2(c) and Fig.3(c)). However, Mn is completely dissolved into the α-Al matrix.

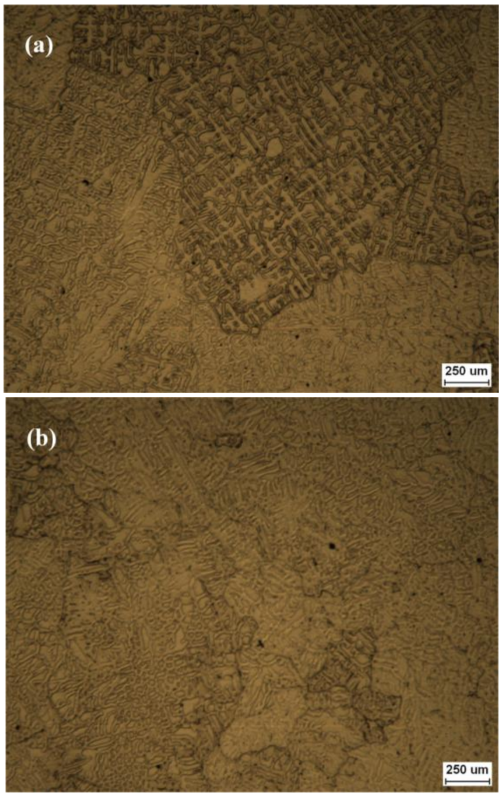

Figure 1: As-cast microstructure of prepared alloys, (a) Alloy-1and (b) Alloy-2

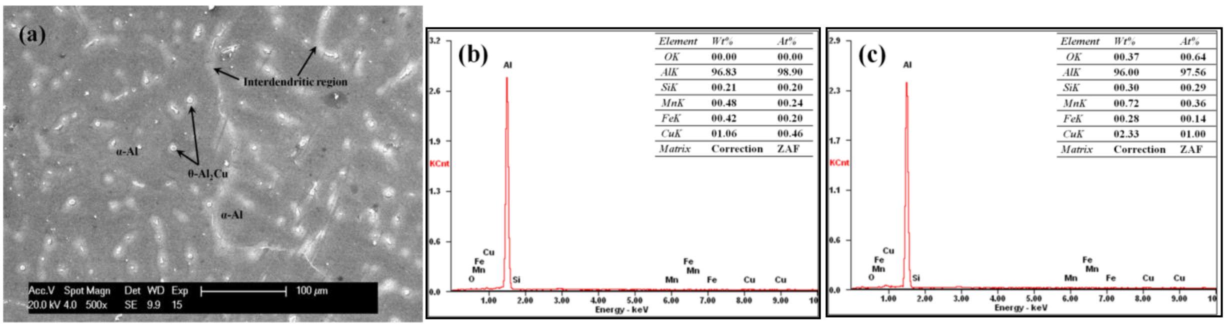

Figure 2: SEM and EDS results of Alloy-1: (a) SEM micrograph, (b) EDS analysis of α-Al dendritic trunks, (c) EDS analysis of interdendritic Cu-rich zone

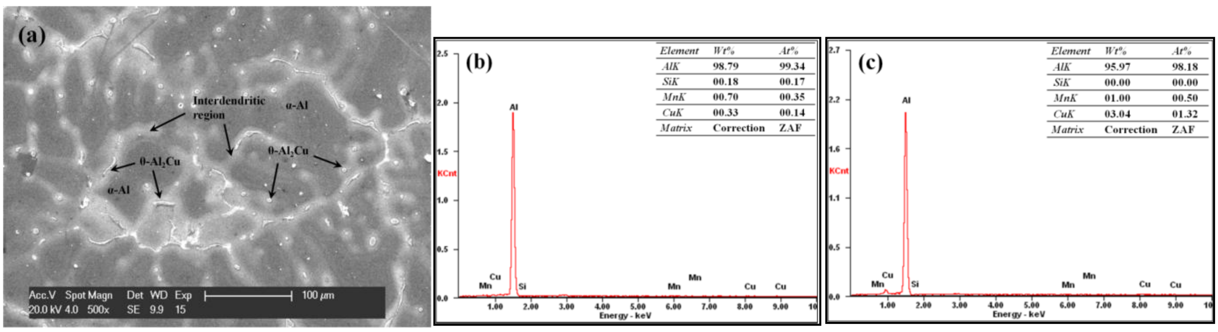

Figure 3: SEM and EDS results of Alloy-2: (a) SEM micrograph, (b) EDS analysis of α-Al dendritic trunks, (c) EDS analysis of interdendritic Cu-rich zone

Optical micrographs (Figure 4) of two alloys after solution treatment (530°C for 16 hrs) show that there are a great amount of intermetallic particles precipitated adjacent to the interdendritic region(described in the as-cast microstructure). SEM micrographs more clearly reveal it. The amount of precipitates in Alloy 2 is much greater than that in Alloy 1. In Alloy 1, most of the precipitates are thought to be $CuAl_2$ phase due to the EDS results (Fig.5(b,c)). In Alloy 2, however, by the EDS results (Fig.6(b,c)), most of the precipitates are rod/plate-like and are thought to be Mn-rich phase (T-phase). It is interestingly noted that the precipitation behavior during solutionizing occurs mostly adjacent to the interdendritic regions where it is Cu-rich due to non-equilibrium solidification. In these regions, the Cu and Mn solutes are locally supersaturated, thus $CuAl_2$ and/or T-Mn phases are precipitated during solutionizing.

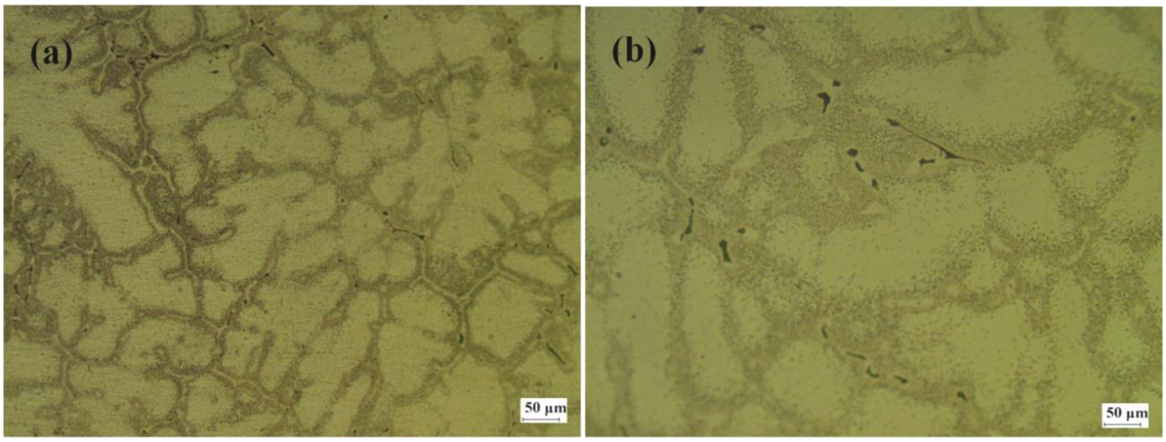

Figure 4: Optical micrographs after solution treatment (530°C for 16 hrs): (a) Alloy-1, (b) Alloy-2

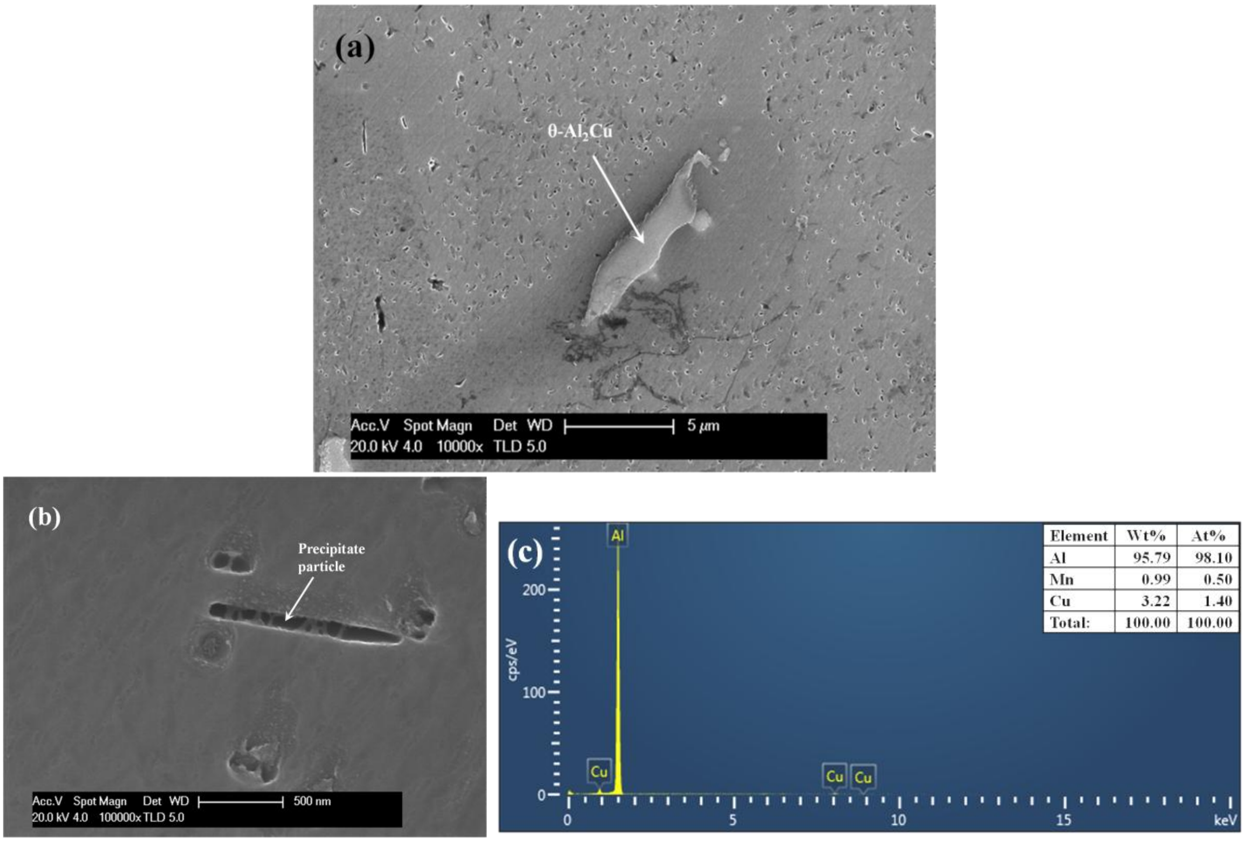

Figure 5: SEM micrographs of Alloy-1 after solution treatment (530°C for 16 hrs), (a) un-dissolved θ-Al_2Cu phase and precipitate particles adjacent to interdendritic region, (b) morphology of fine precipitatates, (c) EDS results of the precipitate in (b)

[a] Corresponding author: hengchengliao@seu.edu.cn

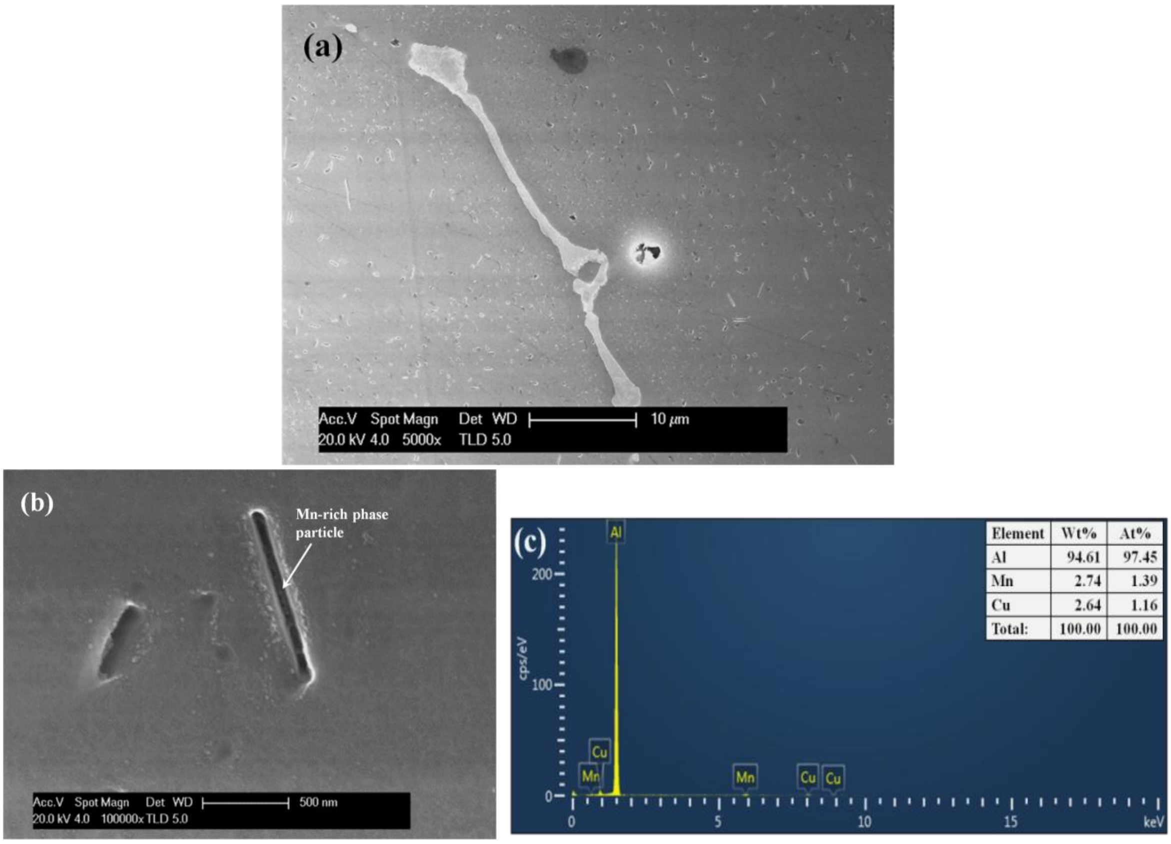

Figure 6: SEM micrographs of Alloy-2 after solution treatment (530°C for 16 hrs), (a) a great amount of precipitates adjacent to interdendritic region, (b) morphology of fine precipitatates, (c) EDS results of the precipitates in (b)

3.2 Mechanical properties

Results of tensile properties of Alloy-1 and Alloy-2, at different temperature, are summarized in Table 2. It shows that Alloy-1 has low value of yield strength i.e. 44MPa at room temperature when compared to that of Alloy-2 i.e. 66MPa. Similar trend is observed in ultimate tensile strength of both the alloys. However, Alloy-1 has experienced higher plastic deformation prior to failure due to low amount of Cu & Mn contents and Alloy-2 has experienced lower plastic deformation. High temperature tensile test is carried out at 300°C. Results of these tests representing the mechanical behavior of Alloy-1 and Alloy-2 are shown in Figure 7(a) and (b), respectively. It is observed that the ultimate tensile strength of Alloy-1 is dropped from 120MPa to 48MPa and the elongation is increased significantly from 37% to 56%. It is considered to be because of dissolution and/or coarsening of the precipitates at high temperature. While the ultimate tensile strength of Alloy-2 decreases to 82MPa and elongation increases from 23% at room temperature to 37% at 300°C. It is clear that the ultimate tensile strength of Alloy 2 is much higher than that of Alloy 1 and it also experiences less plastic deformation. This behavior of Alloy-2 is attributed to the presence of Mn-rich (T-phase) particles within the grain interiors hindering plastic deformation at high temperature. These results are in agreement with literature suggesting that Mn-rich (T-phase) particles can improve high temperature properties by impeding the grain boundary movement[11].

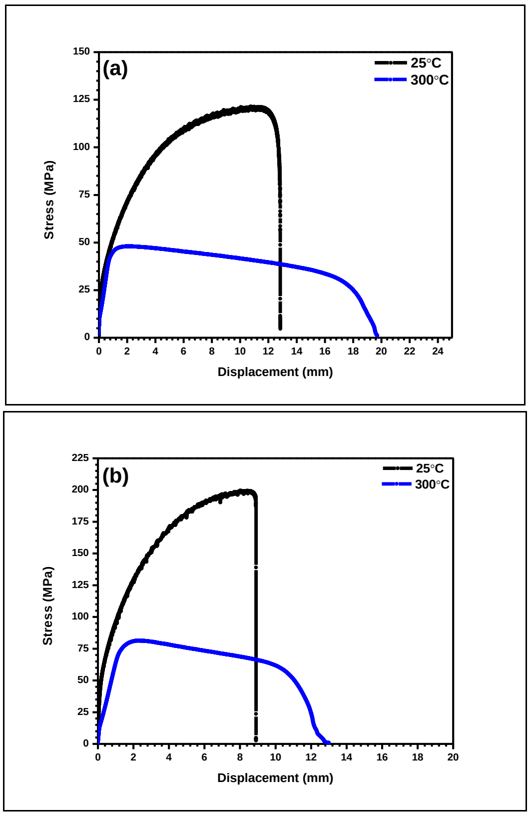

Figure 7: Results of room and high temperature tension experiment, (a) Alloy-1 and (b) Alloy-2

Table 2: Mechanical properties of experimental alloys at 25°C and 300°C

Alloy Name	Temp.	YS (MPa)	UTS (MPa)	Elong.
Alloy-1	25°C	44	120	37%
Alloy-2		66	199	23%
Alloy-1	300°C	-	48	56%
Alloy-2		-	82	37%

4 Conclusions

(1) As-cast microstructure of both the alloys (with varying Cu/Mn content ratio) consists of trunks of α-Al dendrites and interdendritic Cu-rich regions where θ-Al2Cu particles are formed. No ternary (Al-Cu-Mn) intermetallics are observed

(2) After solution treatment, a great amount of precipitates are found to form adjacent to the Cu-rich regions, most $CuAl_2$ particles in Alloy-1 and most T-phase(Al-Cu-Mn intermetallic compound) in Alloy-2

(3) Alloy-2 with low Cu/Mn content ratio exhibits high strength due to higher thermal stability and much greater amount of T-phase particles

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