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Review of Ternary Alloy of Copper-Aluminum-Silicon

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ABSTRACT

The paper, discussed the review of ternary alloy of Copper-Aluminum-Silicon. Cast Cu-Al-Si alloy technology was found to give high shape precision of samples with the complicated geometry that can be easily manufactured. Study, showed that the addition of main/basic elements in higher amounts with permanent casting techniques increases mechanical strength and grain size properties of Cu-Al-Si Alloy System. However, alloying elements in lower amounts provide support for effects such as solidification behavior control, micro-structural refinement and modification of phase morphology, promotion or suppression of secondary phase formation and reduction of oxidation with decreased grain size structure. It could also be seen that the casting technique adopted might influence both the mechanical properties and grain sizes of Cu-Al-Si Alloy System. Also, mechanical properties of Cu-Al-Si Alloy System aging at 105 ℃ / 12h + 165 ℃ / 5h are the best, with ultimate tensile strength of 543 MPa, yield strength of 364 MPa, elongation of 18% and hardness of 170.6 HV.

Key words: Alloy, Casting, Copper, Aluminum, Silicon.

1.0 INTRODUCTION

Cast Cu-Al-Si alloy are widely used in various engineering application, especially automotive parts and computer devices due to light weight, high strength and good cast ability. Okayasu et al (2015) highlighted that this alloy can reduce weight and energy consuming of vehicles, including overheating. In our society, casting processes are widely employed due to their benefit such as the production cost, high quality and high mechanical properties. Another advantage for the cast Cu-Al-Si alloy technology is high shape precision of samples and the complicated geometry that can be easily manufactured. Cast copper-aluminum-silicon alloys commonly are produced by pressure casting processes, including squeeze casting, thixocasting, rheocasting and vacuum casting, because of low cost and high quality.

Zolotarevsky (2007) explained that the various industries have increasing demand for semi-finished products from deformable aluminum alloys, especially alloys of the Cu-Al–Si system. It is obvious that the alloys based on the Cu-Al–Si system have the best casting properties, but most of the high-strength alloys like AK8M3Ch (VAL8) has strength UTS≤350 MPa, which does not meet modern requirements. Significant disadvantages of the most alloys are low casting properties, which prevents manufacturing of products with complicated shape by casting. Therefore, the development of new multi-component cast aluminum alloys with a successful combination of mechanical and casting properties is relevant. Such alloys should meet a number of criteria: they have to have a sufficient amount of eutectic structure of a favorable morphology, which is formed immediately after solidification or upon heat treatment, a minimum effective solidification interval to achieve a sufficiently high level of casting properties, and the Al matrix should be alloyed in such a way as to provide the required mechanical properties. It should be noted that the presence of more than 30 % of the eutectic component in the alloy structure is of crucial importance for ensuring high technological properties.

1.1 STRUCTURE OF Cu-Al–Si ALLOY SYSTEM

The structure of Cu-Al-Si system has a number of features. Hypoeutectic alloys consist of primary dendrites of aluminum and the corresponding eutectic structure. The solidification of eutectic colonies begins with the formation and subsequent growth of primary crystallites of the faceted phase, which are the centers of eutectic colonies. The amount of eutectic structure in the alloys increases with the content of inter-metallic phases. Another feature of the microstructure of alloys of the Cu-Al–Si system is impossibility to form a completely eutectic structure, and there is a structural anomaly a shell of the metallic phase (α-Al) forms around the primary crystallites of the inter-metallic phase. The size of primary crystallites, as well as the thickness of the metallic phase shell, increases with increasing amount of the inter-metallic phase, according to Grechny (1956) as cited in Sezonenko (2024).

The microstructure of cast hypoeutectic Cu-Al–Si (AK9M2) alloys comprises of bright dendrites of solid solution of silicon in α-aluminum and needle-type double eutectic α+Si. The solubility of Al in Si at room temperature is 0.05 %, so it can be assumed that the microstructure of the alloys at low temperatures contains not a β solid solution, but silicon. The microstructure of the eutectic alloy consists of α+Si eutectic. This microstructure is coarse when the standard methods of casting are used.

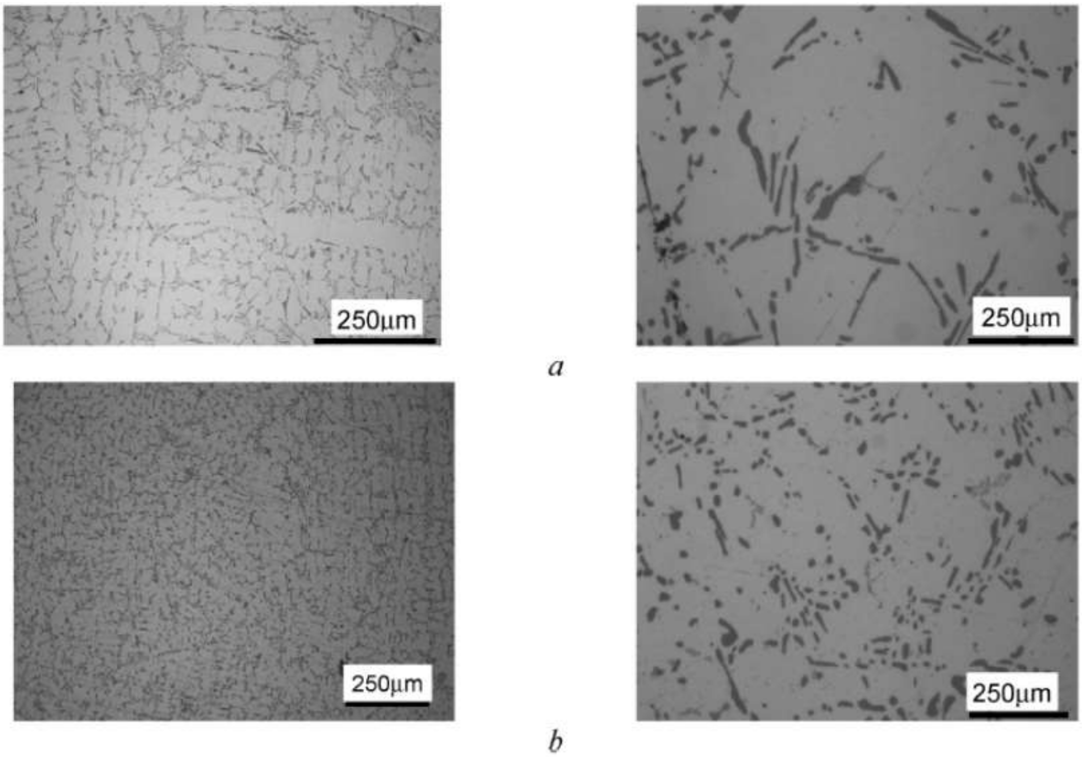

Fig1: Microstructures of Cu-Al–Si alloy: (*a*) hypoeutectic α+Si needle-type structure in as-cast state (*b*) hypoeutectic α+Si needle-type structure after casting under pressure (Source :Andrey Filippov, 2022)

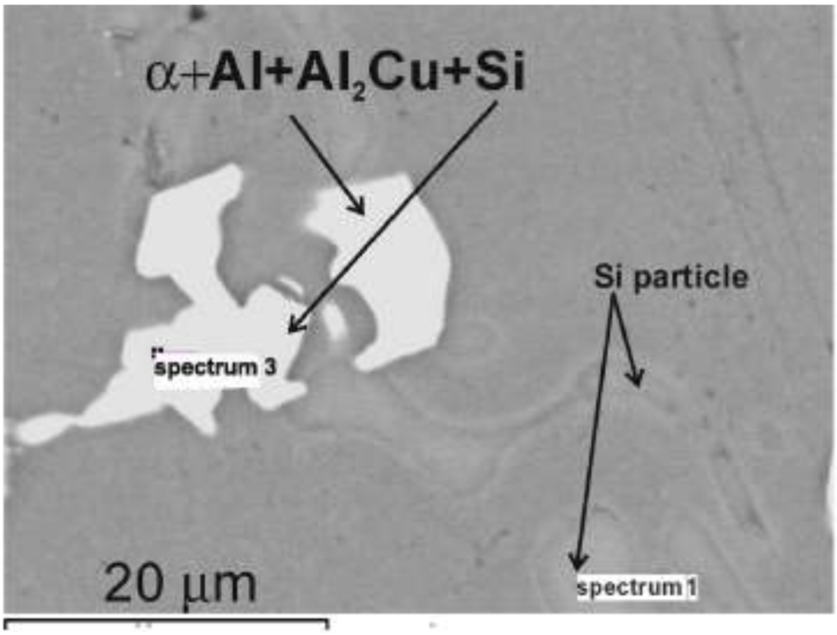

Fig2: SEM microstructures of Al–Si–Cu alloy (*a*), the same alloy with 2.05 % Cu in as-cast state (Source :Andrey Filippov, 2022)

1.2 POSSIBLE PERCENTAGE COMPOSITION OF Cu-Al-Si SYSTEM WITH MANGANESE

Table 1: Possible Composition of Cu-Al-Si System with Mn

Phases	Cu, at %	Al, at %	Si, at %	Mn, at %
α	87.6	9	3	0.4
β	84.5	10.5	4.5	0.5
γ	82.6	7.2	9	1.2

1.3 PHYSICAL PROPERTIES OF Cu-Al-Si ALLOY

Garcia *et al.* (2010) stated that the increase in demand of Cu-Al-Si alloy for building components of automotive, electrical parts, valves and fittings was because of its combination of excellent properties such as corrosion resistant, ductility, malleability, non-magnetism, wear resistance, machinability; good thermal and electrical conductivities. The physical properties of the ternary alloy are given below.

1) High castability, fluidity, and corrosion resistance.
2) Low density of 0.308 ib/cu.in
3) High electrical resistivity of 148micro-ohm-cm
4) Melting point of 1019℃
5) Solidification temperature of 1904℃
6) Electrical conductivity of 7.0%iacs when annealed at 68°F
7) Thermal conductivity of 21btu at 68°F

1.4 TECHNOLOGICAL PROPERTIES OF Cu-Al-Si ALLOY

1) Machinability rating of the ternary alloy is 30
2) Soldering of this alloy is rated as good and brazing is rated as good
3) Forgeability rating of this alloy is 40. Forging temperature is between 1300 and 1600°F
4) Hot working capacity is rated as excellent
5) Cold working capacity is also rated as excellent
6) The annealing temperature for this alloy is between 900 to 1300°F

1.5 METHOD OF DEFORMATION OF Cu-Al-Si ALLOY

Virgil et al (2012) stated that the effect of severe plastic deformation (SPD) during cyclic extrusion (CE) on grain refinement and strain hardening in Cu-Al-Si alloy showed that the average of grain size decrease below 130 nm, i.e. a nanocrystalline material is obtained after deformation. They noticed a decrease in size of dislocation cells and micro bands which was expressed in terms of the effective plastic strain defined such that strain rate reversals slow down its accumulation.

Unlike traditional cold rolling or drawing processes of large plastic deformation, the SPD techniques that employ cyclic strain paths lead to an essentially unchanged shape of the specimen after processing. The resulting micro-structural and mechanical properties, for instance, the sub grain size, disorientation angle across boundaries, and the fraction of the high angle grain boundary (HAGB) area and the flow stress or micro hardness, have been measured could be measured.

Cyclic extrusion (CE) as the method of applying severe plastic deformation originated to Cu-Al-Si alloy. The investigations could as well be done using a laboratory version of the CE equipment. A schematic illustration of the CEC process is shown in Fig below. During plastic flow between two chambers of diameter D0 through the connecting channel of diameter Dm, compression occurs simultaneously with extrusion, so that the sample is restored to its initial shape.

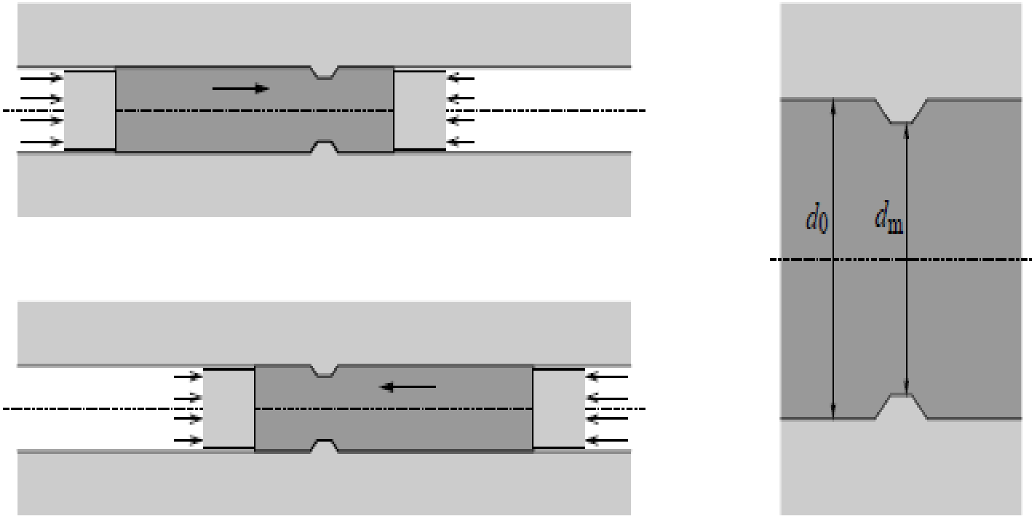

Fig3: Schematic of the cyclic extrusion process

Virgil (2012) reported that, Cu-Al-Si samples were deformed using a hydraulic press up to the accumulated Von Mise strain (vm) = 16. The samples were 10 mm in diameter and approximately 40 mm long. The channel diameter was dm = 8 mm, which corresponds to a strain increment vm = 4 ln(do/dm) = 0.65 exerted in a single CE cycle.

1.6 MECHANICAL PROPERTIES OF Cu-Al–Si SYSTEM ALLOY

Table 2: Mechanical Properties of Cu-Al-Si Alloy System

Specimens	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, %
1	129	418	46
2	131	415	59
3	136	413	48

Mechanical testing showed that the yield strength and the ultimate tensile strength did not depend on the specimens cutting direction relative to the growth direction of the dendrite grains. However, the elongation before fracture obviously depended on both the cutting direction (along or across the growth direction of grains) and the cutting area.

Table 3: Effect of Alloying Elements on Mechanical Properties and Grain size of Cu-Al-Si Alloy System

S/N	**Alloy Composition(wt%)**	**Ultimate tensile strength(MPa)**	**Compressive Strength(MPa)**	**Condition**	**Average Grain size**	**Casting Techniques**
1	Cu-0.004Al-6.83Si-0.28Mg-0.10Mn-0.023Sr-0.016Fe-0.11Ti-0.003	249.9	327.7	As cast	100	Permanent mold casting
2	Cu-0.004Al-9.0Si-0.2Mg-0.55Fe-0.15Ti-0.45Mn-0.25AlSr10	320	455.5	As cast	167	Permanent mold casting
3	Cu-0.65Al-6.5Si-0.45Mg-0.5Fe-3.75Mn	460	408.0	As cast	270.2	Sand casting

1.7 EFFECT OF HEAT INPUT ON Cu–Al–Si SYSTEM ALLOY

Optical metallography allowed evaluation of the heat input effect on the macrostructure of both as-deposited and post-treated samples. The as-deposited samples demonstrated grain structure differences depending upon the heat input values used during the additive manufacturing. A profile view of the wall deposited at 0.19 kJ/mm allows the observation of its non-uniform thickness as well as cold laps. A layer-by-layer nonhomogeneous macrostructure with alternating fine equiaxed and low aspect ratio columnar grains can be clearly seen.

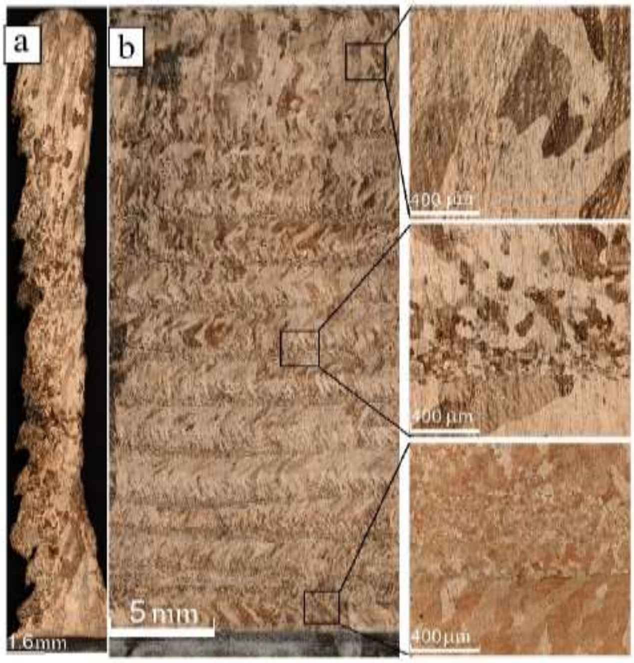

Fig4. Profile (**a**) and front cross section optical view (**b**) of Cu-3wt.%Si-Al obtained at heat input of 0.19 kJ/mm with enlarged insets representing the bottom, medium, and top parts of the wall (Source :Andrey Filippov, 2022)

1.8 EFFECT OF ANNEALING HEAT TREATMENT ON Cu–Al–Si SYSTEM ALLOY

According to Andrey Filippov (2022), annealing and subsequent quenching of the pre-deformed sample allowed the forming of new, finer re-crystallized grains. Pre-deformation at 10% served for introducing dislocations and deformation twins that facilitated re-crystallization, and thus formed the microstructures as shown. Annealing twins also came into the picture, and it seems that they also became wider.

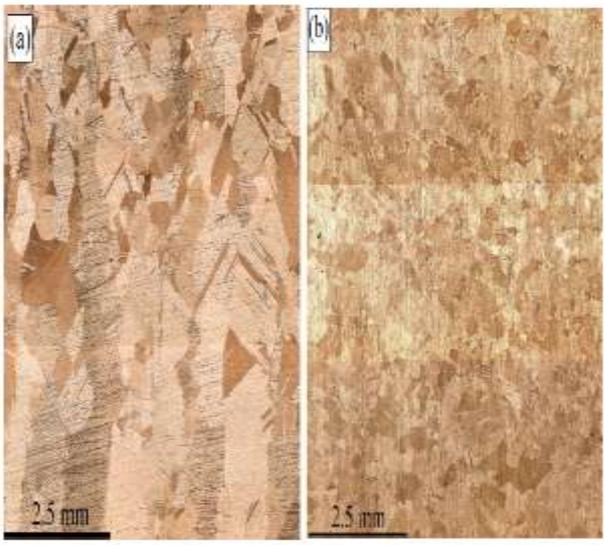

Fig5. The microstructure of annealed at 900 °C for 6 h (**a**) and pre-deformed/annealed (**b**) sample of the Cu-3wt.%Si-Al deposited at 0.31 kJ/mm(Source :Andrey Filippov, 2022)

EQUILIBRIUM DIAGRAM OF Cu–Al–Si SYSTEM ALLOY

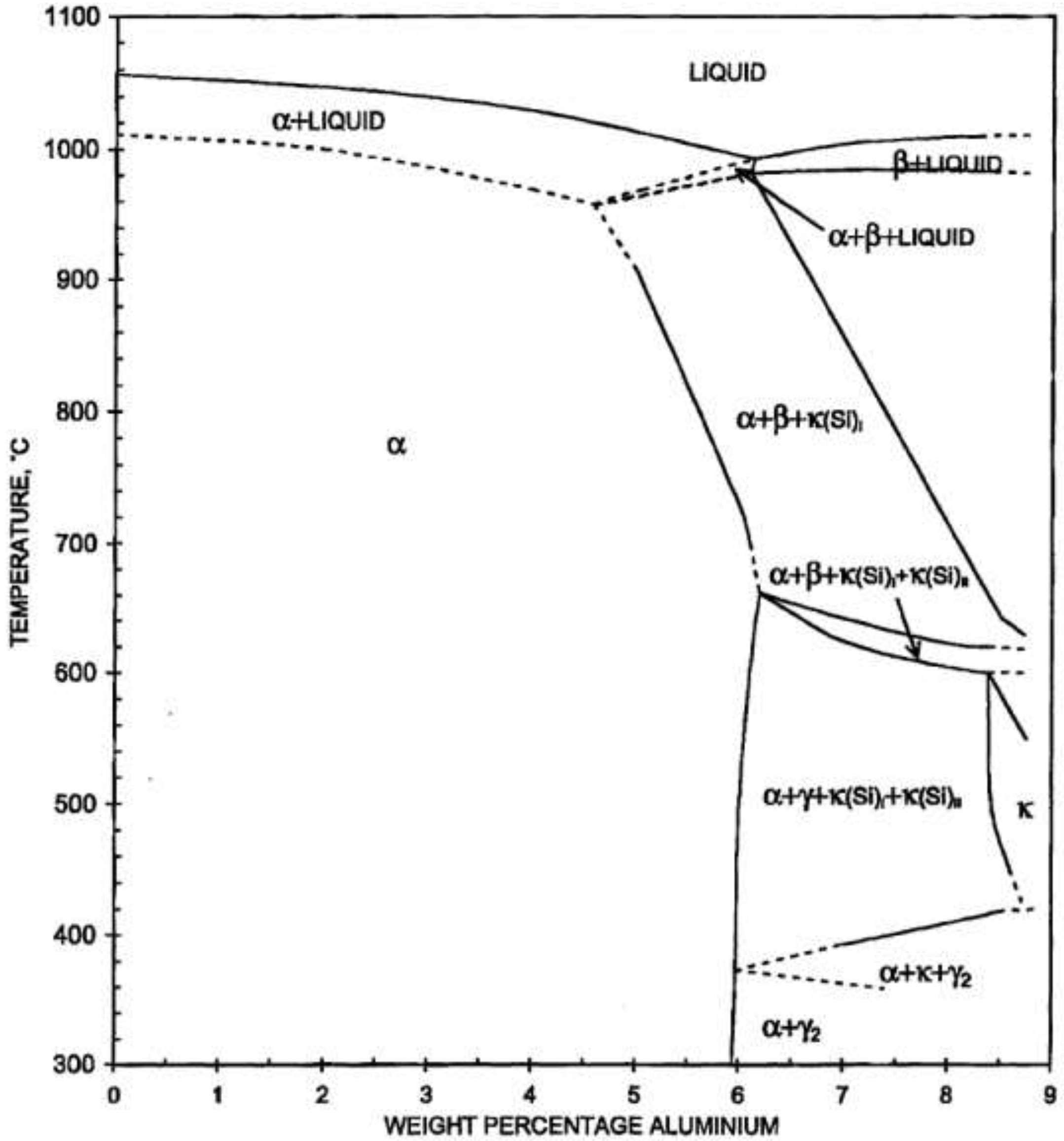

Fig.6 Vertical section of the Cu-AI-Si system at 2% Si

1.9 PRECIPITATION BEHAVIOR DURING RE-AGING OF Cu-Al-Si SYSTEM WHEN ALLOY WITH MAGNESIUM

Nano-scaled precipitation plays a very important role in the strengthening of Cu-Al-Mg-Si alloys, which is also crucial in balancing the mechanical properties and electrical conductivity. Beta phase is an important strengthening phase in Cu-Al-Mg-Si system, which forms during solution plus peak aging (PA) process. It is well recognized that from the metallurgical point of view, both the grain sizes and micro-structural arrays of distinctive materials and alloys have important roles upon the resulting mechanical strength and corrosion responses, as previously reported.

2.0 EFFECT OF TIME ON AGE HARDENING CHARACTERISTICS OF Cu-Cu-Al-Si-Mg

The hardness changes of the samples treated by six aging processes are shown below. With the extension of aging time, the hardness of Cu-Al-Si- Mg alloy first gradually increases to the peak value under T-1, T-2 and T-3 aging processes. The peak hardness of T-1 aging process reaches 120 HV in 18h, T-2 aging process reaches 140.8 HV in 14h, and T-3 aging process reaches 156.2 HV in 12h, and finally tends to a stable value respectively. When the aging temperature reaches 185 ℃, the hardness reaches the peak value of 147.2hv in 10h with the increase of aging time in T-4 process, and then decreases rapidly. When the aging is stable at 205 ℃, under the T-5 aging process, the hardness quickly reaches the peak value of 139.9 HV with the increase of aging time in about 4h, and then rapidly decreases to 107 HV. The hardness of T-6 aging process increases slowly to 115 HV under 105 ℃ / 12h first stage aging process, and then rapidly increases to the peak value of 170.6hv under 165 ℃ / 6h second stage aging process.

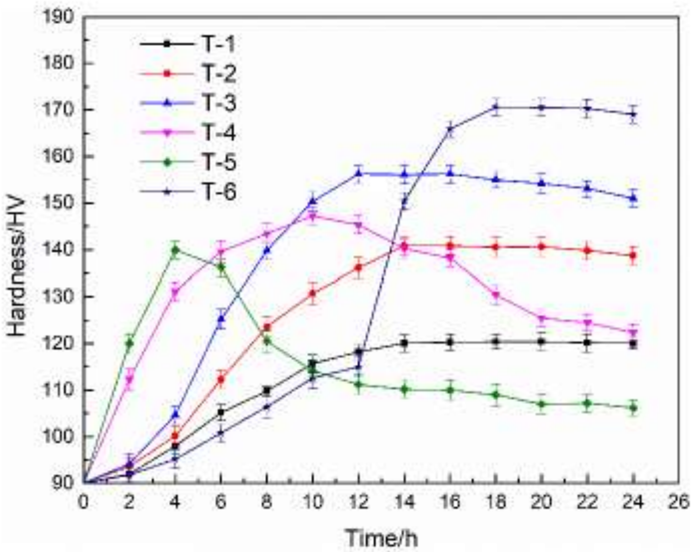

Fig 7. hardness curve of Cu-Al-Si-Mg alloy under different aging systems

2.1 EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF Cu-Al-Si-Mg

According to the hardness test results, take samples at different aging peak hardness for room temperature tensile property test, that is, take T-1 as 125 ℃ / 18h, T-2 as 145 ℃ / 14h, T-3 as 165 ℃ / 12h, T-4 as 185 ℃ / 10h, T-5 as 205 ℃ / 4h, T-6 as 105 ℃ / 12h + 165 ℃ / 6h. Figure shows the room temperature tensile properties of Al-4.5Cu-0.8Mg alloy under different aging processes. It can be seen from Figure that with the increase of aging temperature and the change of aging time, the strength of single-stage aging first increases and then decreases.

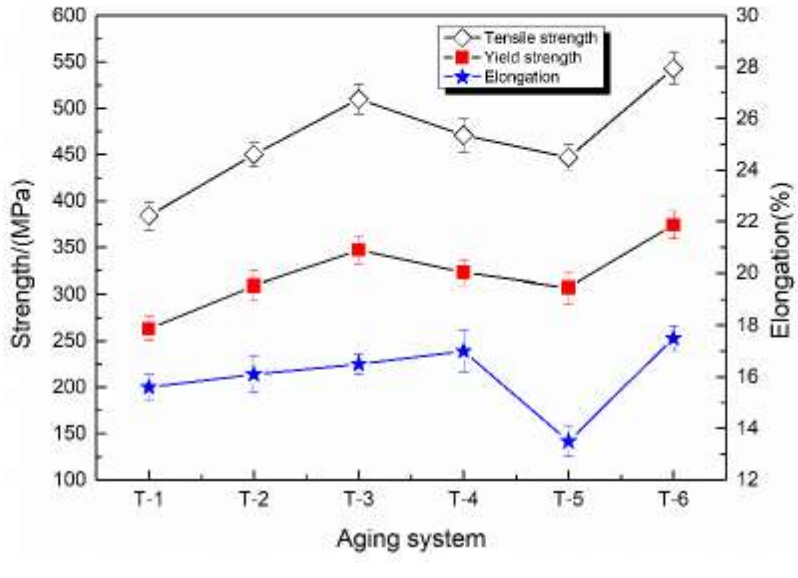

Fig8. Tensile properties of Cu-Al-Si-Mg alloy under different aging system

2.2 EFFECTS OF ALLOYING ELEMENTS ON PROPERTIES OF Cu-Al-Si ALLOY

Main mechanisms for improvement of cast alloys include microstructural refinement, both in terms of dendritic arm spacing and of dendritic grains; modification of the morphology of eutectic phases, leading to refinement, globularization and homogeneous distribution; modification or neutralization of iron (Fe)-rich intermetallics, provided that Fe is the most critical impurity in cast Al alloys, promoting phases with the embrittling character when combined with Al and Si; and promotion of precipitates, including during aging treatment, that can increase hardness, strength and thermal stability. Alloying elements can be categorized into three groups, although one should bear in mind that, at times, a single element can perform more than one role:

1) Main/basic elements are added in higher amounts and mainly control castability and the evolution of properties (Be, Mg, Cr, Mn, Sc, Co, Mo, Fe and W). The higher amount is %wt 5 and lower amount is %wt 0.1

2) Secondary/doping elements in lower amounts (from 0.01up to %wt 0.16) provide support for effects such as solidification behavior control, micro-structural refinement and modification of phase morphology, promotion or suppression of secondary phase formation and reduction of oxidation (Na, Ca, Sr, Sb, B, C, Ti, Y, Ni).
3) Impurities, being elements whose control is limited due to the fabrication process, can affect castability and form insoluble phases that may either limit or, at times, improve certain properties (La, Pr, Ce and Nd).

2.3 CONCLUSION

From the **table 3** above, addition of main/basic elements in higher amounts with permanent casting techniques increases the evolution/rise of mechanical and grain size properties of Cu-Al-Si Alloy System. Addition of alloying elements in lower amounts provide support for effects such as solidification behavior control, micro-structural refinement and modification of phase morphology, promotion or suppression of secondary phase formation and reduction of oxidation with decreased grain size structure. It could also be seen that the casting technique adopted might influence both the mechanical properties and grain sizes of Cu-Al-Si Alloy System.

Mechanical properties of Cu-Al-Si Alloy System aging at 105 ℃ / 12h + 165 ℃ / 5h are the best, with ultimate tensile strength of 543 MPa, yield strength of 364 MPa, elongation of 18% and hardness of 170.6 HV. In addition, increasing aging time of Cu-Al-Si Alloy System increases mechanical hardness property up to 156.2HV in 12hours and finally stabilizes.

Furthermore, the micro-structural deformation investigations of Cu-Al-Si Alloy System, using transmission electron microscopy revealed the characteristic evolution from the ultrafine grained material at lower deformation to a nano-material at the deformation of von mises strain of 16.

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