

Effect of solution treatment and artificial aging on microstructure and mechanical properties of Al–Cu alloy

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Abstract: In order to achieve good mechanical properties of Al–Cu alloys such as high strength and good toughness, precipitation hardening and artificial aging treatment were applied. As defined by the T6 heat treatment, the standard artificial aging treatment for Al–Cu alloy followed heat treatments of solution treatment at 510–530 °C for 2 h, quenching in water at 60 °C and then artificial aging at 160–190 °C for 2–8 h. The effects of solution treatment and artificial aging on the microstructure and mechanical properties of Al–Cu alloy were studied by optical microscopy (OM), scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), transmission electron microscopy (TEM) and tensile test. The results of solution treatment indicate that the mechanical properties of Al–Cu alloy increase and then decrease with the increase of solution temperature. This is because the residual phases dissolve gradually into the matrix, and the fraction of the precipitation and the size of the re-crystallized grain increased. Compared to the solution temperature, the solution holding time has less effect on the microstructure and the mechanical properties of Al–Cu alloy. The artificial aging treatments were conducted at 160–180 °C for 2–8 h. The results show that the ultimate tensile strength can be obtained at 180 °C for 8 h. Ultimate tensile strength increased with increasing time or temperature. Yield strength was found as the same as the ultimate tensile strength result.

Key words: Al–Cu alloy; solid solution treatment; artificial aging; microstructure; mechanical property

1 Introduction

Aluminum alloys are widely used in aerospace and automobile industries due to their low density, good mechanical properties and corrosion resistance [1,2]. Copper is a potent precipitation strengthening agent in aluminum alloy. Cu addition up to 5.0% (mass fraction) leads to alloys with very high strength and good toughness when subjected to natural or artificial aging [3,4]. And 2xxx series aluminum alloys have only recently become commercially available and are under development as potential precipitation hardened materials. But the conventional aluminum alloys cannot meet the higher and higher work environment because of the coarsening of its strengthening precipitates θ (CuAl₂).

It is reported that the microstructure and mechanical properties of Al–Cu alloys are sensitive to structure of ingot, heat treatment and subsequent deformation condition [5,6]. In order to obtain improved mechanical

properties, aluminum alloys are often subjected to different heat treatments [7–10]. During solution treatment, the alloys are exposed to high temperature corresponding to the maximum safe limits relative to the lowest melting point for each specific composition. By doing so, the soluble phases formed during solidification can be re-dissolved in the matrix. And Al–Cu alloys can be strengthened by precipitation of several metastable phases, which are produced by an artificial aging.

The objective of this study is to investigate the effects of solution treatment and artificial aging on microstructure and mechanical properties of Al–Cu alloy. The relationship between the microstructure and mechanical properties were discussed.

2 Experimental

The experimental Al–Cu alloys such as 2011 alloy were prepared with Al–Cu ingot by vertical continuous casting. The chemical composition of the alloy is listed in Table 1. The ingot was homogenized at 500 °C for

Table 1 Chemical composition of ingot used in this study with specification for 2011 Al alloy (mass fraction, %)

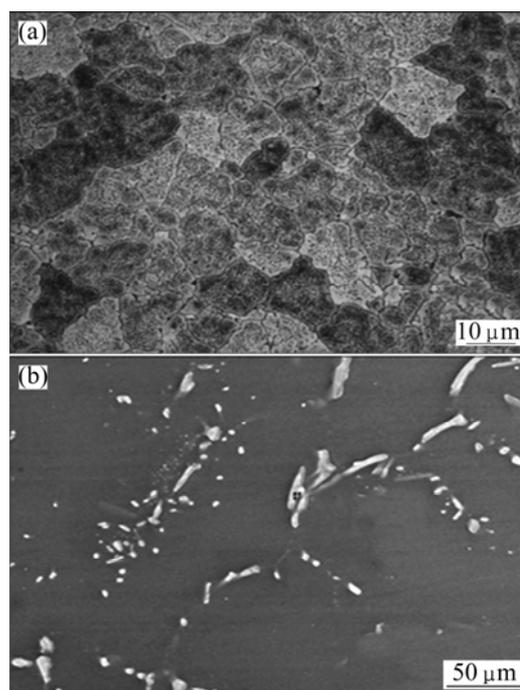
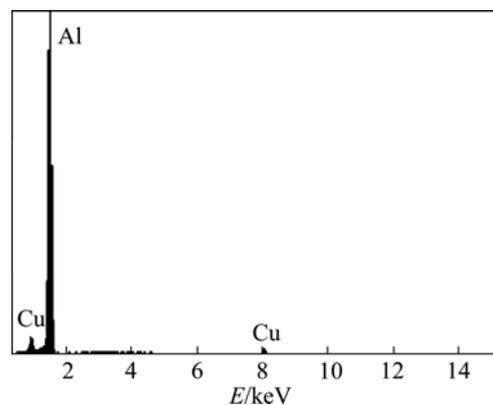
Alloy	Si	Fe	Cu	Bi	Pb	Zn	Al
Specification	0.4	0.7	5.0–6.0	0.2–0.6	0.2–0.6	0.3	Bal.
Al 2011 ingot	0.38	0.48	5.42	0.32	0.26	0.22	Bal.

3 h. As defined by the T6 heat treatment, the Al–Cu alloy followed heat treatments of solution treatment at 510–530 °C for 2 h, quenching in water at 60 °C and then artificial aging at 160–190 °C for 2–10 h. Room temperature mechanical properties tests were performed on Instron 5985 universal testing machine. Metallographic microscope (GX51–223B, Olympus) was employed for metallographic microstructure analysis. The specimens were prepared through a conventional mechanical polishing followed by etching with Keller reagent (2 mL HF, 3 mL HCl, 5 mL HNO₃ and 190 mL water) for OM and SEM observations. And TEM observations were performed on transmission electron microscope (TECNAI F20). The specimens for TEM observation were prepared by the standard twin-jet electropolishing method using 80% methanol and 20% nitric acid solution at –25 °C.

3 Results and discussion

Figure 1 demonstrates the microstructures of as-cast Al–Cu alloy. A typical billet structure consisting of dendritic α phases is given in Fig. 1(a). Serious dendritic segregation exists in the billet. And large amounts of intermetallic phases in the interdendritic region are presented. According to the EDX analysis, the secondary phases are CuAl₂ (Fig. 2). Most residual phases are expected to be dissolved into the matrix by solution treatment at high temperature in order to get the solute atoms as much as possible [11]. However, higher temperature increases the possibility of melting of the residual phases. Thus, it is necessary to optimize the solution temperature.

Figure 3 demonstrates the curves of mechanical properties of the aged Al–Cu alloy solution treated at different temperatures. It is obvious that the tensile strength of the alloy increases with increasing the solution temperatures, reaches a maximum value of 342 MPa at 525 °C, and then decreases with further increasing temperature (Fig. 3(a)). The elongation increases and then decreases with increasing the solution temperature. And the elongation value is 31% when the alloy is solution treated at 525 °C. But the yield strength has no change as temperature increases. As a result, the optimum solution temperature is 525 °C for Al–Cu alloy in this test. Figure 4 presents the optical microstructures

**Fig. 1** Microstructures of as-cast Al–Cu alloy: (a) OM; (b) SEM**Fig. 2** EDX analysis of secondary phase in Fig. 1(b)

of the aged Al–Cu alloy solution treated at different temperatures. It can be seen from Fig. 4 that complete recrystallization occurs in all the alloys. Fine equiaxed grains are observed in the specimen solution treated at 515 °C (Fig. 4(a)). With increasing the solution temperature, the size of the recrystallized grains increases (96.4 μm, Fig. 4(b)). As the temperature increases to 525 °C, the grain is particularly large (108.1 μm, Fig. 4(c)). And some melting compounds both in the grain boundaries and triple conjunctions are observed (Fig. 4(d)), which means that the specimen is overbunt.

The solid solution was carried out at 525 °C for 2 h in order to dissolve the solute, mainly Cu present in the alloy which is responsible for hardening. The main purpose of the solution heat treatment is to obtain a supersaturated solid solution. But in order to maintain

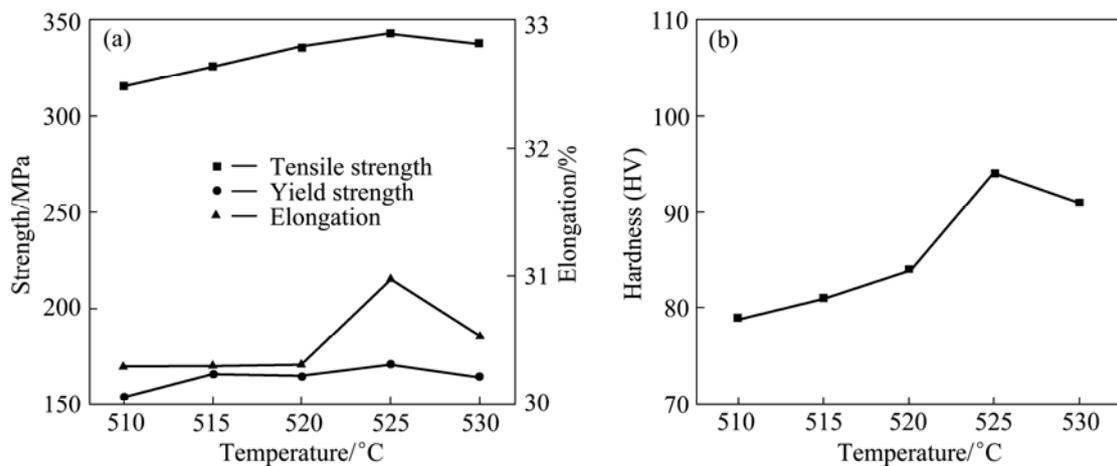


Fig. 3 Mechanical properties of Al-Cu alloy solution treated at different temperatures for 2 h

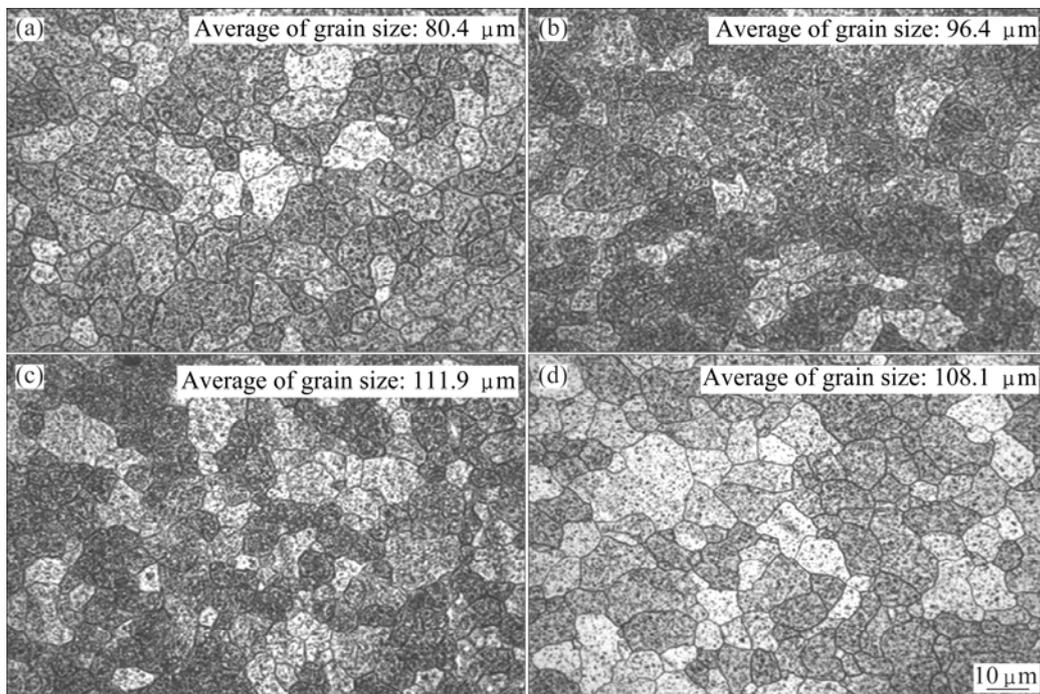


Fig. 4 Optical microstructures of aged Al-Cu alloy solution treated at 515 °C (a), 520 °C (b), 525 °C (c) and 530 °C (d) for 2 h

this desired condition at low temperatures, water quenching is needed. The artificial aging stage consists of further heating the alloy at relatively low temperatures (160–190 °C), and it is during this stage that the CuAl_2 precipitation of dissolved elements occurs. These precipitates are responsible for the hardening of the material which is commonly observed in artificial aging.

Figure 5(a) shows the ultimate tensile strength of Al-Cu alloy after aging. From Fig. 5(a), the increase of temperature is to be expected to dissolve the intermetallic phases into the Al matrix, thus strengthening it. The artificial aging temperatures used were 160, 170, 180 and 190 °C. The ultimate tensile strength shows the maximum after aging at 180 °C for 8 h. Tensile strength increases with increasing aging time

or temperature but decreases after aging for 10 h. However, when aging at 190 °C, a decrease in ultimate tensile strength is observed, which means that the specimen is overaging with increasing aging temperature. Figure 5(b) shows that the yield strength was found as the same as the ultimate tensile strength result. Artificial aging at 160 °C does not reveal an appreciable improvement in yield strength, probably because up to this aging temperature, the GP zones and/or precipitates formed may not be sufficient enough to reflect noticeable changes in the yield strength. The same behavior is observed at 170 °C although the values attained are not as high as those obtained by aging at 180 °C. At 190 °C the decrease in yield strength, characteristic of overaging behavior, may be noted, while at 190 °C, overaging

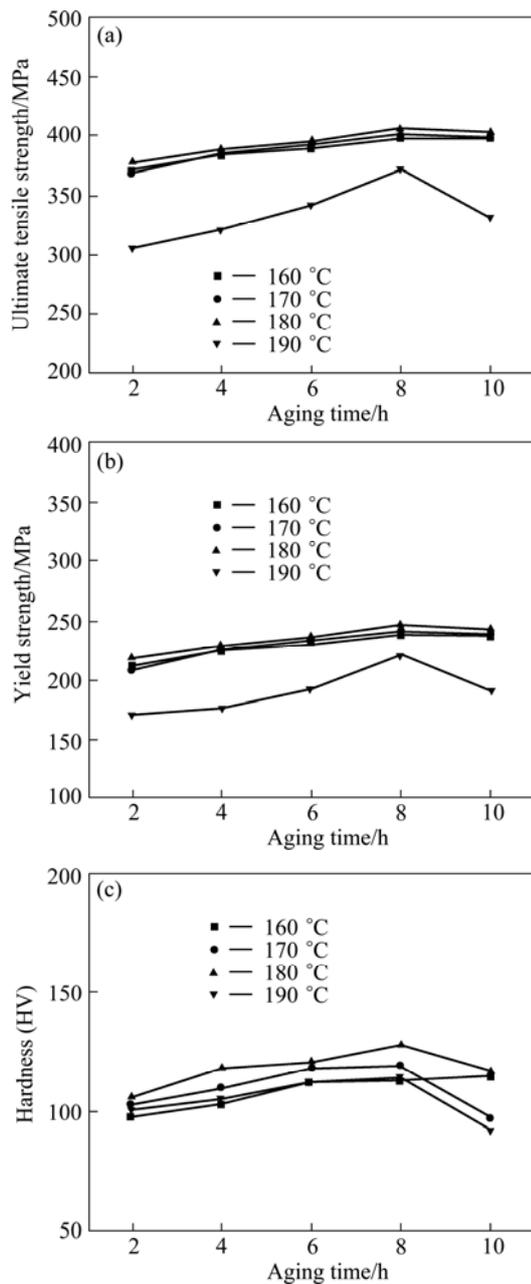


Fig. 5 Mechanical properties of Al-Cu alloy subjected to artificial aging

occurs with increasing aging time.

The tensile strength values reflect the conditions of the bulk casting, since any casting defects, such as inclusions and pores, may affect the values obtained by the test. Microhardness, in turn, reflects the conditions of the Al matrix, since the test is carried out only in the matrix, and only in a small area of the bulk specimen [11–13]. In Fig. 5(c), an increase of the microhardness values obtained may be seen with increasing the aging time when aging at 160 °C or 170 °C. The hardness peak is attained when aging at 180 °C for 8 h. When aging at 180 °C a drop and a slow recovery of the microhardness with aging time are observed, indicating that the

strengthening effect of the artificial aging has already been reached at lower aging temperatures. When the artificial aging temperature is increased to 190 °C, the hardness values show a decrease over time, as to be expected. It will be observed that the best combination of properties, i.e. high tensile strength and microhardness, is achieved when aging at 180 °C for 8 h. The corresponding properties consist of an ultimate tensile strength of 406 MPa, yield strength of 239 MPa and microhardness of HV124. The precipitation of Cu phases is event responsible for the improvement in properties when applying the artificial aging treatments.

When aging the Al-Cu alloy at 180 °C for 8 h, the mechanical properties are the highest values. The precipitation (θ') behaviors after aging 8 h at 180 °C are shown in Fig. 6(a). Al-Cu alloy has now begun to nucleate heterogeneously on dislocations, while the homogeneously nucleated GP zones have developed into within the dislocation-free volumes of the material. The microstructure was found to consist of a high density CuAl_2 (θ') in the background matrix.

Strong (001) Al streaks can be seen in the diffraction pattern shown in Fig. 6(b). A weak set of four CuAl_2 reflections could also be seen in the (220) plane.

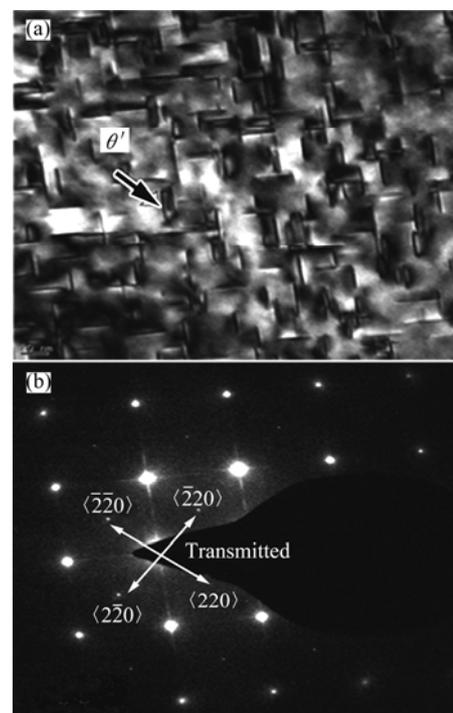


Fig. 6 TEM image (a) and diffraction pattern (b) of Al-Cu alloy after artificial aging at 180 °C for 8 h, near [001] zone

4 Conclusions

Al-Cu alloys were successfully prepared by vertical continuous casting with different process parameters, which are mainly temperature and time, in solution

treatments and artificial aging. It was found that some massive residual phases of CuAl_2 in Al–Cu alloy can be re-dissolved into matrix by solution treatment. As the solution treatment temperature increased to 525 °C, the recrystallized grain size and the fraction of the precipitation in the Al–Cu alloy increased, which also leads to increase in the mechanical properties, especially tensile strength and hardness, of the Al–Cu alloy materials. The overburnt temperature of the Al–Cu alloy was set to 530 °C, which was obtained from hardness results with corresponding microstructure changes. It can be, therefore, suggested that the optimized solution temperature and time were 525 °C and 2 h, respectively. The tensile strength and hardness of the Al–Cu alloy showed 342 MPa and HV 94. Furthermore, the mechanical properties were increased to 406 MPa for tensile strength and HV124 for the Vickers hardness by artificial aging treatment at 180 °C for 8 h after solution treatment. The improvement of mechanical properties is most likely due to the precipitation of hard CuAl_2 phase in the Al–Cu alloy. However, further researches are necessary to investigate on the corrosion resistance and machinability for application of aerospace and automobile parts.

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固溶处理和人工时效对 Al–Cu 合金显微组织和力学性能的影响

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摘要: 对 Al–Cu 合金进行析出强化和人工时效处理以获得优异的力学性能, 如高的强度、好的韧性。其热处理工艺条件为: 510~530 °C 固溶处理 2 h; 60 °C 水淬; 160~190 °C 人工时效 2~8 h。采用光学显微镜、扫描电镜、能谱分析、透射电镜和拉伸实验对经固溶和人工时效处理的 Al–Cu 合金的组织 and 力学性能进行表征。固溶处理实验结果表明, Al–Cu 合金的力学性能随着固溶处理温度的升高先增加, 然后降低。这是由于 Al–Cu 合金的残余相逐渐溶解进入基体中, 从而导致析出相的数量和再结晶晶粒尺寸不断增加。相较于固溶处理温度, 固溶处理时间对 Al–Cu 合金的影响较小。人工时效处理实验结果表明, 合金经 180 °C 时效 8 h, 可以获得最大的拉伸强度。合金的最大拉伸强度和屈服强度随着时效时间的延长和温度的升高而升高。

关键词: Al–Cu 合金; 固溶处理; 人工时效; 显微组织; 力学性能

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