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Effect of second phase precipitation behavior on mechanical properties of casting Al-Cu alloys

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Abstract: The effect of the second phase precipitation behavior on the mechanical properties and fracture behavior of the modified casting Al-Cu alloys was investigated. The tensile strength of the alloys increases firstly and then decreases due to the appearance of θ' precipitation phases, which increases firstly and then become coarser with the aging time increasing from 10 h to 20 h at 155 ℃. The strength of the alloys reaches the peak, resulting from Ω and θ' precipitation phases, and decreases due to Ω phases becoming coarser and θ' precipitation decreasing with the aging time increasing from 10 h to 20 h at 165 ℃. Ω phase becoming coarser and θ' precipitation decreasing result in the strength of the alloys drastically decreasing after aging at 175 ℃ for 20 h. The ductility remains high level with increasing aging time at 155 ℃. The ductility irregularly changes as aging time prolongs at 165 ℃. The ductility is very low and at the same time gradually decreases with increasing aging time at 175 ℃. The Al-Cu alloy with a promising combination of tensile strength and ductility of about 474 MPa and 12.0% after aging at 165 ℃ for 10 h is due to a dense, uniform distribution of Ω precipitation phases together with a heterogeneous distribution of θ' precipitations.

Key words: Al-Cu alloys; heat treatment; mechanical properties; precipitate

1 Introduction

The interest devoted to the study of the casting Al-Cu alloys depends on the extensive use of these materials due to the materials having a combination of high strength and fracture toughness and permitting the design of products characterized by low and very complex geometries in modern industries particularly in the latest generation of the military and civilian aircraft, spacecraft and ground transportation vehicles[1−3]. A lot of effort has been made in order to obtain a promising combination property of strength and ductility of Al alloys. Heat treatment of the Al alloys is one of the most efficient methods to attain a promising combination of strength and ductility due to the precipitation hardening during heat treatment.

Several investigations were carried out on the influence of heat treatment on the mechanical properties of Al alloys[4−9]. In addition, some research on Al alloys also focused on the precipitation phenomena during heat treatment. RINGER et al[10] revealed that in the Al-Cu-Mg alloy, rapid GP zone formation was followed by the formation of θ'' and θ', and after aging for 2.5 h, the microstructure was dominated by θ' together with the S phase and several Ω precipitations.

To the knowledge of authors, there are some investigations into the influence of heat treatment on the mechanical properties, however, little information focused on the effect of precipitation phenomena during the aging process on the mechanical properties of the casting Al-Cu alloys. The objective of the present study is to evaluate the influence of the precipitation phases, the mechanical properties and fracture behavior of the modified casting Al-Cu alloys.

2 Experimental

The compositions (measured by an ARL 4460 Metals Analyzer) of the casting Al-Cu alloy are (mass fraction, %) 6.0 Cu, 0.15 Mn, 0.25 Ti, 0.13 V, 0.13 Zr, 0.001 B and balance Al. The molten Al-Cu alloys

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modified by Pr_xO_y were poured into a steel die to produce tabulate samples of 200 mm×60 mm×12 mm. The as-cast Al-Cu alloys were solution treated isothermally at 510 ℃ for 15 h to dissolve intermetallic compound Al_2Cu prior to cold-water quenching. Artificial aging was carried out at 155, 165 and 175 ℃ for 10, 15 and 20 h, respectively, in the air environment. The heat-treated alloys were cut into dog-bone shaped tensile specimens with a gauge cross-section of 5.0 mm×4.0 mm and a gauge length of 25.0 mm. The tensile tests were carried out on the MTS-810 tester (USA) at a strain rate of 3.33×10^{-4} s^{-1} and at RT. The tensile ductility in this study was measured by calculating the gauge length change of the specimen before and after tensile test. The mechanical property data (with a typical uncertainty of ±1%) in this study were the mean value of at least two specimens.

Metallographic samples were prepared in accordance with standard procedures, and etched with 2.5 HNO_3+1.5 HCl+1.0 HF solution (volume ratio) for 10−30 s at RT. Microstructures and fracture surfaces were examined using an optical microscope (OM) and a scanning electron microscope (SEM) (Model JSM-5310, Japan). Specimens for transmission electron microscopy (TEM) were prepared by twin-jet electron-polishing in a solution of 30% HNO_3-methanol at −30 ℃ and 12 V. TEM observations were carried out on a JEOL-2000EX TEM at 200 kV. The crystallographic structure was analyzed using an X-ray diffractometer (XRD, D/max 2500PC Rigaku, Japan).

3 Results and discussion

3.1 Microstructures and XRD analysis

Fig.1(a) displays the optical microstructure of the as-cast alloys modified by Pr_xO_y. The net-shaped continuous Al_2Cu phase appears at the interdendritic and grain boundaries of the α(Al) matrix, as indicated by arrow 1. The main eutectic reaction occurs at a temperature of 542 ℃, to form Al_2Cu. The optical microstructure of the present alloys after solid solution treatment (as-quenched), shown in Fig.1(b), displays an almost continuous Al_2Cu phase dissolved into the α(Al) matrix. Only a small amount of the remaining Al_2Cu phase can be seen. All solution-treated alloys in the present study have a similar microstructure and grain sizes, as shown in Fig.1(b).

XRD patterns (Fig.2) performed on the as-cast Al-Cu alloys indicate the presence of α(Al) and intermetallic phase (Al_2Cu). The Al_2Cu in the metal matrix is produced from the eutectic reaction by redistribution of solute during Al-Cu melt solidification process. The large amount of Al_2Cu phase in the metal matrix of the as-fabricated alloys is dissolved into the metallic matrix after solution treatment, as shown in Fig.2(b). No Al_2Cu precipitation phase is detected by XRD after aging under various temperatures and time, which can be attributed to the effective dissolution and homogenization of the nanometeric precipitations into the metal matrix.

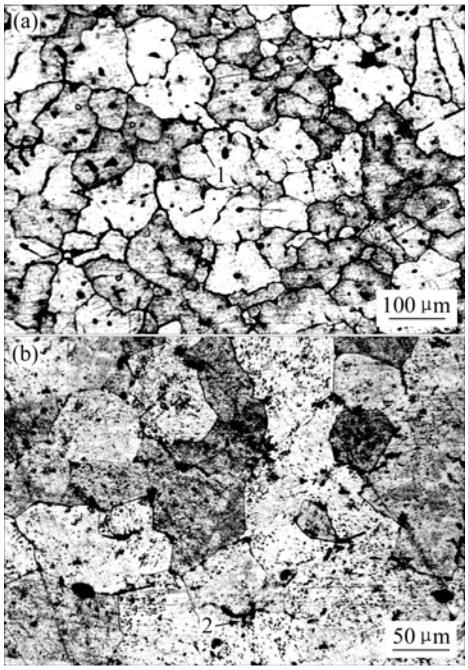

Fig.1 Optical microstructures of present alloys: (a) As-cast (arrow 1: Al_2Cu phase); (b) As-quenched (arrow 2: remains of Al_2Cu phase)

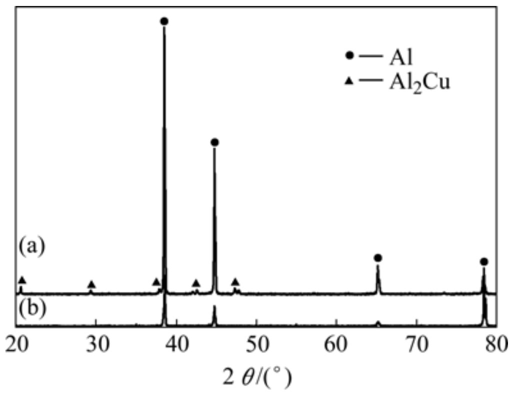

Fig.2 XRD pattern of as-cast (a) and solution-treated (b) Al-Cu alloys

Fig.3 displays the TEM morphologies of the precipitations of the present alloys after aging at different temperatures for different times. Fig.3(a) shows a TEM micrograph of the alloy aged at 155 ℃ for 10 h. The structure does not show obvious precipitation phases. After aging at 155 ℃ for 15 h, there is clear evidence of precipitation phases in the TEM image(Fig.3(b)). The corresponding selected area electron diffraction (SAED, not showed) pattern shows the presence of GP zones and

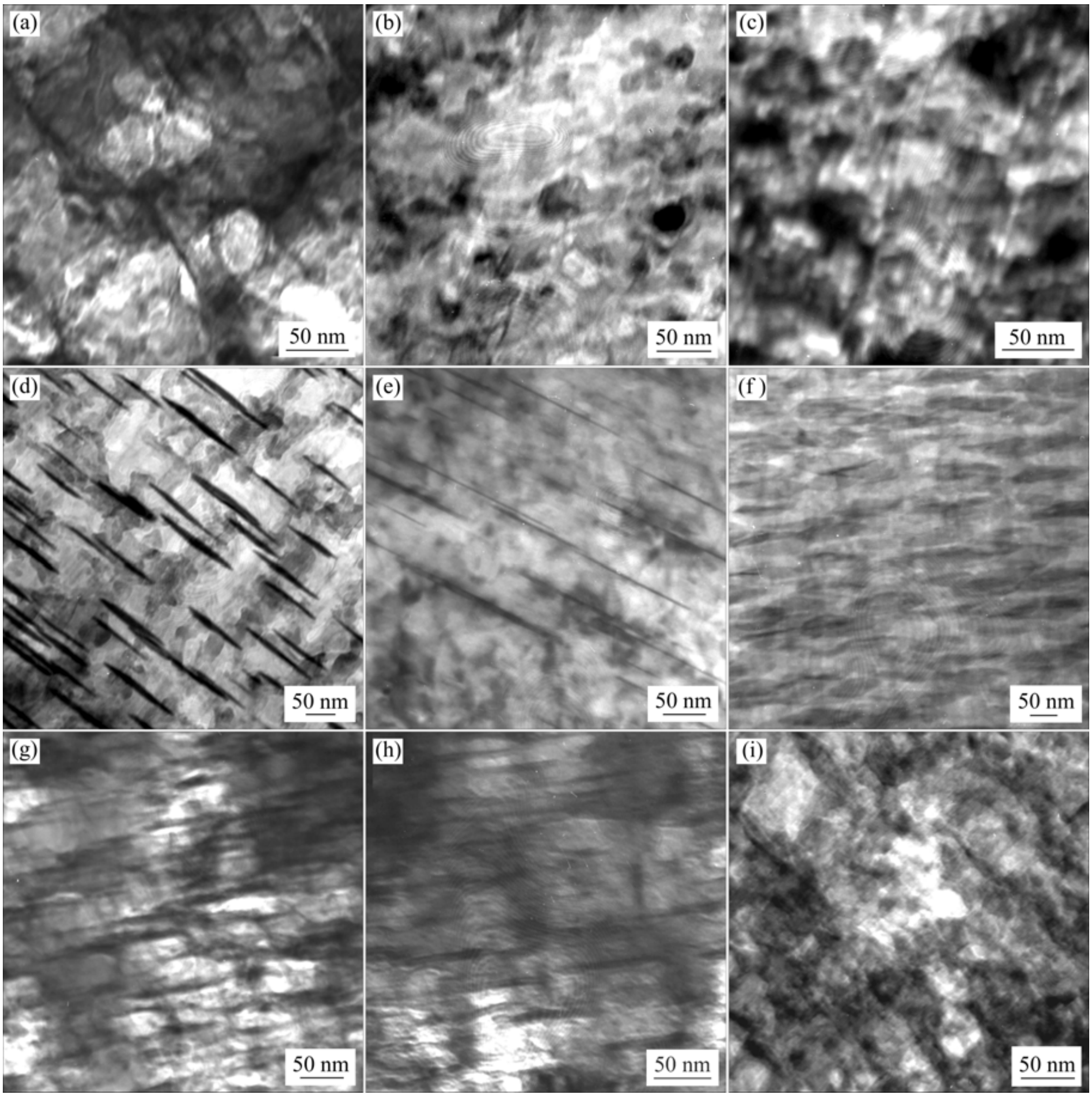

Fig.3 TEM morphologies of precipitates of Al-Cu alloys under different aging conditions: (a) 155 ℃, 10 h; (b) 155 ℃, 15 h; (c) 155 ℃, 20 h; (d) 165 ℃, 10 h; (e) 165 ℃, 15 h; (f) 165 ℃, 20 h; (g) 175 ℃, 10 h; (h) 175 ℃, 15 h; (i) 175 ℃, 20 h

θ'' platelets. After aging at 155 ℃ for 20 h (Fig.3(c)) the size of the precipitates grows clearly. Careful inspection of Fig.3(c) reveals the presence of few faint, plate-like Ω precipitation phases. Fig.3(d) shows that, after aging for 10 h at 165 ℃, the microstructure consists of a dense, uniform distribution of Ω precipitation phases (with the width of 20−30 nm and the length of 120−150 nm) together with a heterogeneous distribution of coarser θ' precipitation phases. With the aging time increasing, Ω precipitation phases become much longer and wider and θ' precipitation phases become much coarser but fewer (Figs.3(e)−(f)). Especially, Ω precipitation phases in the TEM image (Fig.3(f)) with the width of about 50 nm and the length of 120−150 nm are detected, while θ' precipitation phases are not obviously visible. Figs.3(g)−(i) show the TEM morphologies of the precipitations of the present alloys aged at 175 ℃ for different time. After aging for 10 h, the number of Ω precipitation phases (Fig.3(g)) decreases and θ' precipitation phases become rather coarser than those aged at 165 ℃. The number of Ω precipitation phases further decreases and θ' precipitation phases become coarser when aged for 15 h (Fig.3(h)). In contrast to the microstructures in Figs.3(g) and (h), the Ω and coarser θ' precipitation phases in Fig.3(i) are nearly not observed.

The precipitation sequences of the present alloys during aging are as follows:

GP zones and θ'' formation (155 ℃, 15 h)→Ω (155 ℃, 20 h)→Ω and θ' (165 ℃, 10 h)→Ω and θ'

coarsening→nearly no Ω and θ'(175 ℃, 20 h).

3.2 Mechanical properties

The influence of second phase precipitation on the mechanical properties of the present modified casting Al-Cu alloys was studied. Fig.4 shows the relationship between the hardness of the specimens and the aging temperature and times. The results for 65 h reveal that the hardness reaches peak after aging for 15 h at 155, 165 and 175 ℃, respectively. From the hardness values, it is also found that the hardness increases firstly and then decreases with increasing aging temperature for the same aging time.

The measured mechanical properties of the present alloys under different conditions are summarized in Table 1. The variation in the hardness, tensile strength and ductility of the alloys is related to the behavior of the precipitation due to the different aging temperature and time. It is clear that the tensile strength of the alloy aged at 155 ℃ for 10, 15 and 20 h is 439, 461 and 398 MPa, respectively, while the ductility of them still remains almost constant. This is related to the precipitation phenomena during the aging process at 155 ℃. For shorter aging time (10 h), no obvious precipitation phases emerge, which results in the lower strength and hardness; with the aging time increasing (15 h), the presence of GP zones and θ'' precipitation phases leads to the enhancement in strength and hardness; however, with the aging time further prolonging (20 h), the coarser precipitation phases are responsible for the reduction in strength and hardness. The alloy with a promising combination of tensile strength and ductility of about 474 MPa and 12.0% after aging at 165 ℃ for 10 h is due to a dense, uniform distribution of Ω precipitation phases together with a heterogeneous distribution of θ' precipitation phases. It is noted that after aging at 165 ℃, with the aging time increasing from 10 h to 20 h, the tensile strength of the alloys decreases. The tensile strength and hardness of the alloys decrease after being aged at 175 ℃ for different time. For shorter time (10 h and 15 h), even though Ω and θ' precipitation phases decrease and become coarser, the tensile strength of the alloy keeps higher level; for longer aging time, these precipitation phases drastically decrease due to the precipitation phases becoming further coarser, resulting in the strength drastically decreasing.

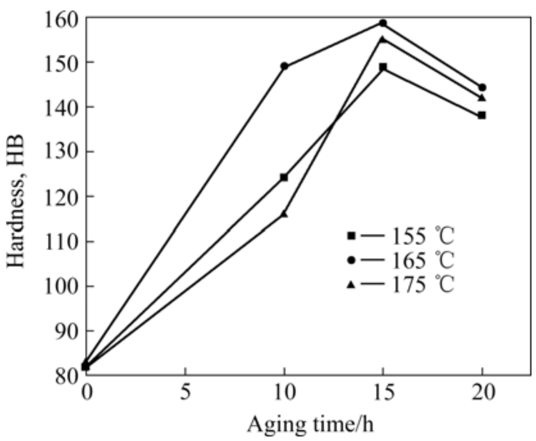

Fig.4 Relationship between hardness of specimens and aging temperatures and time

Table 1 Mechanical properties of modified casting Al-Cu alloys under different heat treatment conditions

Heat treatment	σ_b/MPa	Elongation, δ/%
155 ℃, 10 h	439	8.8
155 ℃, 15 h	461	12.8
155 ℃, 20 h	398	11.6
165 ℃, 10 h	474	12.0
165 ℃, 15 h	463	4.8
165 ℃, 20 h	352	16.8
175 ℃, 10 h	446	7.2
175 ℃, 15 h	450	6.0
175 ℃, 20 h	397	4.4

3.3 Fracture analysis

Fig.5 displays that there are dimples of various sizes and intergranular cracks on the tensile fracture surfaces of the present Al-Cu alloys aged at different temperature for different time. The monotonic fracture surfaces are helpful in elucidating microstructural effects on ductility and fracture properties of the metal alloys. It is clear that the coarse dimples contain secondary constituent particles and the coarse constituents fracture first and act as microcrack precursors. This kind of mixed fracture initiates at second phase precipitations and links up along the matrix grain boundaries, which was been studied in the 7055 alloys previously[11].

For the tensile fracture morphology of the alloy aged at 155 ℃, there are a few fine and coarse dimples and some cracks (arrowed), as shown in Fig.5(a). However, there are a large amount of fine and uniformly dispersed dimples in the alloys aged for 15 h, 20 h, respectively. The result agrees well with the ductility data in Table 1. It is clear that few θ' precipitation phases appear due to a lower aging temperature, which may be responsible for the lower tensile strength but the higher ductility of the alloys for similar aging time. The tensile fracture morphologies (Figs.5(d)−(f)) of the alloys aged at 165 ℃ are consistent with their ductility data. These tensile fracture morphologies show that a large amount of small dimples exist on the tensile fracture surfaces of the alloys aged for 10 h and 20 h, while few dimples and some coarse cracks and cavities appear in the alloy aged for 15 h. This indicates that the overall deformation

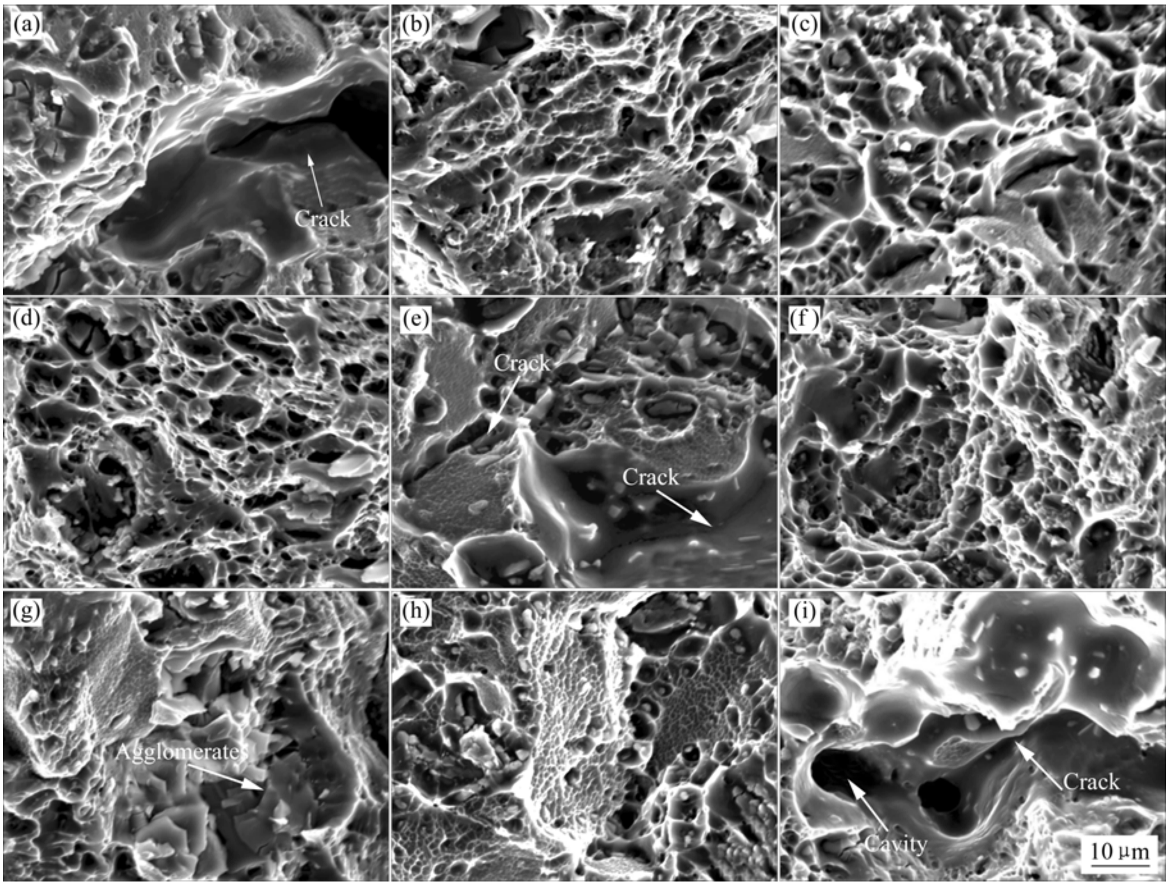

Fig.5 Tensile fracture surfaces of Al-Cu alloys under different conditions: (a) 155 ℃, 10 h; (b) 155 ℃, 15 h; (c) 155 ℃, 20 h; (d) 165 ℃, 10 h; (e) 165 ℃, 15 h; (f) 165 ℃, 20 h; (g) 175 ℃, 10 h; (h) 175 ℃, 15 h; (i) 175 ℃, 20 h

occurs uniformly in the alloys aged for 10 h and 20 h and the local deformation for the alloy aged for 15 h. More research work is underway to better understand the interesting phenomena on the mechanical properties of the alloys aged at 165 ℃ for different aging time. When the aging temperature increases up to 175 ℃, the fracture mode of the alloys shows brittleness fracture. It is found that few dimples and some intergranular cracks exist on the tensile fracture surfaces of these alloys and several θ' precipitations agglomerates (arrowed) appear at the dimple centers. This may be responsible for microcrack initiation due to the inherent incompatibility between them and the Al matrix during deformation, resulting in the low ductility of these alloys. In addition, no improvement in strength is obtained when aged at 175 ℃ with sacrificing much of the ductility, which may be attributed to large Ω becoming coarser and θ' precipitation phases decreasing till disappearing at higher aging temperature, resulting in the tensile strength decreasing.

4 Conclusions

1) The evolution of microstructures of the casting Al-Cu alloys during aging was investigated.

When aging at 155 ℃ for 10 h, no obvious precipitation phases are formed; GP zones and θ' are formed after 15 h; plate-like Ω precipitation phases emerge after 20 h.

When aging at 165 ℃ for 10 h, the microstructure is dominated by Ω and θ' precipitation phases; while aging for 15 h and 20 h, Ω precipitation phases become much longer and wider and θ' precipitation phases become much coarser but fewer.

When aging at 175 ℃ for 10 h, the number of Ω precipitation phases decrease and θ' precipitation phases become rather coarser than those aged at 165 ℃. After aging for 15 h, the number of Ω precipitation phases further decreases and θ' precipitation phases become coarser; after aging for 20 h, no Ω and coarser θ' precipitation phases are observed.

2) Mechanical properties of the present Al-Cu alloys vary significantly with aging temperature and time. The ductility remains high level with aging time increasing at 155 ℃; the ductility changes irregularly as aging time prolongs at 165 ℃; the ductility is very low and gradually decreases with aging time increasing at 175 ℃. The tensile strength results agree with the hardness tests

in the present study.

3) The Al-Cu alloy with a promising combination of tensile strength and ductility of about 474 MPa and 12.0% after aging at 165 ℃ for 10 h is due to a dense, uniform distribution of *Ω* phase precipitates together with a heterogeneous distribution of *θ*′ precipitates.

4) Fracture morphologies change with the aging temperatures and time. There are a few fine and coarse dimples and some cracks existing on the fracture surfaces of the alloy aged at 155 ℃ for different aging time. The fracture morphologies of specimens aged at 165 ℃ show that a large amount of small dimples exist in the alloys except for that aged for 15 h. Few dimples, several particle agglomerates and some intergranular cracks exist on the fracture surfaces of the alloys aged at 175 ℃.

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