The novel low cost as-casting Al-based composites with high strength and ductility

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Abstract
In this paper, three alloys Al₈₁Cu₁₃Si₆, Al₈₈Cu₈Si₄ and Al₉₂Cu₅.₆Si₂.₄ were prepared by a simple solidification process. By controlling the alloy composition, different microstructures and mechanical properties have been achieved. The Al₈₁Cu₁₃Si₆ alloy with micro-scale binary eutectic compositions embedded in an ultrafine ternary eutectic matrix exhibits the high yield strength (up to 750 MPa) but fails with a brittle fracture. While the Al₉₂Cu₅.₆Si₂.₄ alloy with hypereutectic composite structure exhibits the optimum comprehensive mechanical properties with both high tensile strength and ductility. The present results provide a new perspective to prepare Al-based alloy with high strength and ductility by designing the some new composite with optimum microstructure.

1. Introduction

Al alloys have attracted much attention over the past decades due to their excellent specific strength, corrosion resistance, formability and low cost, and have been widely used in the realms of aviation, aerospace and automotive [1–3]. To further improve the strength, precipitation strengthening is the main strategy and widely used, especially for the 2xxx and 7xxx series Al alloys. Many researches have been devoted to enhance the mechanical properties of Al alloys by tailor the microstructure of the precipitates, in terms of distribution, size, volume fraction and inter-particle spacing, through microalloying, deformation, and aging treatments [4–6]. However, precipitates coarsen rapidly at elevated service temperatures due to thermally induced diffusion of the alloying element, leading to severe loss in strength and ductility. To overcome this shortcoming, some precipitates with more coarsening resistant such as Al₃X (e.g. X = Sc, Er, etc) and Ω precipitates have been developed [7, 8]. The Ω precipitation is considered as a variant of equilibrium θ-Al2Cu. It has a high coarsening resistance at elevated temperature and is usually found in the Al–Cu–Mg alloy. Moreover, some novel co-additions and synergistic coupling among multiple precipitates have also been proposed [9–13]. Gao et al [14] reported that the creep rate of the Al–Cu alloy with coexisting and coupled (θ-Al2Cu precipitates + Al₃Sc particles) nano-precipitates can be reduced by an order of magnitude under 300 °C.

However, these methods have multiple processing steps, for example the four-stage heat treatment processing protocol and longstanding aging treatment in the reference. Therefore, it is inevitable to increase the cost of commercialization.

Recently, Park et al [15] reported that Al₉₅Cu₁₇ binary ultrafine eutectic alloy presented a high strength of 1.2 GPa at ambient temperature just using the simple and low-cost copper mold casting. This Al₉₅Cu₁₇ eutectic alloy consists of the α-Al and θ-Al₂Cu phases arranged in an alternating fashion with a lamellar spacing of 200–300 nm. This ultrafine lamellar eutectic microstructure usually exhibits a good thermal stability. However, like the most bulk nano-structured alloys, this nano/ultrafine lamellar eutectic alloys also fail catastrophically at ambient temperature by the highly localized deformation behavior. To enhance the ductility, some inhomogeneous microstructures such as the micron-scale soft and ductile dendritic phase have been introduced into Al-based ultrafine matrix [16–19]. Recently, Lisboa de Guveia, et al [20] reported that mechanical properties...
can be adjusted by microstructure and cooling rate. However, limited tensile plasticity has been obtained, even though some Al-based ultrafine eutectic composites show a good compressive plasticity.

In this paper, the Al–Cu–Si composites are prepared by the progressive solidification in order to minimize the cast flaws which are usually inevitable using copper mold casting. By further adjusting the volume fraction and grain size of the primary dendrites, the developed composites exhibit excellent tensile plasticity. The relationship between microstructure and mechanical properties of the Al–Cu–Si composites is also discussed in detail. The present results will give a new clue to enhance the tensile ductility of the ultrafine-grained composites by matching the microstructure characteristics of the primary dendrites, such as the volume fraction and grain size.

2. Experimental procedures

The Al-based alloys with nominal compositions of Al92Cu5.6Si2.4, Al88Cu8Si4 and Al81Cu13Si6 were prepared by arc-melting the mixture pieces of Al, Cu and Si. And then the button ingots were cast into rod-shaped samples with 7 mm diameter by gravity casting. In order to eliminate the cast flaws, these rod-shaped samples were remelted by induction heating method and progressively solidified at a withdrawal velocity of 4.0 mm s\(^{-1}\) under the directional solidification device. The temperature gradient was about 17 K mm\(^{-1}\).

Optical microscopy (OM) was used to investigate the microstructure and x-ray diffractometry (XRD) was used to identify the phase of the resulting samples. The XRD peaks and phase identification were identified using MDI Jade 5.0 Version based on PDF 22004 Database. The specimens for tensile test were machined into a gauge length of 12.4 mm and 2.5 mm in diameter according to the ASTM E8M. Room temperature tensile tests were conducted on the Instron-8801 testing machine using an initial engineering strain rate of \(5 \times 10^{-4} \text{ s}^{-1}\). At least three samples for mechanical testing were measured to ensure that the results are reproducible and statistically meaningful. The fracture morphologies were investigated by the scanning electron microscopy (SEM).

3. Results and discussion

Figure 1(a) shows XRD patterns of the three alloys. As can be seen from the patterns, the three alloys are all composed of \(\alpha\)-Al solid solution, \(\theta\)-Al\(_2\)Cu intermetallic compound and primary Si phase due to the same kind of metal elements. However, there’s slight difference in intensity, especially in peaks of \(\alpha\)-Al phases, which is caused by the differences in constitution and volume fraction of phases.

Figures 1(b)–(d) exhibit microstructures of the as-cast Al–Cu–Si alloys. Figure 1(b) shows the microstructure of Al81Cu13Si6 alloy, which exhibits an obviously complex microstructure with length scale heterogeneity. Few micrometer-scale dendrites (denoted by red arrows) is found, lamellar cellular structures
(denoted by blue arrows) are randomly distributed in a nanoscale eutectic structures (denoted by yellow arrows). As reported in previous studies [16, 20, 21], the cellular structures are identified as binary eutectic of α-Al and θ-Al2Cu, the ultrafine ternary eutectic matrix is consisted of the α-Al, θ-Al2Cu and β-Si.

Figure 1(c) reveals an obviously hypoeutectic structure of Al88Cu8Si4 alloy. According to previous study, the high volume fraction of primary phase (account for 52 vol%, denoted by red arrow) can be easily identified as α-Al solid solution [22], with its grain size ranging from 5–10 μm. Some ultrafine ternary eutectic matrixes (denoted by yellow arrow) are also found. As can be seen in figure 1(d), with the increase in the Al content, the volume fraction and grain size of α-Al phase increase to 65% and 20–30 μm, respectively, and only a few ultrafine ternary eutectic matrixes are remained.

Figure 2 shows the engineering tensile stress-strain curves of alloys. As shown, the Al81Cu13Si6 alloy exhibits highest yield strength (up to 750 MPa) but fails with a brittle fracture. However, according to previous studies [16, 23], plasticity above 10% can be achieved by Al-alloy with similar composition and microstructure under compression. We think that this contradiction in the plasticity should be attributed to the difference in the deformation mechanism for the compression and tension. In the tension, microcracks are more likely to propagate to failure. The Al88Cu8Si4 alloy shows an obvious ductility with a tensile strength of 600 MPa. The plasticity is significantly further increased for the Al92Cu5.6Si2.4 alloy, which exhibits an engineering strain of 10% with a tensile strength of 500 MPa. Similar to the previous studies [22, 24–27], the present results also clearly show that the α-Al phase plays a vital role in the mechanical properties of the Al–Cu–Si alloys. Generally, with the increase in the volume fraction of the soft α-Al phase, the ductility of alloys should be enhanced. The larger grain size of α-Al phase is also more favorable to prevent the propagation of microcracks or shear bands, and results in the improvement of ductility. Furthermore, Xia et al [26] reported that the work hardening ability of the soft primary phase had strong effective on the plasticity in the Cu–Al alloys. Therefore, we propose that the optimum comprehensive mechanical properties of the Al–Cu–Si alloys can be obtained by tailoring the volume fraction, morphology and work hardening ability of the α-Al phase. The more quantitative analyze will be conducted in our future researches.

Figure 3 shows the microscopic fracture morphologies of samples. As shown, the Al81Cu13Si6 alloy shows a cleavage-like feature under tensile stress. Only one main crack runs through the whole specimen with few plastic deformations, according with stress-strain curves shown in figure 2. As depicted in figure 3(b), the rough fracture surface of Al88Cu8Si4 exhibits apparently different fracture behavior, indicating ductile deformation occurred before fractured. It can be seen that the primary dendrite α-Al phase plays an important role in improving the plasticity. As the volume fraction and grain size of dendrite α-Al phases increasing, more dimple-like patterns are observed continuously distributing in the Al92Cu5.6Si2.4 alloy as shown in figure 3(c).

4. Conclusion

In conclusion, the three alloys Al81Cu13Si6, Al88Cu8Si4 and Al92Cu5.6Si2.4 were prepared by the progressively solidified. The Al81Cu13Si6 alloy exhibits highest yield strength (up to 750 MPa) but fails catastrophically under
tensile stress. With the increase of the Al content and the primary $\alpha$-Al dendrites, the ductility increases significantly, such as the Al$_{92}$Cu$_{5.6}$Si$_{2.4}$ alloy exhibits an engineering strain of 10% with a relatively high tensile strength of 500 MPa. These excellent mechanical properties of the present alloys are comparable to those of AA2050-T84 and AA7050-T7451 alloys, which are widely used as aircraft-grade aluminum alloys for their high strength and low weight [3]. Moreover, the alloys in this study are as cast without heat treatment. This simple in composition and preparation process will promote the commercial application of the present alloys. We also expect that the optimum comprehensive mechanical properties of the Al–Cu–Si alloys can be further improved by tailoring the volume fraction, morphology and work hardening ability of the $\alpha$-Al phase.

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References

[1] Witkin D et al. 2003 Al–Mg alloy engineered with bimodal grain size for high strength and increased ductility Scr. Mater. 49 297–302
[2] Nakai M and Eto T 2000 New aspect of development of high strength aluminum alloys for aerospace applications Mater. Sci. Eng. A 285 62–8
[3] Chemin A E A et al. 2019 Characterization of phases, tensile properties, and fracture toughness in aircraft-grade aluminum alloys Mater. Des. & Pro. Commun 1 679
[4] Ivanov R, Deschamps A and De Geuser F 2018 Clustering kinetics during natural ageing of Al–Cu based alloys with (Mg, Li) additions Acta Mater. 157 186–95
[5] Quaresma J M V, Santos C A and Garcia A 2000 Correlation between unsteady-state solidification conditions, dendrite spacings, and mechanical properties of Al–Cu alloys Mater. Sci. Eng. A 31 5167–78
[6] Chen J et al. 2009 Investigation of precipitation behavior and related hardening in AA 7055 aluminum alloy Mater. Sci. Eng. A 500 34–42
[7] Dorin T et al. 2017 Effect of Sc and Zr additions on the microstructure/strength of Al–Cu binary alloys Mater. Sci. Eng. A 707 58–64
[8] Unla N et al. 2003 A The effect of cold work on the precipitation of $\Omega$ and $\theta'$ in a ternary Al–Cu–Mg alloy Metall. Mater. Trans. A 34 2757–69
[9] Zhao G W, Ding C and Gu M C 2019 Effects of cooling rate and initial composition on the solidification path and microstructure of Al–Cu–Si alloys Int. J. Cast. Metals. Res. 32 36–45
[10] Li Q et al. 2018 High-strength nanotwinned Al alloys with 9R phase Adv. Mater. 30 1704629
[11] Zhou D, Qiu F and Jiang Q 2015 The nano-sized TiC particle reinforced Al–Cu matrix composite with superior tensile ductility Mater. Sci. Eng. A 622 118–93
[12] Kim J T et al. 2018 Cooperative deformation behavior between the shear band and boundary sliding of an Al-based nanostucture-dendrite composite Mater. Sci. Eng. A 735 81–8
[13] Kim J T et al. 2018 Microstructure and mechanical properties of hierarchical multi-phase composites based on Al–Ni-type intermetallic compounds in the Al–Ni–Cu–Si alloy system J. Alloys Compd. 749 205–10
[14] Gao Y H et al. 2019 Stabilizing nanoprecipitates in Al–Cu alloys for creep resistance at 300 °C Mater. Res. Lett. 7 18–25
[15] Park J M et al. 2010 Multi-phase Al-based ultrafine composite with multi-scale microstructure Intermetallics 18 1829–33
[16] Park J M et al. 2009 High-strength bulk Al-based bimodal ultrafine eutectic composite with enhanced plasticity J. Mater. Res. 24 2605–9
[17] Lee S W et al. 2014 Micro- to nano-scale deformation mechanisms of a bimodal ultrafine eutectic composite Sci. Rep. 4 6500
[18] Li X P et al. 2015 A selective laser melting and solution heat treatment refined Al–12Si alloy with a controllable ultrafine eutectic microstructure and 25% tensile ductility Acta Mater. 95 74–82
[19] Tiwary C S, Roy Mahapatra D and Chattopadhyay K 2012 Effect of length scale on mechanical properties of Al–Cu eutectic alloy Appl. Phy. Lett 101 171901
[20] Gouveia D et al 2019 Slow and rapid cooling of Al–Cu–Si ultrafine eutectic composites: interplay of cooling rate and microstructure in mechanical properties J. Mater. Res. 34 1381–94
[21] Ramakrishnan B P et al 2017 Effect of laser surface remelting on the microstructure and properties of Al–Al 2 Cu–Si ternary eutectic alloy Sci. Rep. 7 1–10
[22] Kim J T et al 2016 Understanding the relationship between microstructure and mechanical properties of Al–Cu–Si ultrafine eutectic composites Mater. Des 92 1038–45
[23] Kim J T et al 2019 Influence of directional microstructure on mechanical properties in Al-based ultrafine bimodal lamellar structured alloy Mater. Des & Pro. Commun 1 e52
[24] Park J M et al 2018 High strength ultrafine eutectic Fe–Nb–Al composites with enhanced plasticity Intermetallics 16 642–50
[25] Cheng J L, Yun Y L and Rui J X 2019 Enhanced tensile plasticity in ultrafine lamellar eutectic Al–Cu based composites with α-Al dendrites prepared by progressive solidification Appl. Sci. 9 3922
[26] Xia S H and Wang J T 2010 A micromechanical model of toughening behavior in the dual-phase composite Int. J. Plast. 26 1442–60
[27] Liu G et al 2013 Nanostructured high-strength molybdenum alloys with unprecedented tensile ductility Nature Mater 12 344–50