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著者(和文)	陳 宣良
Author(English)	Xuanliang Chen
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論 文 要 旨

THESIS SUMMARY

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学生氏名： Student's Name	陳　宣良	指導教員（主）： Academic Supervisor(main)	小林　郁夫
		指導教員（副）： Academic Supervisor(sub)	

要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

The Al-Mg-Cu alloy with a low Cu/Mg ratio is heat-treatable Al alloy and belongs to newly developing alloying systems. This alloy is expected to have potential applications in the automotive industry, due to its rapid aging hardening, good formability, and corrosion resistance. The mechanical properties and microstructure of Al-Mg-Cu alloys processed by plastic deformation and aging heat treatment have been studied by using several experimental techniques.

The effects of 3%–50% cold rolling (CR) following solution heat treatment on the age hardening of an Al-3Mg-1Cu alloy have been investigated. Pre-deformation has a strong effect on subsequent age-hardening behavior. Rapid age hardening of the base alloy is absent in CR alloys. Instead, recovery was observed in the highly pre-deformed samples. The hardness peak advances with the increasing reduction rate. A larger fraction of precipitates was observed along the dislocation lines and the S phase formation peaks in the DSC curves of the CR alloys appeared at lower temperatures, indicating that the precipitation of S phases was accelerated by deformation-induced dislocations. Since Guinier–Preston–Bagaryatsky (GPB) zones were observed in the 20 min aged CR samples and two types of S phases were detected in the CR samples aged for 1 day, the GPB zones and S phases were thought to cause first and second hardness increases in cold rolled samples, respectively. The contributions of clusters/GPB zones and S phases to hardness were evaluated in both non-deformed and deformed alloys for comparison. The hardness of the plateau was found to be dynamically balanced by the dissolution of clusters/GPB zones and the formation of S phases. In the base alloy, clusters/GPB zones and S phases contribute together to the peak hardness, and clusters/GPB zones are still stable even after long-term aging. However, the contribution of GPB zones becomes lower in the CR alloys, and all of them will transform into S phases after long-term aging. It was found that paint-baking (443 K for 20 min) performed on the as-rolled samples resulted in a good strength-elongation balance because of the annihilation of dislocations and the formation of GPB zones. The results are significant for the development of combined mechanical deformation and heat treatment processes.

The GPB zone and the S phase are the key strengthening precipitates in Al-Mg-Cu alloys. However, their respective structures evolution during aging has not been fully understood. In this work, the precipitation process and the structure of precipitates in an Al–3Mg–1Cu

(wt.%) alloy were investigated. A series of common GPB zones and a novel type of GPB zone named “GPBX” were observed in the cold-worked samples aged at 443 K for 20 min. In the subsequent aging, two types of S phases were found to coexist, labeled S-I and S-II phases. Density functional theory calculation results indicate that the GPBX zone is stable and the S-I and S-II phases have almost the same formation enthalpy. Common GPB zones transform to S-I phases, while S-II phases are formed from GPBX zones preferentially along dislocation lines. Also, a structural model for the S-II phase is proposed, supported by atomic-resolution HAADF-STEM in association with first-principles energy calculations. The misorientation angles of the S phases were discussed. Changes in morphologies of two types of S phases during aging were observed, and related growth mechanisms were proposed. Finally, the similar behavior of Cu and Si regarding the formation of precipitates has been discussed. GPB zones were confirmed to be structurally linked to β” and U2 precipitates reported in 6xxx (Al-Mg-Si) series Al alloys. The complex structure mixed with different types of precipitates is confirmed. The revealed precipitate structures and their interrelationships may provide insights into future alloy design.

Aging is known as a traditional strengthening method for heat treatable Al alloys. Recently, cyclic strengthening has received widespread attention as a novel method. Cyclic deformation was applied to introduce dislocations and promote cluster formation in an Al-Mg-Cu alloy. The cyclically strengthened (CS) samples have both higher strength and ductility than the peak-aged samples. The aging behavior of CS samples as well as the effect of pre-aging on cyclic strengthening were also studied. The recovery and precipitation promotion were found during the aging of CS samples regardless of the pre-aging for 20 min. Since more clusters (or precipitates) have been formed in pre-aged CS samples, they show higher strength than those CS samples without pre-aging. Interestingly, after subsequent aging, the mechanical properties of CS samples with and without pre-aging for 20 min became the same. This indicates that there is no essential difference between clusters formed during cyclic deformation and aging. In summary, aging and cyclic deformation methods were combined to maximize the effects of precipitation strengthening and work hardening. The strength limit obtained by individual aging or cyclic deformation methods was successfully broken through. These provide new insights into alloy strengthening.

Overall, this study deepens the understanding of relationships among microstructure (at atomic- and nano-scale), mechanical properties, plastic deformation and aging heat treatment of aluminum alloys.