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Strengthening Al-Mg-Si Alloys with Ultra Fine Sub-grain Structure

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It has been demonstrated that the grain refinement with suitable solute atoms is one of the possible ways to enhance the strength without losing the ductility. In this study, grain refinement of Al-Mg and Al-Mg-Si system alloys in the range of sub-micro meter is demonstrated by using caliber rolling. Yield strength of both system alloys increased to approximately double that of the conventionally extruded alloys with coarser grain structure. The strain hardening rate after yielding was, however, found to be reduced by the severe plastic working. After aging treatment, the element Si could enhance the yield strength and the strain hardening rate which resulted in the ductility enhancement. The formation of fine precipitates at nanometer scale, in combination with the ultra-fine sub-grain structure, plays an important role in the improvement.

Keywords: *Strengthening, Severe plastic deformation, Grain refinement, Solute atoms*

1. Introduction

Recently, reducing CO_2 emission has become a strong social demand to prevent global warming. Since lightweight structure in vehicles is one of the promising ways for the reduction, strengthening Al alloys with abundant elements provides a good solution. Enhancing fracture toughness and/or ductility is additional requirement for the reliable application. It has been reported that the grain refinement with suitable solute atoms is one of the possible ways to enhance the strength without losing the ductility. Examples of combination of strength and ductility are shown in Fig. 1 for commercially available Al alloys listed in ASM handbook [1]. There exists a certain limitation of the combination even after the suitable aging treatment. Several advanced processing methods, e.g., mechanical alloying [2,3], crystallization from amorphous powders [4], vapor quenching [5], severe

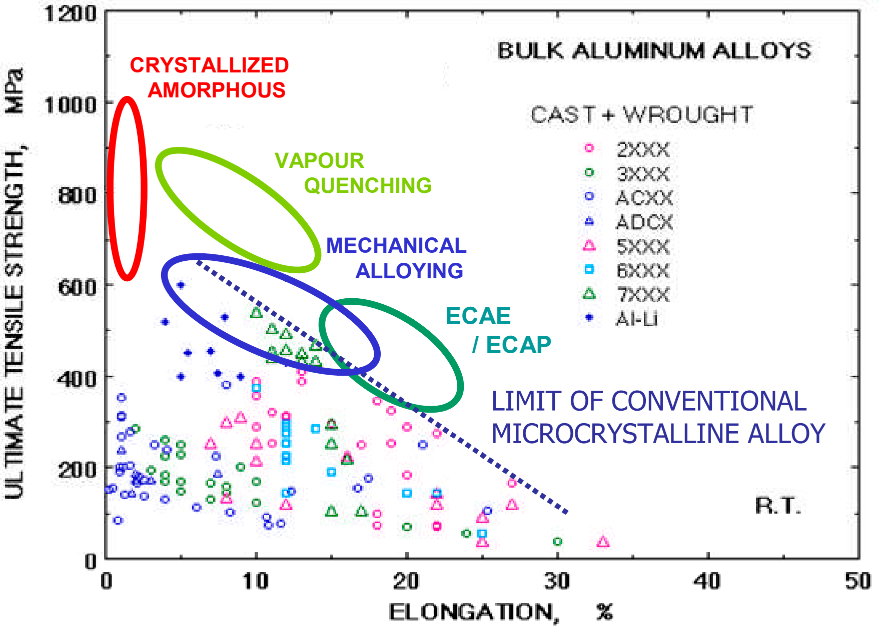


Fig. 1 Combination of strength (UTS) and ductility (elongation) in Al alloys [1].

plastic working [6,7], have been demonstrated to enhances the combination as marked in this figure. The major strengthening factors in these products are noted to be refining the matrix grains and homogeneous distribution of fine disperse phase. On the other hand, it has been reported that the elongation-to-failure in Al alloys tends to decrease with refining the grain size as shown in Fig. 2 [8]. In this figure, trends at a quasi-static strain rate and a high stain rate are plotted as narrow and bold lines, respectively. Deviation between two strain rates tends to decrease with decreasing grain size [9]; elongation-to-failure at the high strain rate decreases markedly in the powder metallurgy processed alloys [10]. The elongation-to-failure of ECAE Al-Mg alloy, however, decreases gradually even at the high strain rate. Therefore, the fine grained Al alloys strengthening with suitable solute atoms are possible candidates for high strength Al alloys with ductility in a wide range of strain rate.

In this study, grain refinement of Al-Mg and Al-Mg-Si system alloys into the range of sub-micro meter is demonstrated by using caliber rolling. Role of sub-grain boundary and distributed precipitates in nano-meter scale is investigated to enhance the combination of strength and ductility in these system alloys.

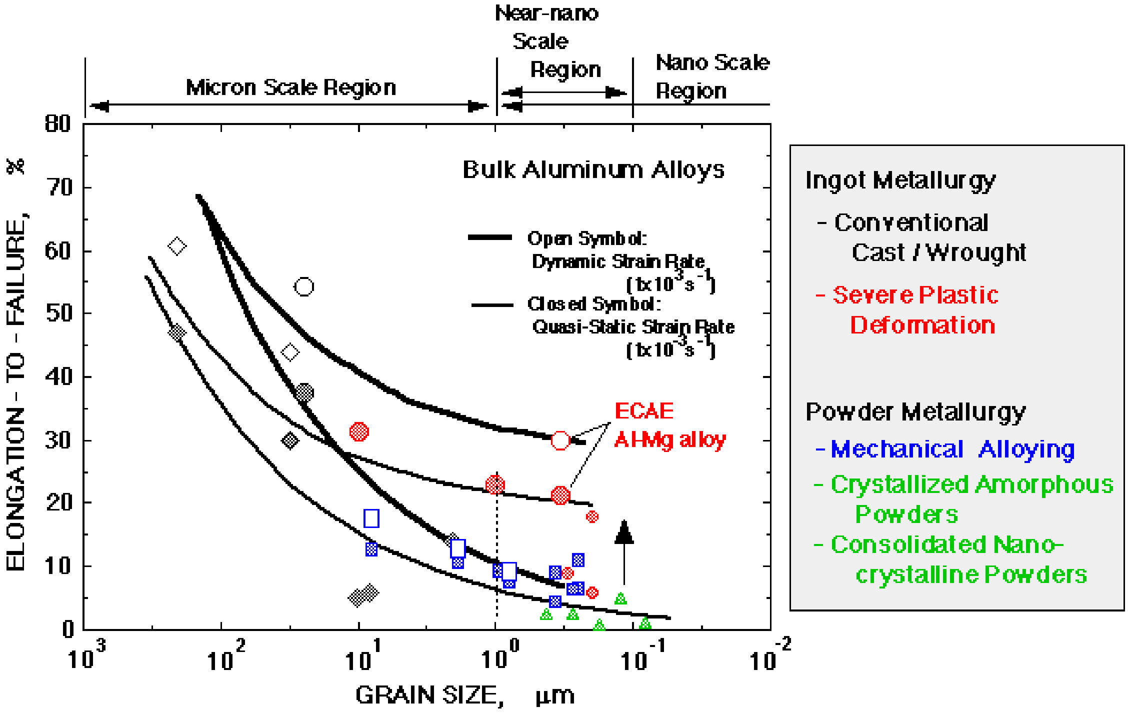
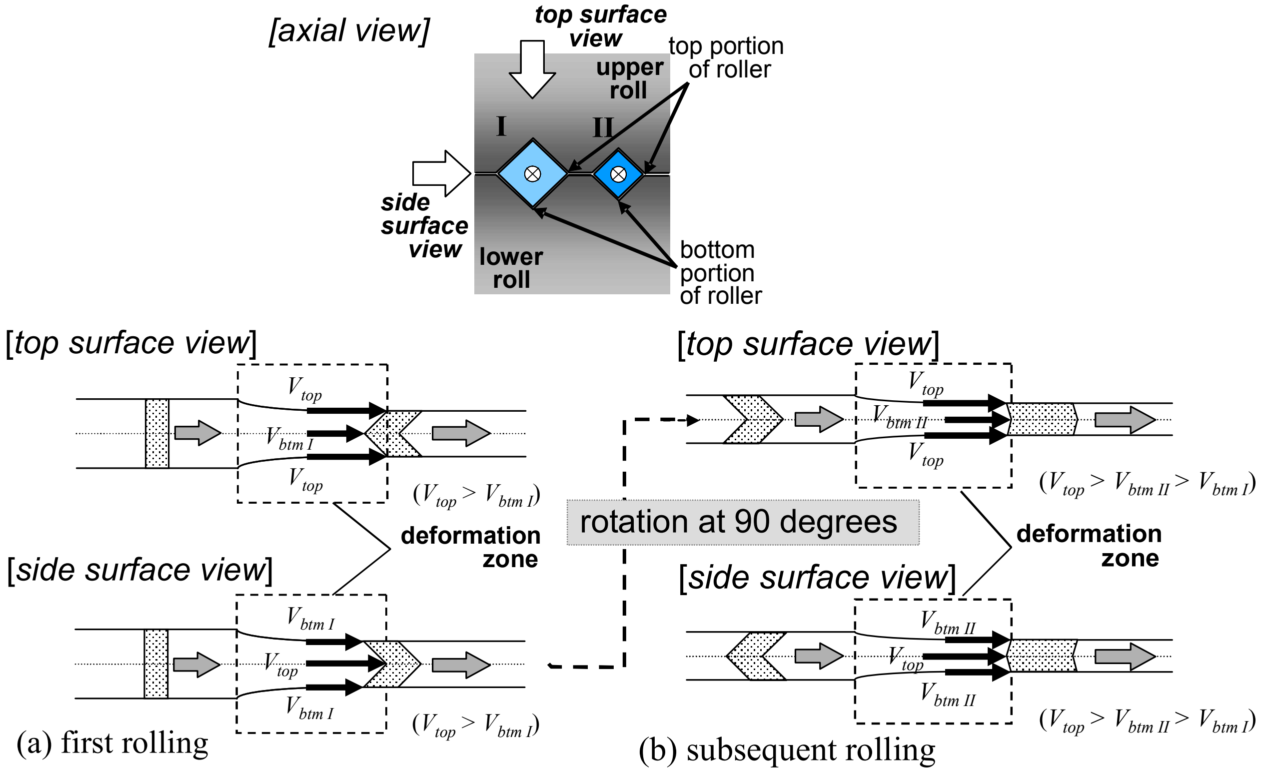


Fig. 2 Variation of elongation-to-failure with decreasing grain size in Al alloys [8].

2. Severe Plastic Deformation by Caliber Rolling

In this study, grain refinement is demonstrated by applying a repetitive oblique shear strain using caliber rolling, which can operate continuously at a commercial processing speed and commercial scale. Caliber rolling has been used mostly in the research of steels to control the cross sectional shape of products [11] and/or strengthening the material with toughness [12]. Aoki and Yanagimoto reported the effect of caliber shape on the strain distribution in the cross section using the plasticine models. [11]. Inoue et al. have demonstrated that the accumulated strain in the cross section could be effectively increased using caliber rolling by numerical simulation [13]. A schematic illustration of the caliber rolling is shown in Fig. 3 [14]. The upper roll has a channel of identical dimensions with the counterpart lower roll. However, the bottom portion of the caliber has a smaller roll diameter than that of the top portion of the caliber roll. Therefore the outer rolling speed at the bottom (V_{btm}) is slower than that at the top (V_{top}). When a billet is subjected to rolling, the material is deformed plastically during certain duration. The cross sectional area of the billet is reduced at a fixed ratio, while the discrepancy of V_{top} and V_{btm} creates a certain shear strain simultaneously after passing the roll, as illustrated in Fig. 3(a). After rotating the rolled billet 90 degrees clockwise around the rolling axis, the billet is subjected to rolling in the same way as the former pass. The cross section is reduced again with the same reduction ratio, but the shear direction is the opposite from that of the former pass, as illustrated in Fig. 3(b). Thus the resultant texture after the secondary pass is weakened as compared to that of the formerly rolled billet, although the accumulated strain in the secondary processed billet is higher than that in the former one. Since the actual deformation may be more complicated due to a lateral extension etc. throughout the processing, a detailed numerical simulation by the finite element method has been performed to understand the deformation sequence [15].



(a) first rolling

(b) subsequent rolling

Fig. 3 Schematic illustrations of caliber rolling and material flow during rolling [14].

3. Effect of Grain Refinement on Improving Mechanical Properties

In this experimental work, commercially extruded Al-Mg alloy of 5052 and Al-Mg-Si alloy of 6063 used as the starting materials. The major chemical composition of these alloys are Al-2.5% Mg-0.18% Cr-0.02% Mn-0.07% Si-0.16% Fe and Al-0.51% Mg-0.47% Si-0.19% Fe by mass %, respectively. Initial materials were received as an as-extruded bar for 5052 alloy and aged in T6 for 6063 alloy. These bars were solution treated at 618 K and 793 K, respectively. A cylindrical billet was machined from the heat treated bar with a diameter of 40 mm and a length of 100 mm.

The billet was subjected to plastic working by the caliber rolling facility. The billet was rolled by using a series of calibers in a single roll. The outer speed of the roller was fixed at 0.5 m/s. The reduction ratio of the cross sectional area was designated to be -18% for each caliber with an analogous shape as shown in Fig. 1. The billet was rolled repetitively step-by-step with the fixed reduction ratio of caliber dimensions by rotating the rolled bar 90° during each pass. In the final pass, the rolled bar was rotated 90° and rolled with the same caliber as that of the previous pass. Each pass took 3 ~ 7 seconds; therefore, a processing time of approximately 80 seconds was required from the 1st to the 16th pass. The cumulative reduction in area (A/A_0; A: cross sectional area of the rolled bar,

A_0: cross sectional area of the initial billet) was estimated to be about 93% after 16 passes, corresponding to a strain ($\varepsilon_q = -ln\ (A/A_0)$) of 2.6, and was estimated from the nominal reduction in area.

The mechanical properties were examined using the specimens machined from the initial extrusion and the caliber rolled (hereafter denoted as CalR) bars having a gauge diameter of 3 mm and a gauge length of 15 mm for the tensile tests. The CalR alloys were examined in the as-rolled state for 5052, and aged state for 6063 alloy. The axial direction of each specimen was parallel to the rolling or extrusion direction. The tensile tests were conducted at a strain rate of $1\text{x}10^{-3}\ s^{-1}$ at room temperature by an Instron tester. Nominal stress-strain relations in tension for the CalR alloys and the extruded alloys are shown in Fig. 4. The initial 6063-T6 alloy shows higher strength than the as-extruded 5052 alloy due to the precipitation strengthening. After applying the severe plastic deformation by caliber rolling, yield stress of 5052 alloy was increased around 80% higher than that of the as-extruded state, while the elongation-to-failure was decreased. Inspection of the microstructure by TEM revealed that fine sub-grains were formed after the severe plastic deformation. Thus, the accumulative strain after the repetitive caliber rolling promotes dislocation tangling followed by formation of sub-grain structure and then enhances the strength. The CalR 6063 alloy followed by aging exhibits 50% higher strength than the 6063-T6 alloy. The yield strength of 6063 CalR-aged alloy is as high as that of the 5052 CalR alloy, while the uniform elongation and elongation-to-failure are larger. It is noteworthy that the combination of strength and ductility in the 6063 CalR-aged alloy was enhanced in the similar level of that in a commercial 6061-T6 extrusion although the contents of magnesium and silicon were reduced. Inspection by TEM revealed that the formation of sub-grain structure and uniformly distributed precipitates in nano-meter scale possibly enhances the strength of Al-Mg-Si alloy without losing the ductility.

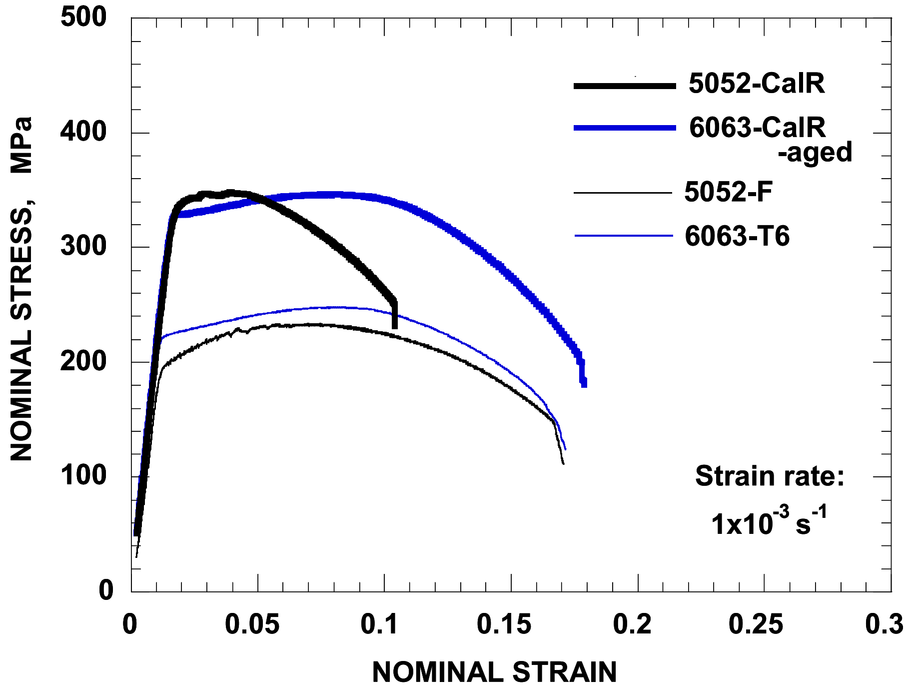


Fig. 4 Nominal stress-strain relations of caliber rolled (CalR) 5052 and 6063 alloys. Including are commercially extruded 5052 and 6063-T6 alloys for the reference.

4. Summary

Accumulative strain by a caliber rolling effectively increases the strength of 5052 and 6063 alloys. Subsequent aging for 6063 Al-Mg-Si alloy increased the strength and strain hardening rate. Tensile elongation is possibly enhanced by formation of sub-grains in sub-micrometer scale with homogeneously distributed nano-scale precipitates by the aging.

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