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LETTER

Dynamic recrystallization behavior during compressive deformation in Mg–Al–Ca–RE alloy

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Mg alloys have a high potential for reduction in CO_2 emission because of their high specific strength and stiffness [1]. For more applications of Mg alloys, it is desirable to improve creep resistance because Mg alloys often show poor creep resistance. It has been reported that Mg alloys containing Ca showed high creep resistance and elevated temperature strength [2, 3]. Recently, Bohlen et al. [4] suggested that dynamic recrystallization (DRX) occurred due to particle-stimulated nucleation (PSN). Recrystallization due to PSN tends to occur in metals containing large-sized particles more than 1 μm [5]. Insoluble second phases such as Al_2Ca and Mg_2Ca are present in Mg–Al–Ca system alloys, so that DRX is expected to be enhanced due to the PSN mechanism in Mg–Al–Ca system alloys. Several studies [6–8] showed that DRX occurs during hot deformation in Mg–Al–Ca system alloys. However, DRX in Mg–Ca alloys has not been understood sufficiently. In the present paper, compression tests are conducted on Mg–6Al–2Ca–2RE (in mass%) alloy at 523–573 K with 10^{-3}–1 s^{-1} and its DRX behavior is investigated.

A Mg–6Al–2Ca–2RE (in mass%) alloy ingot was prepared by die-casting (Mitsui Mining & Smelting Co., Ltd.). The chemical composition of the alloy is listed in Table 1. Annealing was carried out at 683 K for 108 h for homogenization. Microstructure of the annealed alloy is shown in Fig. 1. The grain size of the alloy was approximately 20 μm. The second-phase particles were observed at the grain boundaries. Energy-dispersive X-ray spectroscopy in a transmission electron microscope showed that the precipitates were (Al, Ca, RE) compounds.

The cylindrical specimens with 10-mm diameter and 12-mm height were cut from the ingot after homogenization. Compression tests were carried out at 523 and 573 K with constant true strain rates of 10^{-3}–1 s^{-1}. Microstructure of the specimens after the compression tests was observed with an optical microscope. It took less than 5 seconds for the specimens to cool off to room temperature after stopping the test. The grain size was measured by the line intercept method ($d = 1.74L$, where d and L are the grain size and the line intercept length, respectively).

Microstructures of the specimens deforming to $\varepsilon = 1.6$ at 573 K with $10^{-3} - 1\ s^{-1}$ are shown in Fig. 2. DRX was completed throughout the specimen and the grains were almost equiaxed in these specimens. The average grain sizes were 8.8, 6.7, 7.1, and 7.1 μm at the true strain rates of 10^{-3}, 10^{-2}, 10^{-1}, and 1 s^{-1}, respectively. In Mg–Zn–Y–Zr alloy [9], the DRX grain size depended on the strain rate. In the Mg–Al–Ca–RE alloy, however, effect of strain rate on the DRX grain size was small. It appears that the distribution and size of the particles did not depend on the strain rate.

Microstructure of the specimen deforming to $\varepsilon = 1.6$ at 523 K with $10^{-3}\ s^{-1}$ is shown in Fig. 3. DRX occurred at 523 K as well as 573 K, but non-recrystallized regions were partially observed at 523 K. The grain size of the recrystallized regions was 5.5 μm, which was a little lower than the grain sizes at 573 K.

Some studies [10, 11] showed that the DRX grain size of Mg alloys is governed by the Z-parameter ($=\dot{\varepsilon}\exp(Q/RT)$), where $\dot{\varepsilon}$ is the strain rate, Q is the activation energy for

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Table 1 Chemical composition of Mg–6Al–2Ca–2RE alloy (in mass%)

Al	Zn	Mn	RE	Ca	Fe	Cu	Si	Ni	Mg
6.4	0.01	0.23	2.3	2.2	<0.004	<0.004	<0.08	<0.001	Balance

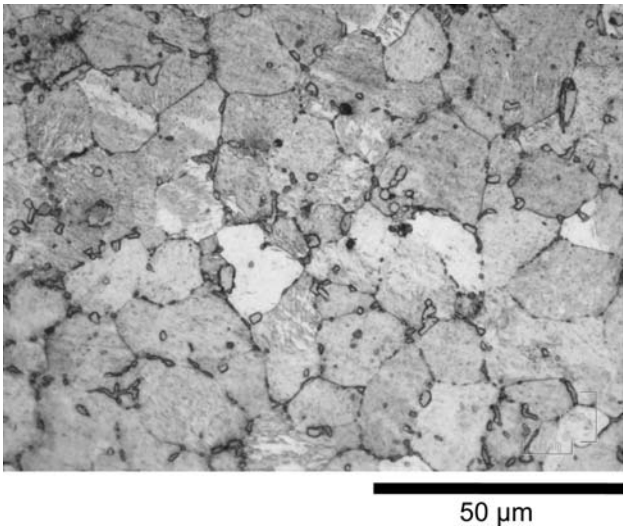

Fig. 1 Microstructure of Mg–6Al–2Ca–2RE (in mass%) alloy prior to compression tests

dominant diffusion, T is the absolute temperature, and R is the gas constant. The DRX grain size depends on the Z-parameter in the form of

$$d^{*} \propto Z^{-p}, \tag{1}$$

where d^{*} is the DRX grain size, Z is the Z-parameter, and p is the grain size exponent. The variation in DRX grain size as a function of Z-parameter for the present Mg alloy is shown in Fig. 4, assuming that the activation energy is that

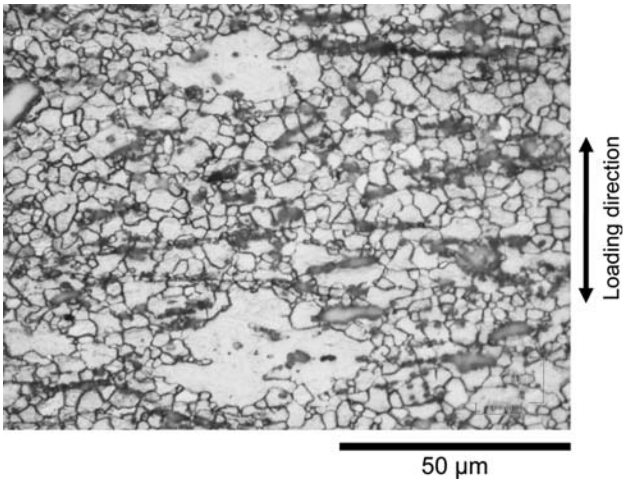

Fig. 3 Microstructure of Mg–6Al–2Ca–2RE alloy specimen deformed to $\varepsilon = 1.6$ at 523 K with 10^{-3} s^{-1}

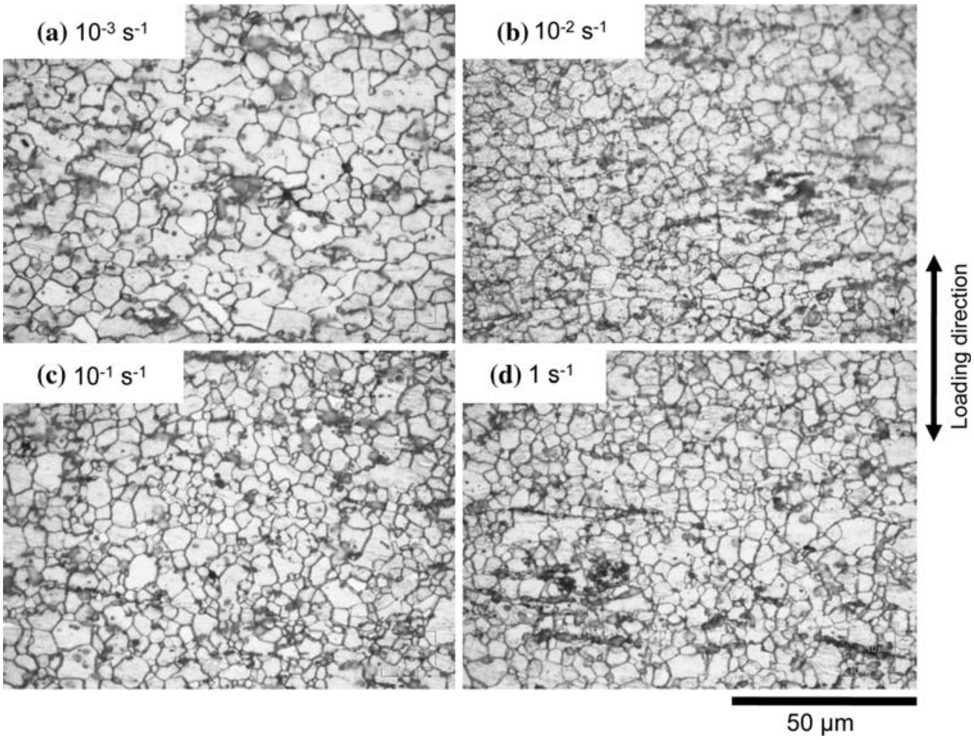

Fig. 2 Microstructures of Mg–6Al–2Ca–2RE alloy specimens deformed to $\varepsilon = 1.6$ at 573 K with $10^{-3} - 1$ s^{-1}. Strain rates are (**a**) 10^{-3} s^{-1}, (**b**) 10^{-2} s^{-1}, (**c**) 10^{-1} s^{-1}, and (**d**) 1 s^{-1}

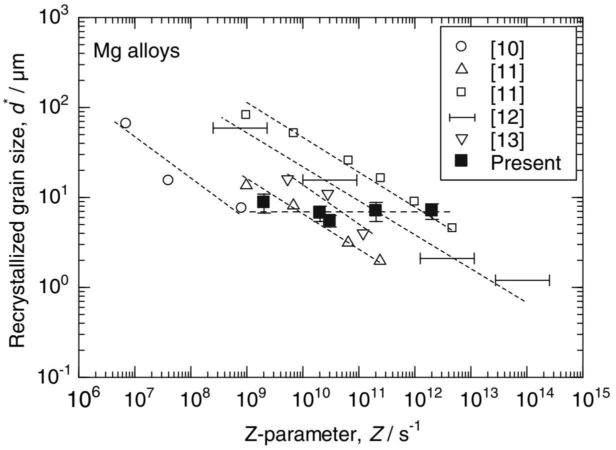

Fig. 4 Variation in dynamically recrystallized grain size as a function of Z-parameter for Mg alloys

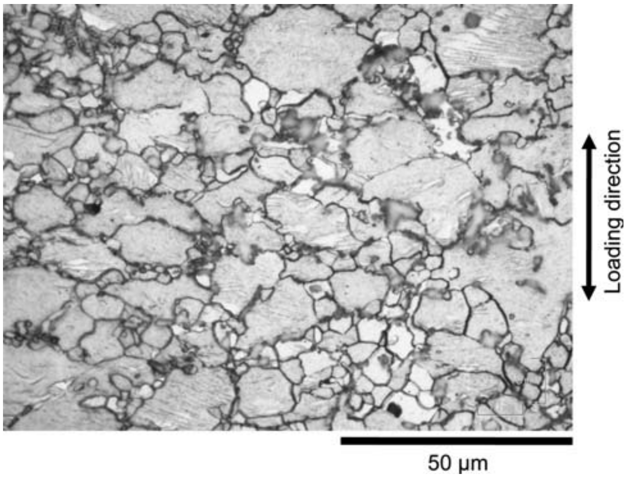

Fig. 5 Microstructure of Mg–6Al–2Ca–2RE alloy specimen deformed to $\varepsilon = 0.35$ at 573 K with 1 s^{-1}

for lattice diffusion of Mg (135 kJ/mol) [14]. The published data of Mg–Al–Zn alloys [10–13] are also shown in Fig. 4. The DRX grain size decreased with increasing Z-parameter and the grain size exponent was 0.3–0.4 in the Mg–Al–Zn alloys. However, the DRX grain size hardly depended on the Z-parameter in the present Mg–Al–Ca–RE alloy. Hence, it is suggested that DRX mechanism in the Mg–Al–Ca–RE alloy is different from that of the Mg–Al–Zn alloys.

It has been reported that continuous DRX occurs during hot deformation in Mg–Al–Zn alloys [15, 16]. On the other hand, Myshlyaev et al. [17] and Sitdikov et al. [18] showed that twins develop into polygonal cells with high misorientation in Mg–Al–Zn alloys, indicating that twinning plays an important role in DRX. Microstructure of the specimen deformed to $\varepsilon = 0.35$ at 573 K with 1 s^{-1} is shown in Fig. 5. In twin DRX, secondary twinning occurs within coarse lamellas of primary twins [17, 18]. Such double twinning, however, was not observed in the Mg–Al–Ca–RE alloy. This is probably due to the high compression temperature [19]. Thus, twin played no role in DRX in the Mg–Al–Ca–RE alloy. Small recrystallized grains were locally observed around the particles, indicating that DRX was enhanced by the particles.

When DRX is governed by continuous recrystallization, the DRX grain size strongly depends on the strain rate and temperature [20]. On the other hand, when DRX results from the PSN mechanism, effect of the deformation conditions on the DRX grain size may be minor. As shown in Fig. 4, DRX behavior of the Mg–Al–Ca–RE alloy was different from that of the Mg–Al–Zn alloys. Therefore, it is likely that DRX behavior of the Mg–Al–Ca–RE alloy was strongly affected by the particles. Further research is needed to understand the mechanism of DRX in the Mg–Al–Ca–RE alloy.

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