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# FRACTURE MECHANISM AND TOUGHNESS IN FINE- AND COARSE-GRAINED MAGNESIUM ALLOYS

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## Abstract

The fracture mechanisms in the extruded magnesium alloys with two different grain sizes, 2 and 50 μm, were investigated by SEM, TEM and EBSD microstructural observations. The coarse-grained alloy showed that the {10-12} type deformation twins formed at the beginning of test, and the crack was propagated into the boundaries between twins and matrix. On the other hand, the fine-grained alloy showed that the sub-grain boundaries formed instead of the deformation twins. No formation of twins at the early deformation stage causes a crack-tip blunting, and thus, the fracture toughness has a high value.

## Introduction

Magnesium alloys have a high potential for application as structural materials because of being the lightest among all structural alloys in use. For use in structural applications, their mechanical properties must satisfy both reliability and safety requirements. A method of ensuring that is to investigate their fracture toughness. Several reports exist on the fracture toughness of magnesium [1] and magnesium alloys [2,3], and the wrought magnesium alloys have higher fracture toughness compared to the cast magnesium alloys [4]. However, the fracture toughness in magnesium alloys has generally been reported to be lower than that in aluminum alloys [4].

The fracture toughness in magnesium and magnesium alloys is reported to be affected by several microstructural features, such as texture [5] and dispersion of particle morphologies (particle shapes [6], sizes [6,7], volume fraction [8] and interfaces [4,9]). The fracture toughness is also influenced by the grain size [1,10]. Above all things, since the grain refinement enhances not only the fracture toughness but also changing the fracture features, the control of grain size is known to be the most effective method to improve the mechanical properties. One of the reasons for the enhancement fracture toughness is that the fine-grained magnesium alloys tend to have a decrease in the formation of deformation twins, which is the origin of fracture [11]; the dominant plastic deformation mechanism changes from twins to dislocation slip by the refinement of the grain structures [12,13]. However, the detailed mechanisms during the fracture toughness test in fine- and coarse-grained magnesium alloys have not been understood yet. Therefore, in this study, the deformed microstructure of fracture toughness tested fine- and coarse-grained magnesium alloys were investigated using scanning electron microscopy (SEM), transmission electron microscopy (TEM) observations combined with the focused ion beam (FIB) and electron backscattered diffraction (EBSD).

## Experimental Procedure

The materials used in the present study were extruded Mg-6.2wt.%Zn and Mg-3wt.%Zn-1wt.%Al (AZ31) alloys. The grain sizes of Mg-Zn alloy and AZ31 alloy were 2 and 50 μm, respectively, which consisted of high-angle grain boundaries. The detail initialed microstructures and mechanical properties in each alloy have been already reported elsewhere [8,14].

The specimen was a three point bending sample with a width of 10 mm, a thickness of 5 mm and a length of 44 mm, based on ASTM E399 [15]. The specimen was machined directly from the extruded bar with parallel to extrusion direction. The fracture toughness tests were discontinued, when the load reached around half of the maximum value or the maximum value, in order to obtain the deformed samples. The deformed microstructures were examined at the crack-tip region by EBSD in the coarse-grained alloy and TEM observation in the fine-grained alloy, respectively. The TEM samples were picked up by the FIB at the crack-tip region of 5 × 10 μm. The fracture surfaces after the fracture toughness tests were also observed by SEM in the both alloys.

## Results and Discussion

### Coarse-grained Alloy

Typical EBSD analysis near the crack-tip region in the coarse-grained alloy is shown in Figure 1: (a) the sample where the test was stopped at around half of the maximum load and (b) the sample where the test was stopped at the maximum load. Figure 1 shows that many deformation twins were formed near the crack-tip region even before the crack-propagation, i.e., before the crack blunted. The deformation twins are the {10-12} type, <*c*>-axis tensile deformation twins. The same type of deformation twins has also been observed in samples, deformed by the tensile and the compression tests [16,17]. One of the possible reasons for the easy formation of {10-12} deformation twins compared to the other types of deformation twins, i.e., {10-11} and {10-13} deformation twins (<*c*>-axis compression deformation twins) is due to the lower critical resolved shear stress (CRSS) [18,19]. Figure 1(b) shows that, in the sample where the test was stopped at the maximum load, the crack propagates into the boundaries between the deformation twins and the matrix, which is marked by the arrows.

### Fine-grained Alloy

A typical TEM micrograph at the crack-tip region in the fine-grained alloy is shown in Figure 2: (a) around half of the maximum load and (b) maximum load in the fracture toughness tests. Selected area electron diffraction (SAED) patterns inset in each image show streaked or split spots, suggesting a local variation in orientation and the presence of sub-grain structures. The microstructural features of the deformed sample are very different from that before the testing. Since the as-extruded alloy is a fully recrystallized structure with high-angle grain boundaries [8], the sub-grain structures are found to form during the crack-blunting. No deformation twins are found in Figure 2(a). On the other hand, Figure 2(b) shows not only the existence of many fine sub-grain structures, but also the {10-12} deformation twins, which is a well known type and similar to Figure 1. This observed deformation twins are nano-scale size.

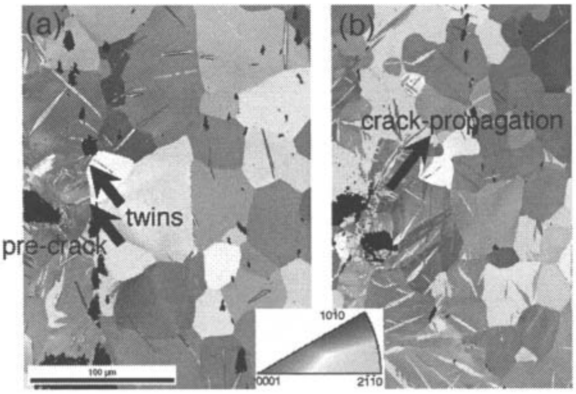

Figure 1. Typical EBSD images in the coarse-grained alloy: (a) half of maximum load and (b) maximum load in the fracture toughness tests.

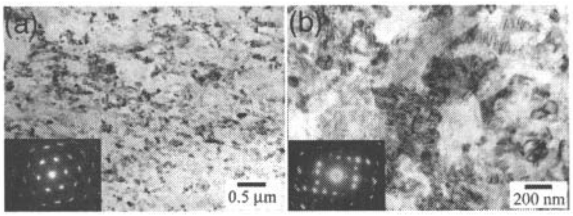

Figure 2. Typical TEM micrograph in the fine-grained alloy: (a) half of maximum load and (b) maximum load in the fracture toughness tests.

Fracture Mechanisms

Typical SEM micrographs of the fracture surface after the fracture toughness test are shown in Figure 3: (a) coarse- and (b) fine-grained alloys, respectively. The pre-crack direction is marked in this figure. The coarse-grained alloy shows that the fracture surface consists of a few parts with ductile patterns but is mainly comprised of brittle-like patterns related to the twin boundary fracture, marked by white arrows. On the other hand, the fine-grained alloy shows many dimple patterns, which is a typical trace of ductile fracture.

The effect of grain size on the fracture mechanism is discussed hereafter. Simple illustrations are shown in Figure 4: (a) coarse- and (b) fine-grained alloys. On applying a stress, a plastic zone is created ahead of the crack-tip, because the stress concentration occurs at the crack-tip. When the grain size is the coarse or medium (≥ ~ 10 μm), the stress to form the twins is smaller than that for dislocation slip: the dominant deformation mechanism is twinning. Thus, the deformation twins quite easily form at the very beginning of the fracture toughness test. The twin boundary plays the role of strain accumulation [14]; however, since the accumulated plastic strain by the twins is smaller than that of the grain boundary migration by the dislocation slip, the twins are associated with the crack propagation route. Therefore, as soon as the deformation twins are formed ahead of the crack-tip, the crack is propagated along the twins without blunting, i.e., no formation of a void, and the fracture morphology is of a brittle feature (shown in Figure 3(a)).

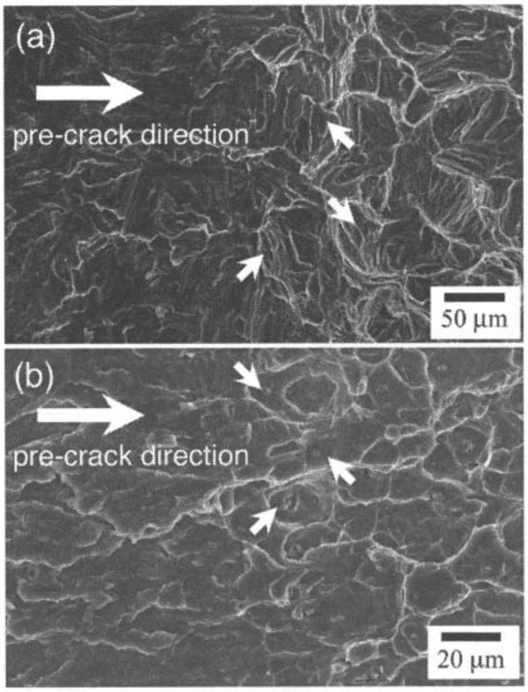

Figure 3. Typical SEM micrographs of the fracture surface after the fracture toughness test: (a) coarse- and (b) fine-grained alloys.

On the other hand, in fine-grained materials, since the volume fraction of the grain boundary increases with grain refinement, the deformation behavior is affected by the grain boundary characteristics. Non-basal slip systems are activated even at room temperature due to the operation of compatibility stress at grain boundary [20]. In addition, the grain boundary sliding occurs due to high diffusion rate along grain boundaries [21]. These deformation mechanisms make up for the lack of slip systems at the beginning of the test. As the fracture toughness test proceeds, the crack-tip blunts sufficiently and causes high fracture toughness and a ductile fracture (shown in Figure 3(b)), because of absence of the crack-propagation sites, such as the twin boundaries. On applying a stress, since a large stress operates at the crack-tip, the twins form as nano-scale size. The deformation twins of a micron-scale size in metallic materials are the origin of crack-nucleation; however, the existence of nano-scale twins is reported to contribute to the enhancement of strength and ductility [22]. The nanocrystalline Ni alloys with a grain size of ~ 10 nm are also observed within the intergranular fracture [23], the fracture surface by the SEM observation of these alloys appears a void-like fracture, i.e., ductile feature [23,24]. Therefore, the size of the deformation twins is assumed to be too fine not only to affect the fracture mechanism but also for the brittle fracture to occur.

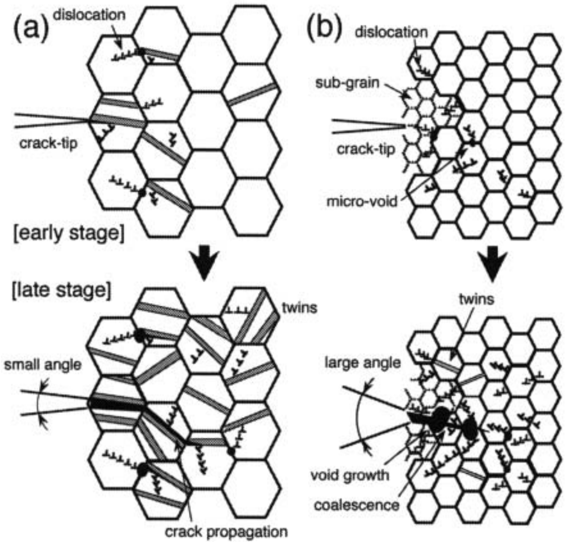

Figure 4. Illustrations of fracture mechanism: (a) coarse- and (b) fine-grained alloys.

## Summary

The effect of grain size on fracture mechanisms was investigated by SEM, TEM and EBSD microstructural observations. The following results were obtained.

1) The coarse-grained alloy showed that the {10-12} type deformation twins formed at the beginning of test. On applying a strain, the crack propagated into the boundaries between twins and matrix.

2) The fine-grained alloy showed that many fine sub-grains formed instead of deformation twins. Non formation of deformation twins at the beginning of test caused sufficient crack-tip blunting; therefore, the fracture toughness had a high value.

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