Effect of Grain Refinement on Tensile Ductility in ZK60 Magnesium Alloy under Dynamic Loading

Toshiji Mukai¹, Masashi Yamanoi^{2, *}, Hiroyuki Watanabe¹, Koichi Ishikawa¹ and Kenji Higashi²

¹Mechanical Engineering Department, Osaka Municipal Technical Research Institute, Osaka 536-8553, Japan

²Department of Metallurgy and Materials Science, College of Engineering, Osaka Prefecture University, Sakai 599-8531, Japan

Magnesium alloys are generally brittle owing to their HCP structure. In this study, improvement of tensile mechanical properties under dynamic loading has been demonstrated for a pure magnesium and a ZK60 magnesium alloy. The solution-treated ZK60 alloy exhibits yielding at a dynamic strain rate of $1.8 \times 10^3 \text{ s}^{-1}$, which was not observed in a pure magnesium. The yield stress of the ZK60 alloy increases at the dynamic strain rate with a similar slope of Hall-Petch relation at a quasi-static strain rate. Enhancement of ductility can be also achieved by refining grain structures for the ZK60 alloy. The high ductility of the fine-grained alloy is due to the absence of macroscopic cracking at mechanical twin boundaries. It is found that the absorption energy per weight in the fine-grained ZK60 is twice higher than that of high strength aluminum alloys.

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1. Introduction

Magnesium alloys are the lightest metallic structural materials and are, hence, very attractive in such applications as automotive, railway and aerospace where weight reduction and improvement in comfort are required.¹⁾ To be used for structural components in automobiles, the material should exhibit sufficient ductility as well as the specific strength not only at static but also at dynamic strain rates, since components are often fractured by shear or tensile force under a dynamic loading against foreign object damage. Magnesium alloys are generally brittle owing their HCP structure. It is well known that tensile mechanical properties in metals depend on the crystal structure. Values of elongation-to-failure (ϵ_f) in some structural metals at a quasi-static and a dynamic strain rate ($> 10^3 \text{ s}^{-1}$) are shown in Fig. 1 for aluminum,²⁾ copper,³⁾ titanium,³⁾ magnesium,⁴⁾ zinc,³⁾ iron³⁾ and molybdenum.³⁾ The ϵ_f in FCC metals (aluminum and copper) exhibits a positive strain rate sensitivity: the value of ϵ_f at a dynamic strain rate is higher than that at a quasi-static strain rate, while ϵ_f in BCC metals (Iron and molybdenum) exhibits a negative strain rate sensitivity. The strain rate sensitivity in HCP metals depends on their ratio of c/a ; i.e., titanium ($c/a = 1.586$) exhibits a positive strain rate sensitivity, while magnesium ($c/a = 1.624$) and zinc ($c/a = 1.856$) exhibit a negative strain rate sensitivity. It is noted that magnesium exhibits lower ductility at a dynamic strain rate. Thus, ductility in magnesium should be enhanced with controlling the microstructure.

It has been demonstrated that the ductility in magnesium alloys containing Li could be enhanced with increasing the content of lithium.⁴⁾ The enhancement of ductility might be structural evolution with increasing the content of solute atoms. On the other hand, Chapman & Wilson⁵⁾ demonstrated that the ductility enhancement in magnesium could be achieved by refining its grain structure. Mohri *et al.*⁶⁾ reported the ductility

enhancement of a Mg-Y-RE (Rare Earth) alloy by hot extrusion. Mukai *et al.*⁷⁾ have also demonstrated that the ductility in WE43 magnesium alloy can be enhanced by the grain refinement even at a dynamic strain rate of $\sim 2 \times 10^3 \text{ s}^{-1}$. They mentioned that the enhancement of ductility was due to the transition of fracture behavior with refining the microstructure. The variation of elongation-to-failure at a static strain rate as a function of the inverse of grain size are shown in Fig. 2 for magnesium^{5,8-11)} and magnesium alloys.^{6,7,12-16)} ϵ_f for ingot-metallurgy processed magnesium and magnesium alloys tends to increase with decreasing grain size except the data of powder-metallurgy processed magnesium alloys. It is obvious that grain refinement is effective for the ductility enhancement at static strain rates. However, it is not clear whether the grain refinement would contribute to the high ductility even at dynamic strain rates. In the present study, the possibility of fine-grained magnesium and ZK60 magnesium alloy is investigated to raise the high speed impact performance against the foreign object damage by increasing the strength and enhancement of ductility under dynamic loading.

Fig. 1 Values of elongation-to-failure (ϵ_f) for some structural metals, Al,²⁾ Cu,³⁾ Ti,³⁾ Mg,⁴⁾ Zn,³⁾ Fe,³⁾ Mo³⁾ at a quasi-static and a dynamic strain rates ($> 10^3 \text{ s}^{-1}$).

*Graduate Student, Osaka Prefecture University.

Fig. 2 The variation of elongation-to-failure in magnesium^{6,9-13} and magnesium alloys^{7,8,14-19} as a function of the inverse of grain size at a quasi-static strain rate.

2. Experimental Procedure

2.1 Materials

The materials used in the present study are pure magnesium (99.9% purity) and a commercial magnesium alloy of ZK60 (Mg-6Zn-0.5Zr, by mass%). Magnesium was received as ingot. To obtain a fine-grained magnesium, the ingot was extruded at a temperature of 418 K and annealed for 1 hr at 473 K. A coarse-grained magnesium was also obtained by the extrusion at 573 K. Typical grain structures of the pure magnesium for two conditions are shown in Figs. 3(a) and (b), respectively. Grain sizes of the fine-grained and the coarse-grained magnesium are measured to be 9 and 31 μm , respectively. Grains are found to be almost equi-axed for both materials. On the other hand, ZK60 alloy was received as a commercially extruded bar. The initial grain size of the as-extruded ZK60 was approximately measured to be 3 μm . The extruded alloy was solution treated at 773 K in to develop coarser grain sizes. Typical microstructures of the ZK60 alloy solution treated at a temperature of 773 K for (a) 15 min, (b) 60 min, (c) 480 min are shown in Figs. 4(a) ~ (c). The developed grain sizes of the solution-treated alloy for 15, 60 and 480 min are measured to be 4, 30 and 120 μm , respectively. Optical imaging microscopy revealed that the texture and distribution of misorientation angle in the intermediate-grained ZK60 were very similar to that in the coarse-grained

Fig. 3 Typical microstructures of 3N-purity magnesium (a) annealed at 473 K for 1 hr followed by extrusion at 418 K and (b) extruded at 573 K.

alloy. Thus, the difference of the microstructure between two materials is noted to be grain size only.

2.2 Apparatus

Tensile specimens, machined directly from the extruded bars, had their tensile axes parallel to the extruded direction. The gauge length of the specimen was 5.0 mm, and the diameter was 2.5 mm. Tensile tests at a dynamic strain rate ($1.8 \times 10^3 \text{ s}^{-1}$) were performed using a modified Hopkinson pressure bar.¹³ The schematic illustration of the tensile Hopkinson-bar apparatus is shown in Fig. 5. Tensile tests at a quasi-static strain rate ($1 \times 10^{-3} \text{ s}^{-1}$) were also performed by Instron testing machine. Deformed specimen was inspected by an optical microscope to investigate the fracture mechanism.

3. Results and Discussion

3.1 Stress-strain relations at dynamic strain rate

The nominal stress-strain relations for magnesium and ZK60 alloy are shown in Figs. 6(a) and (b), respectively. Including is the datum of Mg-6Zn-0.5Zr (by mass%) alloy extruded at 583 K with the grain size of 2 μm .¹³ The shape of the curve in the solution-treated ZK60 exhibits slight strain hardening during the plastic deformation contrary to the result of Magnesium exhibiting obvious strain hardening. It can be also seen that the solution-treated ZK60 exhibits a yield-

Fig. 4 Typical microstructures of ZK60 alloy, solution-treated at a temperature of 773 K for (a) 15 min, (b) 60 min and (c) 480 min.

Fig. 5 Schematic illustration of a tensile Hopkinson-bar apparatus.

Fig. 6 Nominal stress-strain relations at a dynamic strain rate of $1.8 \times 10^3 \text{ s}^{-1}$ for (a) magnesium and (b) ZK60 alloy. Including is the datum of Mg-6Zn-0.5Zr extruded at 583 K.¹³⁾

ing at an early stage of deformation, which is not observed in magnesium. Comparing with the previous result for the extruded Mg-6Zn-0.5Zr alloy, the solution-treated ZK60 exhibits a higher amplitude of stress drop. Thus, it is possibly noted that solute atoms of Zn or Zr affect the yielding of the Mg-Zn-Zr alloy at the dynamic strain rate. It is especially noted that the flow stress and the elongation-to-failure of the present magnesium and ZK60 alloy increase with refining the grain size.

To clarify the effect of grain refinement on the yield stress, Hall-Petch (H-P) relations in the present materials are shown in Fig. 7 for static and dynamic strain rates. Including are the data for some magnesium⁵⁾ and magnesium alloys.^{12-14, 17)} For the result of the present ZK60 alloy at the dynamic strain rate, the stress was taken as the lower yield stress. The H-P relation in the present ZK60 alloy at a quasi-static strain rate is in a good agreement with the previously reported data.^{12, 13)} The slope of the H-P relation is also similar to those for other magnesium⁵⁾ and magnesium alloys.^{12-14, 17)} All materials in Fig. 7 were fabricated by extrusion and exhibit similar slope. Therefore, it is suggested that the developed texture may be similar. The data at the dynamic strain rate are also represented by a single line. It is well known that the slope of the line, k -value, depends on the slip system.^{5, 18)} Since the line at the dynamic strain rate is almost parallel to that at the quasi-static strain rate, it is noted that slip system is also possibly limited at the dynamic strain rate for the ZK60 alloy.

Fig. 7 Hall-Petch relations for the present Magnesium and ZK60 magnesium alloy. Including are the previous results for magnesium⁵⁾ and magnesium alloys^{12–14,17)} at a quasi-static strain rate.

3.2 Fracture behavior under dynamic tensile loading

The ε_f of the present alloy obviously increased with refining grain size even at a dynamic strain rate as shown in Fig. 6. To investigate the fracture mechanism of the solution-treated ZK60 alloy, deformed microstructure was inspected. The deformed microstructure of the coarse-grained ZK60 alloy is shown in Fig. 8. The tensile direction is horizontal. As can be seen in this figure, mechanical twins are obviously formed under the dynamic tensile loading. Near the fracture surface, macroscopic cracking is also observed at a twin boundary as indicated by white arrows in Fig. 8. Therefore the fracture of the coarse-grained ZK60 is noted to be a coalescence of macroscopic cracks along the twin boundary or grain boundary. The deformed structure of the intermediate- and fine-grained ZK60 were also shown in Figs. 9(a) and (b), respectively. The tensile direction is horizontal. For the intermediate-grained alloy, macroscopic crack is also observed, and highly dense mechanical twins are formed comparing with the deformed structure of the coarse-grained alloy. In the fine-grained material, there can not be seen the macroscopic cracks owing to the absence of macroscopic twin boundaries. It is summarized that the ductility enhancement in the fine-grained ZK60 is owing to the avoidance of stress localization with refining grain structure.

3.3 Enhancement of absorption energy

Tensile properties of the present ZK60 at a dynamic strain rate are summarized in Table 1. In Table 1, data for a commercial Al-Mg alloy, 5056-O (annealed),¹⁹⁾ and two high strength aluminum alloys, 7075-T6²⁰⁾ and IN905XL (mechanically alloyed aluminum)²¹⁾ are listed for samples with the same dimension. The strain rates for each sample are similar. ε_f of the fine-grained ZK60 is twice higher than those of the high strength aluminum alloys, while the relative strength is similar to those of the aluminum alloys. To investigate the possibility for structural use in vehicle components, the absorption energy is estimated. The absorption energy Q_{AB} of each sample can be evaluated by the integration of the stress-

Fig. 8 Deformed microstructure of ZK60 with the grain size of 120 μm fractured at a strain rate of $1.8 \times 10^3 \text{ s}^{-1}$. The tensile direction is horizontal, and white arrows indicate the macroscopic cracking along the twin boundary.

Fig. 9 Deformed microstructure of ZK60 with the grain size of (a) 30 μm and (b) 5 μm , fractured at a strain rate of $1.8 \times 10^3 \text{ s}^{-1}$. The tensile direction is horizontal, and a white arrow in (a) indicates the macroscopic cracking along the twin boundary.

strain relation as the following equation.

$$Q_{AB} = \int_0^{\varepsilon_f} \sigma \cdot d\varepsilon \quad (1)$$

Table 1 Tensile properties of ZK60 alloy at a dynamic strain rate. Including are the data for some aluminum,^{19–21)} magnesium⁴⁾ and magnesium alloy.⁷⁾

Materials	Density [ρ] (Mg/m ³)	Strain rate (s ⁻¹)	Ultimate tensile strength [UTS] (MPa)	Elongation-to-failure [ϵ_f] (%)	Specific strength [UTS/ ρ] (kNm/kg)	Absorption energy [Q_{AB}] (J)	Q_{AB} per weight (J/kg)
Aluminum							
5056-O ¹⁹⁾	2.64	1.7×10^3	267	53	101	2.71	42.8
7075-T6 ²⁰⁾	2.80	1.0×10^3	628	11	224	1.59	23.1
IN905XL ²¹⁾	2.58	1.0×10^3	534	9.6	207	1.14	17.6
Magnesium							
Mg ⁴⁾	1.74	1.1×10^3	293	5.5	168	0.39	9.4
WE43 (d : 73 μ m) ⁷⁾	1.84	1.1×10^3	368	7.5	200	0.70	15.9
WE43 (d : 1.5 μ m) ⁷⁾	1.84	1.1×10^3	336	27	183	2.04	47.3
Mg (d : 30 μ m)	1.74	1.8×10^3	288	12	166	0.82	20.1
Mg (d : 9 μ m)	1.74	1.8×10^3	305	19	175	1.47	36.1
ZK60 (d : 120 μ m)	1.84	1.1×10^3	284	16	155	1.10	25.7
ZK60 (d : 30 μ m)	1.81	1.8×10^3	315	18	172	1.39	32.4
ZK60 (d: 4 μm)	1.83	1.8×10^3	380	22	208	1.89	44.1

Q_{AB} in the fine-grained ZK60 alloy is markedly higher than those in the referenced alloys as well as the fine-grained WE43 magnesium alloy. It is noted that grain refinement is effective to raise the absorption energy against the dynamic loading. Absorption energy needs to be estimated for the same mass of materials, owing to the limitation of the vehicle weight. Thus, the absorption energy per weight is also evaluated as shown in Table 1. It is especially noted that the Q_{AB} per weight in the fine-grained ZK60 is twice higher than that of high strength aluminum alloys. It is expected that the fine-grained ZK60 alloy exhibits the high speed impact performance during foreign object damage owing to the enhancement of ductility with grain refinement.

4. Summary

Improvement of tensile mechanical properties under dynamic loading was demonstrated for pure magnesium and a solution-treated ZK60 magnesium alloy. The solution-treated ZK60 alloy exhibits yielding at a dynamic strain rate of $1.8 \times 10^3 \text{ s}^{-1}$, which can not be observed in the pure magnesium. The yield stress of the ZK60 alloy increased at the dynamic strain rate with a similar slope of Hall-Petch relation as that at a quasi-static strain rate. Enhancement of ductility can be also achieved by refining the grain structure for ZK60 alloy. The high ductility of the fine-grained alloy is owing to the absence of macroscopic cracking at mechanical twin boundaries with grain refinement. The absorption energy per weight in the fine-grained ZK60 is twice higher than those of high strength aluminum alloys.

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