Memoirs of the Faculty of Engineering, Okayama University, Vol.25, No. 2, pp. 1 - 8, March 1991

Mechanical Characteristics of Cast Ti Fiber-Reinforced Mg Composite

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(Received February 12, 1991)

SYNOPSIS

Tensile strength and elongation of cast magnesium reinforced with titanium fiber were measured by tensile test. The pull-out test of a titanium rod partially embedded in a magnesium matrix was performed to evaluate interfacial bonding strength between magnesium and titanium. It was found that when the fiber volume fraction was changed from 1% to 14%, the tensile strength was improved with increase of volume fraction, while the improvement of elongation tended to be restrained beyond the volume fraction of 10%. The interfacial strength was revealed to be strong, and this was substantiated by the scanning electron microscopy showing an excellent wettability between the titanium fiber and the magnesium matrix.

1. INTRODUCTION

Magnesium that is the lightest of all practically used metals has two thirds the specific weight of aluminum, and has a high specific strength. Further, the former exceeds the latter both in tensile strength and in elongation, which is of great value in practical use. Magnesium, on the other side, is chemically so active as to be more corrosive and also mechanically strange in its deformation mode. It is expected that these deficiency will be overcome and magnesium will be used in much wider fields. Thus, there have been many reports concerned

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with magnesium base alloys with additions of such elements as rare earths, manganese, zirconium, and so on.(1,2) In parallel to those, improvement of the mechanical properties of magnesium by reinforcement have been attempted.(3,4)

Magnesium which has a low specific weight has come into notice as matrix material of composites. Several works concerned with FRMs of magnesium, especially those reinforced with ceramic fiber such as C(5), SiC(6), and Al_2O_3,(7) are reported. But it should be noticed that the composites reinforced with ceramic fiber are poor in plastic workability. Composites reinforced with metal fibers, on the other hand, are supposed to be excellent on this point of view. Wettability between the fiber and the matrix is essential on the fabrication of FRM. Besides, it is desirable that no reaction occurs at the interface between the fiber and the matrix. If the reaction products make the interface brittle, they are likely to prevent the stress from transferring from the matrix to the fibers. Some fibers need to be coated for protection against reactions with the matrix.

Taking these affairs into account, the present authors chose titanium as fiber materials. It is expected Ti/Mg composite has a good specific strength, for titanium fiber does not lose much the lightness of magnesium and has an enough strength. The most important point is that its reactivity to magnesium is low at the fabrication temperature (973K, T_{mp} of magnesium being 923K), and that titanium does not produce intermetallic compounds with magnesium and dissolves into magnesium up to about 1wt%. Moreover, titanium is not attacked by oxygen in magnesium, judging from the standard free energy of oxidation at that temperature. It is believed, therefore, that the choice of titanium fiber as a reinforcing material for magnesium is adequate if their wettability is good.

In the investigations of FRMs, there are comparatively many reports on the composites reinforced by short preformed fibers.(8,9) But in this paper the mechanical characteristics of a composite reinforced with unidirectionally oriented continuous filaments are investigated by the tensile test, and its bonding strength and interfacial property are evaluated by the pull-out test and observations with the scanning electron microscope.

2. EXPERIMENTAL PROCEDURES

2.1 Materials and Fabrication

Commercially pure magnesium (99.95%, UBE KOUSAN) was used as a matrix of composite. Low carbon steel (S25C) was employed as a material of the crucible because of its non-reactivity with magnesium, which fact is very important for the industrial utility. The crucible was made separable into two pieces in order for the product to be taken out easily. Magnesium in the crucible was melted in a vertical furnace at 973K, a bundle of Ti fibers (99.6%, ϕ0.2mm) was immersed into the molten magnesium, and then magnesium was solidified in the same crucible. These processes were performed in an argon atmosphere in order to avoid oxidation. Fiber volume fraction, V_f, was varied by changing the amount of fiber. SiC fiber (ϕ0.14mm) was also used to be compared with the titanium fiber. Cast magnesium in which a titanium rod (99.5%, ϕ3mm) was immersed instead of fibers was fabricated in the same way.

The products thus fabricated were cylindrical shells (ϕ25mmx70mm), each containing fibers or a rod in its center. The ones which contained fibers were worked into specimens for the tensile test, the gauge length of which was 15mm long with 3mmx4mm rectangular cross section. V_f was evaluated from the fraction of area of the fibers measured in the cross section of specimen since the fibers were unidirectional and continuous. The V_f was 1% to 14% for titanium fiber, and 10% for SiC fiber. A specimen of pure magnesium cut out of the product was also prepared for the tensile test.

The cylindrical shell containing a rod was also worked into the specimen for the pull-out test as illustrated in Fig.1. A rod with a radius 1.5mm was located at the center of a coaxial cylindrical shell of magnesium matrix with an outer radius 12mm. One end of a titanium rod was embedded in magnesium matrix and the other end to be gripped was protruded from the matrix. A portion of the rod was narrowed to 0.5mm in radius. The depth, z, designated in Fig.1, was changed.

2.2 Tensile Test

Tensile test was carried out with Shimadzu autograph, IS-5000, for the specimens of Ti/Mg composite and SiC/Mg composite at the displacement rate of 0.5mm per minute at room temperature, the tensile axis being parallel to fibers. The pure magnesium specimen above described, the titanium rod, and the titanium fiber were also tested.

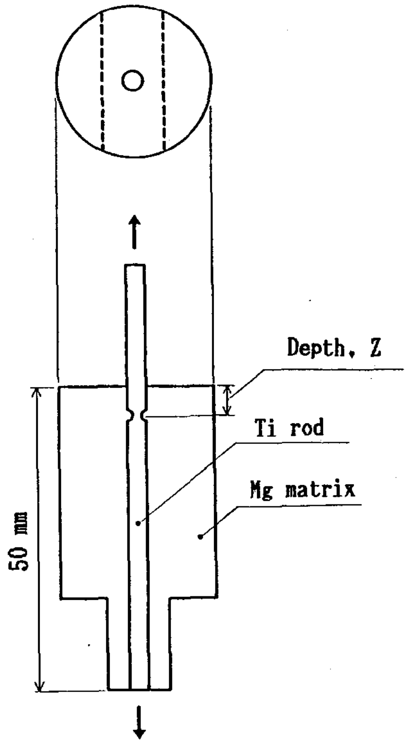

Fig.1 A schematic diagram of a cylindrical shell for pull-out test.

2.3 Pull-out Test

Pull-out test of titanium rod from magnesium matrix was attempted at a constant displacement rate of 0.5mm per minute with the titanium rod and the magnesium matrix gripped. The depth, z, then was 16, 7, 5, and 3mm.

2.4 Observation of the Fracture Surface and the Interface

Fracture surfaces of the specimens for both the Ti/Mg and the SiC/Mg composite were observed by scanning electron microscope (SEM, HITACHI S-450). Cross sections parallel to the direction of fibers were observed by a scanning electron microscope to characterize the interface after the deformation. Surfaces of the Ti fibers, the ones as-received and the ones taken out from the composite by dissolving magnesium matrix with 30% nitric acid, were also observed. Surface of the as-received SiC fiber was also examined.

3. RESULTS AND DISCUSSION

3.1 Pull-out Test

Pull-out test was carried out to evaluate the interfacial strength between the magnesium matrix and the titanium rod. The titanium rod was not pulled out from the magnesium matrix and fractured at the exposed part for all specimens prepared, which result suggests the strong interfacial bonding strength. Since pull-out of the titanium rod did not occur even for the depth of 3mm, the lower limit of the interfacial shear stress was evaluated using Eq.(1).

$$\sigma_{Ti} = 2\tau_s \chi / r_{Ti} \qquad (1)$$

where σ_{Ti} and r_{Ti} are the tensile strength and the radius of titanium rod, respectively, τ_s is the interfacial shear stress, and χ is the length of interface along the rod (equal to the depth z in Fig.1). Using measured σ_{Ti} value 41kgf/mm^2, the value of τ_s was evaluated to be 10.3kgf/mm^2, fairly large compared with that of steel wire/

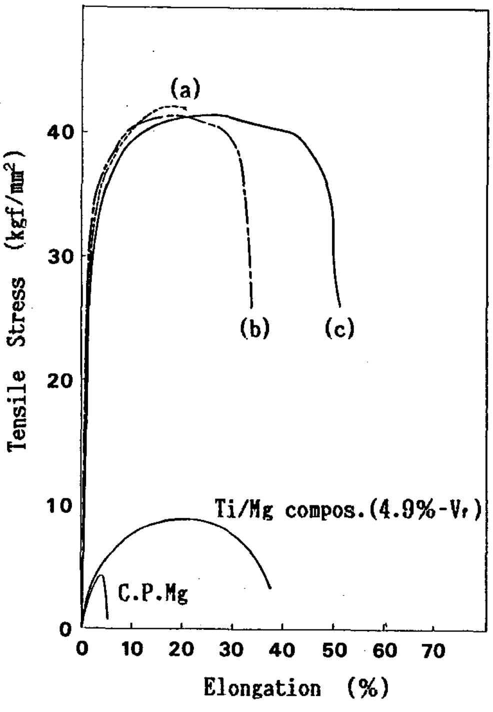

Fig.2 Stress-strain curves of Ti rod and Ti fiber. (a) Ti fiber, (b) Ti rod annealed in Ar, (c) Ti rod annealed in vacuum

epoxy resin composite, 1kgf/mm^2.(10) The value of 10.3kgf/mm^2 was applied to the interface between the titanium fiber and the magnesium matrix because tensile strength of the fiber annealed at 973K in Ar was the same as that of the rod (Fig.2). As a consequence, the critical length of the titanium fiber (ϕ0.2mm) was calculated from Eq.(2).

$$l_c = \sigma_{Ti} r_f / \tau_s \qquad (2)$$

where l_c is the critical length and r_f is the radius of the fiber. The titanium fibers in the composites prepared were found to be long enough compared with the critical length, 0.3mm, calculated by Eq.(2).

3.2 Tensile Test

Tensile strength of the Ti/Mg composites was improved with increase of V_f as shown in Fig.3. The elongation, on the other hand, increased at first with V_f, but decreased beyond the V_f of 10%. With increase of V_f, more shrinkage cavities tend to be introduced in the magnesium matrix when high pressure is not applied, and may cause a decrease of elongation. Fig. 4 shows that the

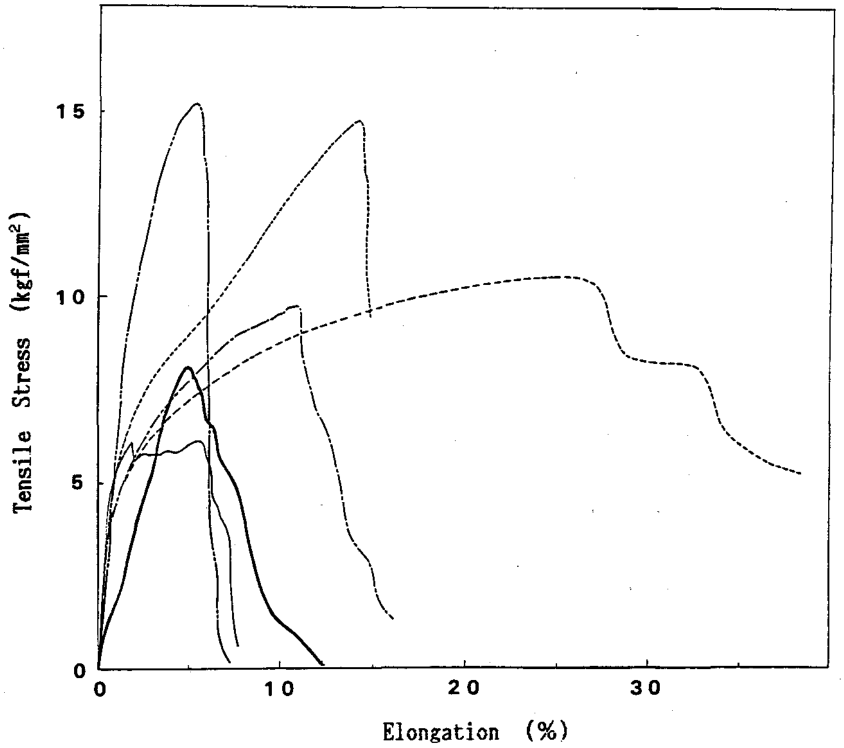

Fig.3 Stress-strain curves of composite and pure magnesium.

▬▬▬ C.P. Mg, ——— V_f1%, —-— V_f2.9%,
- - - - V_f4.9%, ········ V_f11.6%, —--— V_f14%.

experimental values of tensile strength were larger than the values calculated by the rule of mixture, Eq.(3).

$$\sigma^* = (1 - V_f)\sigma_m + V_f\sigma_f \qquad (3)$$

where σ^* is the tensile strength of composite, and the subscripts f and m denote the fiber and the matrix.

SiC fibers, on the other hand, were pulled out from the magnesium matrix in tensile test, probably due to the poor wettability between the fiber and the matrix.

It is well known that the tensile strength of composites reinforced with fiber is lower than that evaluated from the rule of mixture not only in the case of ceramic fiber such as SiC whose strength scatters, but also in the case of metal fiber. The tensile strength observed in the present study, however, was rather larger than that of the rule, which suggested formation of some strong products formed by interfacial reaction.

3.3 Microscopic Observation

Scanning electron micrographs of the interface and the fracture surface of Ti/Mg composite (V_f14%) and SiC/Mg (V_f10%) are shown in Fig.5. Fibers were not distributed uniformly over the cross section. Around the fibers SiC/Mg composite showed brittle fracture surface while Ti/Mg composite did not, probably because wettability between SiC and magnesium was poor. The Ti/Mg composite of 4.9%V_f, having a good elongation, showed more ductile fracture surface than the one of 14%V_f. For the specimen of 14%V_f, fibers distributed inhomogeneously in the cross section and V_f was not less than 40% in some region, which fact may cause generation of shrinkage cavities and stress concentration followed by a decrease of elongation.

Scanning electron micrographs of the surface of Ti and SiC fiber are shown in Fig.6. Surface of the as-received Ti fiber, (a), was fairly rough compared with that of the as-received SiC fiber, (b). Interfacial bonding strength with the titanium fiber is, therefore, expected to be much better than that with the SiC fiber owing to surface wedge effect. Surface of the titanium fiber embedded in the magnesium matrix was covered partially with a porous layer some dozen μm in thickness, which was expected to cause

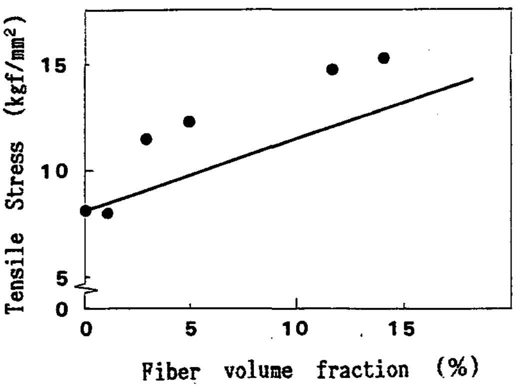

Fig.4 Tensile strength vs. V_f plot of Ti/Mg composite. Straight line is evaluated by the rule of mixture.

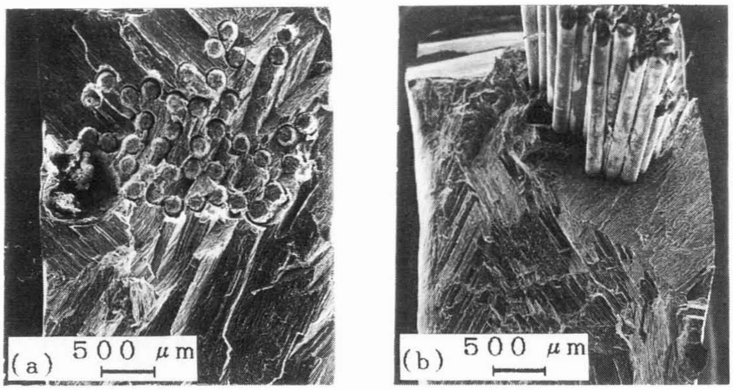

Fig.5 Scanning Electron micrographs of fracture surface.
(a) Ti/Mg composite, (b) SiC composite.

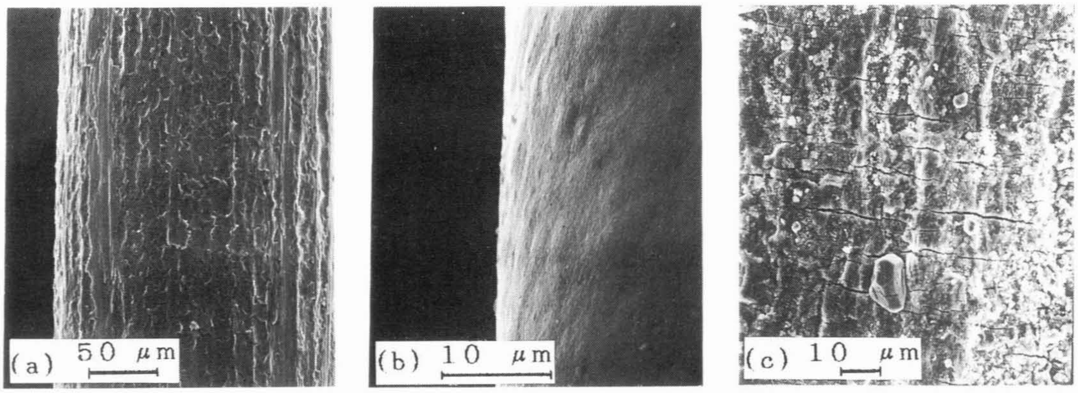

Fig.6 Scanning electron micrographs of surface of fiber.
(a) as-received Ti fiber, (b) as-received SiC fiber,
(c) exposed surface of Ti fiber in the neighborhood of fracture surface.

strong interfacial bonding, and a few fine cracks running across the tensile axis was observed in the neighborhood of the fracture surface (Fig.6c).

The interface between fiber and matrix was observed in the cross section parallel to the direction of fiber (Fig.7). In the Ti/Mg composite the matrix was sticked firmly to the titanium fiber, while in the SiC/Mg composite the wettability between fiber and matrix was found to be poor.

5. CONCLUSION

(1) Wettability between the titanium fiber and the magnesium matrix was fairly good. The interfacial bonding strength estimated by the pull-out test was

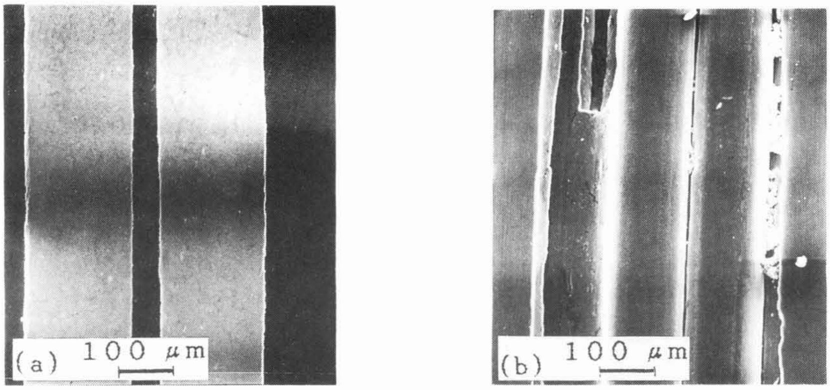

Fig.7 Scanning electron micrographs of the interface.
(a) Ti/Mg composite, (b) SiC composite.

larger than 10.3kgf/mm^2, much larger than that of steel wire/ epoxy resin composite.

(2) Tensile strength was improved with increase of fiber volume fraction V_f, but elongation decreased beyond 10% of V_f.

(3) The Ti/Mg composite showed higher stress levels than that expected from the rule of mixture.

(4) Existence of chemical reaction band some dozen μm in thickness was found by the scanning electron microscopy.

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