Effect of Alumina Content on the Mechanical Properties of Alumina Particle Dispersion Magnesium

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To enhance the mechanical properties of magnesium (Mg) alloys, powders of pure Mg ($\text{Al}_2\text{O}_3/\text{Mg}$) dispersed with over 10 vol% alumina (Al_2O_3) particles were made by ball milling powder mixtures of pure Mg and Al_2O_3 particles with particle sizes of 0.3 and 1 μm . The effect of the Al_2O_3 content of hot-pressed discs formed from the $\text{Al}_2\text{O}_3/\text{Mg}$ powders on the mechanical properties of the discs was investigated. The Al_2O_3 particles were found to be uniformly dispersed in the $\text{Al}_2\text{O}_3/\text{Mg}$ discs. The hardness of the discs increased sharply at an Al_2O_3 content of 20 vol%. This is considered to be because of the excellent interfacial bonding between Mg and Al_2O_3 when the $\text{Al}_2\text{O}_3/\text{Mg}$ discs contain a sufficient amount of Al_2O_3 particles and have a sufficient interparticle distance. The maximum hardness of a 20 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ disc (with an Al_2O_3 particle size of 0.3 μm) was 220 HV, which is much higher than the hardness of AZ91 Mg alloys. The bending strength of the $\text{Al}_2\text{O}_3/\text{Mg}$ discs increased from 0 to 10 vol% Al_2O_3 and then decreased from 20 vol% Al_2O_3 . It is considered that the 0 and 10 vol% discs have similar fracture deflections and that the 10 vol% discs with Al_2O_3 particles can withstand higher compression and tension forces than the 0 vol% discs which do not contain any particles. The reason for the lower bending strength of the 20 vol% Al_2O_3 disc is thought to be because it is harder and more brittle, making it easier for voids to form in the discs, and thus making it easier for cracks to propagate on the specimen surface.

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1. Introduction

In recent years, advances in automotive lighting have led to an increase in the demand for magnesium (Mg) alloys, which are lightweight substitutes for aluminum (Al) alloys. However, Mg alloys generally have inferior mechanical properties to Al alloys.

One potential method to improve the mechanical properties of Mg alloys is to form composites of Mg alloys and ceramic particles and/or fibers. Recently, composites of pure Mg or Mg alloys with ceramic particles and/or fibers have been fabricated by casting and powder metallurgical processes. These composites have been widely studied.

The fabrication of composites of pure Mg reinforced by alumina (Al_2O_3) particles by the powder metallurgical process has been studied.^{1–4} In an attempt to improve the dispersion strengthening of Mg in Al_2O_3 , instead of mixing pure Mg powder with several vol% of Al_2O_3 nanoparticles, Unverricht *et al.*⁴ ball milled the two powders to uniformly disperse Al_2O_3 particles in Mg. When investigating the dispersion strengthening, an Al_2O_3 content of several vol% is used.

However, little research has been conducted on uniform dispersions of over 10 vol% Al_2O_3 particles in pure Mg powder produced by mechanical milling pure Mg and Al_2O_3 particles. The hardness and the wear resistance of a powder of over 10 vol% Al_2O_3 particles uniformly dispersed in pure Mg ($\text{Al}_2\text{O}_3/\text{Mg}$) are expected to be higher than those of an Al_2O_3 dispersion strengthened powder, because the strength of Al_2O_3 particles will enhance that of the $\text{Al}_2\text{O}_3/\text{Mg}$ powder.

The surface properties of pure Mg or Mg alloys are

expected to be improved by bonding $\text{Al}_2\text{O}_3/\text{Mg}$ to Mg substrates using processes such as plasma spraying or hot rolling.⁵

Moreover, $\text{Al}_2\text{O}_3/\text{Mg}$ powders can be used to fabricate sintered compacts that have superior mechanical properties by various pressure sintering processes such as hot pressing, hot isostatic pressing, spark plasma sintering and hot roll sintering.⁶

We have made $\text{Al}_2\text{O}_3/\text{Mg}$ powders by ball milling powder mixtures of pure Mg powder and 0–22.7 vol% Al_2O_3 particles with Al_2O_3 particle sizes of 1 μm . We then investigated the mechanical properties of hot-pressed discs obtained from these $\text{Al}_2\text{O}_3/\text{Mg}$ powders and found that they have higher hardnesses than AZ91 Mg alloys.⁷

In the present study, the effect of the Al_2O_3 content of the hot-pressed discs fabricated from over 10 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ powders with Al_2O_3 particle sizes of 0.3 and 1 μm on the mechanical properties of the discs was investigated.

2. Experimental Procedures

2.1 Test powders

Pure magnesium powder with a particle size of 180 μm , (Mg powder, Kojundo Chemical Laboratory Co. Ltd.; purity: 99.5%) and α -alumina particles with particle sizes of 0.3 and 1 μm (Al_2O_3 particles, Kojundo Chemical Laboratory Co. Ltd.; purities: 99.99% and 99.9%, respectively) were used as the starting materials.

2.2 Trial process

Figure 1 depicts the trial process for Al_2O_3 particle dispersion magnesium ($\text{Al}_2\text{O}_3/\text{Mg}$) discs. $\text{Al}_2\text{O}_3/\text{Mg}$ pow-

Fig. 1 Trial process for Al_2O_3 particle dispersion Mg discs.

ders were milled in an attritor ball mill. Powder mixtures of 200 cm^3 Mg and 0–30 vol% Al_2O_3 particles were fed into an Al_2O_3 container together with 3 dm^3 5 mm diameter Al_2O_3 balls. Mixtures of Al_2O_3 particles with Mg powder with Al_2O_3 particle contents of 0, 10, 20, and 30 vol% were produced.

The Al_2O_3 agitator arm was rotated at 300 rpm for 180 ks in an argon atmosphere to mill the mixed powders. 2 mass% stearic acid was added as a lubricant. The obtained $\text{Al}_2\text{O}_3/\text{Mg}$ powders were compacted into green discs using a hydraulic press at 637 MPa for 60 s. The green discs were hot compressed at 40 MPa and 848 K for 3.6 ks in a carbon sample holder with an argon atmosphere. The furnace was then cooled to room temperature and $\text{Al}_2\text{O}_3/\text{Mg}$ discs were obtained.

2.3 Evaluation

The average particle sizes of the $\text{Al}_2\text{O}_3/\text{Mg}$ powders were obtained by measuring the size distribution using a laser diffraction particle size analyzer (Sympatec GmbH, Helos & Lodos). $\text{Al}_2\text{O}_3/\text{Mg}$ discs with a disc thickness tolerance of $\pm 0.05\text{ mm}$ were finished by polishing with abrasive paper and buffing. Microstructural observations and qualitative analysis of the $\text{Al}_2\text{O}_3/\text{Mg}$ powders and discs were performed using an optical microscope (Olympus Co. Ltd., STM5-UM), a field-emission scanning electron microscope (SEM; Hitachi Ltd., S-4300SE), an electron probe microanalyzer (EPMA, Jeol Ltd., JXA-8500F), and an x-ray diffractometer (Philips Co. Ltd., X'pert Pro MPD).

The disc densities were measured using a hydrometer. The relative density was obtained by dividing the measured density by the theoretical density:

$$\rho_R = \frac{\rho}{\rho_0} \times 100 \quad (1)$$

where ρ_R is the relative density, ρ is the measured density of a disc, and ρ_0 is the theoretical density (e.g., Mg-10 vol% Al_2O_3 has a theoretical density of $1.96 \times 10^3\text{ kg/m}^3$).

The hardness of the $\text{Al}_2\text{O}_3/\text{Mg}$ discs were measured using a Vickers hardness tester at 49 N for 10 s. Five values were measured for each of the three discs.

The $\text{Al}_2\text{O}_3/\text{Mg}$ discs were machined to give plates with dimensions of 19.6 mm (length) $\times$ 5 mm (width) $\times$ 1.4 mm (thickness). After buffing both surfaces, the plates were used in bending tests. The bending strength was calculated using the following formula for a beam:

$$\sigma_F = \frac{3P_{\max}L}{2dt^2} \quad (2)$$

where σ_F is the bending strength, $P_{\max}$ is the maximum load, L is the distance between the support points, d is the specimen width, and t is the specimen thickness. Values were obtained for five to six discs. All discs failed at the center of span.

3. Results and Discussion

3.1 Observations of $\text{Al}_2\text{O}_3/\text{Mg}$ powders and discs

3.1.1 $\text{Al}_2\text{O}_3/\text{Mg}$ powders

Figure 2(a) and (b) respectively show SEM images of the surface and the cross-section of the 20 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ powder with an Al_2O_3 particle size of $1\text{ }\mu\text{m}$. Figure 2(a) shows the size variation of the $\text{Al}_2\text{O}_3/\text{Mg}$ powder. The average powder size was about $20\text{ }\mu\text{m}$. The other powders exhibited similar morphologies and average sizes.

The recovery ratio of $\text{Al}_2\text{O}_3/\text{Mg}$ powder extracted from the ball-mill decreased because the volume of powder solidification by milling increases with increasing Al_2O_3 content.

The average particle size of $\text{Al}_2\text{O}_3/\text{Mg}$ powders is considered to remain approximately constant with increasing Al_2O_3 content, because although the $\text{Al}_2\text{O}_3/\text{Mg}$ powders become finer with increasing Al_2O_3 content, they are more likely to agglutinate at higher Al_2O_3 contents.

Figure 2(c) is a high magnification image of Fig. 2(b). Elemental analysis for Mg, Al, and O using EPMA revealed that the gray regions in Fig. 2(c) are Mg and the fine white particles are Al_2O_3 particles. Figures 2(b) and (c) show that the Al_2O_3 particles are uniformly dispersed in the Mg powder. Similar tendencies were observed for the other $\text{Al}_2\text{O}_3/\text{Mg}$ powders.

3.1.2 $\text{Al}_2\text{O}_3/\text{Mg}$ discs

Figure 3(a) shows a photograph of an $\text{Al}_2\text{O}_3/\text{Mg}$ disc and Fig. 3(b)–(g) show SEM images of 10, 20, 30 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ discs. Figure 3(b), (d), and (f) show discs made from the $1\text{ }\mu\text{m}$ Al_2O_3 particles and Fig. 3(c), (e), and (g) show discs made from the $0.3\text{ }\mu\text{m}$ Al_2O_3 particles.

The discs had diameters in the range 20–21 mm and thicknesses in the range 1.5–2.0 mm. Al_2O_3 particles are uniformly dispersed in the Mg in all the discs; voids are present in the 30 vol% discs.

Figure 4 shows the Al_2O_3 particle amount per $100\text{ }\mu\text{m}^2$ and the interparticle distance as functions of Al_2O_3 content; these values were measured from the SEM images in Fig. 3(b)–(g) and other SEM images. The Al_2O_3 particle amount increased and the interparticle distance decreased with increasing Al_2O_3 content. The $0.3\text{ }\mu\text{m}$ Al_2O_3 particles have a higher particle density and a smaller interparticle distance than the $1.0\text{ }\mu\text{m}$ Al_2O_3 particles.

The measured Al_2O_3 particle amount is much higher than the calculated particle densities. For all Al_2O_3 contents, the Al_2O_3 particle sizes determined from the measured Al_2O_3 particle amount was about 0.2 and $0.3\text{ }\mu\text{m}$ for particle sizes of 0.3 and $1.0\text{ }\mu\text{m}$, respectively. These measured values are almost the same as the median size of 100 Al_2O_3 particles in SEM images. The particles sizes used in this study (0.3 and

Fig. 2 SEM images of (a) the surface and (b) the cross-section of 20 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ powder. (c) High-magnification image of (b).

1.0 μm) represent the median sizes obtained by measuring size distributions by laser diffractometry. Even although different methods were used to measure the particle size, the Al_2O_3 particles in the $\text{Al}_2\text{O}_3/\text{Mg}$ powders and discs are considered to have become finer than the original Al_2O_3 particles.

3.2 Properties of $\text{Al}_2\text{O}_3/\text{Mg}$ discs

3.2.1 Density

Figure 5 shows the effect of Al_2O_3 content on the relative density of the $\text{Al}_2\text{O}_3/\text{Mg}$ discs. The relative density of the 0–20 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ discs exceeds 100%. This is assumed to be due to the formation of MgO by oxidation of the Mg powder as a result of exposure to air when ball milling the

$\text{Al}_2\text{O}_3/\text{Mg}$ powders with active surfaces and of vaporization of stearic acid when heating the green compacts. Additionally, the solid-state reaction of Mg and Al_2O_3 particles is also considered to have an effect.

SEM observations of the 0–20 vol% discs reveal that the discs do not contain significant amounts of microscopic pores. The discs are thus considered to have been fully densified.

The relative density of the 30 vol% discs is less than 100%. This is assumed to be due to their lower sinterabilities because of their lower workabilities as a result of their higher Al_2O_3 contents.

3.2.2 Hardness

Figure 6 shows the effect of Al_2O_3 content on the Vickers hardness of the $\text{Al}_2\text{O}_3/\text{Mg}$ discs. The Vickers hardness of AZ91 alloys are also shown for comparison (these values were obtained by converting from the Brinell hardness numbers given in Ref. 8)).

For both Al_2O_3 particle sizes, the hardness of the $\text{Al}_2\text{O}_3/\text{Mg}$ discs decreased slightly when the Al_2O_3 content increased from 0 to 10 vol%, increased sharply at 20 vol%, and decreased at 30 vol%. The discs containing the 0.3 μm Al_2O_3 particles had higher hardness than those containing the 1.0 μm Al_2O_3 particles. The maximum hardness of the 20 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ discs is 220 HV, which is much higher than those of the AZ91 Mg alloys (indicated by the diagonal line in Fig. 6).

The following possible causes for the sharp increase in the hardness in the 20 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ discs are discussed below:

- (1) Al_2O_3 particle dispersion strengthening
- (2) Inhibition of Mg grain growth
- (3) Solid-state reaction of Mg with Al_2O_3 particles
- (4) Interfacial bonding between Mg and Al_2O_3 particles

(1) Al_2O_3 particle dispersion strengthening

To consider the effect of Al_2O_3 particle dispersion strengthening, the stress necessary to pass dislocations between dispersed particles (known as “Orowan stress”) was investigated.

The Orowan stress τ_0 is given by:

$$\tau_0 = \frac{1.6T}{\bar{l}b} \quad (3)$$

where T is line tension of dislocation, $\bar{l}$ is the average Al_2O_3 particle spacing, and b is Burgers vector.

T/b is assumed to be constant. The ratio of the Orowan stress of the 20 and 10 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ discs were obtained from the average Al_2O_3 particle spacing for particle sizes of 0.3 and 1 μm (see Fig. 4). The ratios were 1.1 and 1.4 for Al_2O_3 particle sizes of 0.3 and 1 μm , respectively. The Orowan stress increased little with increasing Al_2O_3 content.

In contrast, the ratio of the Vickers hardnesses of discs with Al_2O_3 contents of 20 and 10 vol% are 3.6 and 3.0 for Al_2O_3 particle sizes of 0.3 and 1 μm ; these ratios are greater than the Orowan stress ratio.

Therefore, Al_2O_3 particle dispersion strengthening is considered to have very little effect because there almost no correlation between the Vickers hardness and the Orowan stress.

Fig. 3 (a) Appearance of $\text{Al}_2\text{O}_3/\text{Mg}$ disc. SEM images of 10 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ discs with Al_2O_3 particle sizes of (b) $1\ \mu\text{m}$ and (c) $0.3\ \mu\text{m}$, 20 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ discs with Al_2O_3 particle sizes of (d) $1\ \mu\text{m}$ and (e) $0.3\ \mu\text{m}$ and 30 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ discs with Al_2O_3 particle sizes of (f) $1\ \mu\text{m}$ and (g) $0.3\ \mu\text{m}$.

(2) Inhibition of Mg grain growth

Mg grain growth is considered to be inhibited with increasing Al_2O_3 particle content during hot pressing. Figure 7 shows optical microstructures of the 10 vol% and 20 vol% discs. The discs were electrolytically etched and the Mg grain sizes were measured. All the discs have Mg grain

sizes in the range $5\text{--}8\ \mu\text{m}$. The 0 and 30 vol% discs have similar grain sizes.

Al_2O_3 particles are considered to be present in both the Mg grains and grain boundaries, because the Al_2O_3 interparticle distance is $0.15\text{--}0.3\ \mu\text{m}$ (see Fig. 4), and the Al_2O_3 particles are uniformly dispersed in Mg (Fig. 3(b)–(g)).

Fig. 4 Al_2O_3 particle amount and interparticle distance as functions of Al_2O_3 content in $\text{Al}_2\text{O}_3/\text{Mg}$ discs.

Fig. 5 Effect of Al_2O_3 content on the relative density of the $\text{Al}_2\text{O}_3/\text{Mg}$ discs.

There is considered to be very little inhibition of Mg grain growth with increasing Al_2O_3 particle density, because grain growth is independent of the Al_2O_3 particle size and the Al_2O_3 content.

Fig. 6 Effect of Al_2O_3 content on the Vickers hardness of the $\text{Al}_2\text{O}_3/\text{Mg}$ discs.

(3) Solid-state reaction of Mg with Al_2O_3 particles

The compound produced by the solid-state reaction of Mg with Al_2O_3 particle is considered to increase with increasing amount of Al_2O_3 particles. Figure 8 shows X-ray diffraction (XRD) results for $\text{Al}_2\text{O}_3/\text{Mg}$ discs with different Al_2O_3 contents. As shown in Fig. 8, magnesium oxide (MgO) is identified in all the discs, in addition to Mg and Al_2O_3 . An XRD peak assigned to an Al-Mg intermetallic compound ($\text{Mg}_{17}\text{Al}_{12}$) is detected for the 20 vol% disc with an Al_2O_3 particle size of 0.3 μm and for the 30 vol% discs, in addition to peaks due to Mg, Al_2O_3 , and MgO .

Moreover, although MgAl_2O_4 is considered to be produced by the solid-state reaction of MgO and Al_2O_3 ,⁹⁾ it could not be identified in the XRD results of the present study.

Figure 9 shows X-ray relative intensities for Mg (101) and MgO (220) of the $\text{Al}_2\text{O}_3/\text{Mg}$ discs indicated by the arrows in Fig. 8. The relative intensity of the $\text{Al}_2\text{O}_3/\text{Mg}$ discs increases with increasing Al_2O_3 content. The amount of MgO is considered to increase due to the solid-state reaction of Mg with Al_2O_3 particles progressing with increasing Al_2O_3 particle density.

The solid-state reaction of Mg with Al_2O_3 particles is as follows:

Al is considered to be soluble in Mg due to the production of MgO by the reaction. Equation (4) shows that $\text{Mg}_{17}\text{Al}_{12}$ is produced when the Mg solid solution exceeds the solid solubility limit of Al to Mg.

For the 20 vol% discs, $\text{Mg}_{17}\text{Al}_{12}$ is detected only from the disc with an Al_2O_3 particle size of 0.3 μm . This is thought

Fig. 7 Optical microstructures of 10 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ discs with Al_2O_3 particle sizes of (a) 1 μm and (b) 0.3 μm and 20 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ discs with Al_2O_3 particle sizes of (c) 1 μm and (d) 0.3 μm .

Fig. 8 XRD results for the $\text{Al}_2\text{O}_3/\text{Mg}$ discs with Al_2O_3 particle sizes of (a) 1 μm and (b) 0.3 μm .

to be because the finer Al_2O_3 particles react more readily with Mg due to their larger contact area with the Al_2O_3 particles.

The precipitation hardening of $\text{Mg}_{17}\text{Al}_{12}$ is thought to have little effect on the sharp increase in the hardness of the discs, because the XRD results reveal that only a small amount of $\text{Mg}_{17}\text{Al}_{12}$ is produced and because the difference of the hardness between pure Mg and precipitation-hardened AZ91 Mg alloy is not so great (the pure Mg (sand casting) and the AZ91 Mg alloy (sand casting and T6 temper) are 30HB¹⁰) and 70HB,⁸) respectively). Moreover, both the MgO products and solid solution hardening of Mg with Al are thought to have little effect on the hardness since the 10 vol% discs have a similar hardness to the 0 vol% discs.

(4) Interfacial bonding between Mg and Al_2O_3 particles

To investigate the interfacial bonding between Mg and Al_2O_3 particles, we observed indentations produced by the Vickers hardness test. Figure 10 shows the results. The edge of the plastically deformed indentation reveals that no abrasion occurs at the interface between the Mg and Al_2O_3 particles. Based on the results, the sharp increase in the hardness observed at 20 vol% is considered to be due to excellent interfacial bonding between Mg and Al_2O_3 particles, because terms of (1)–(3) are considered to have very little effect on the sharp increase.

Therefore, the sharp increase in the hardness is predicted to promote Al_2O_3 particle strengthening because of the hardness of the Al_2O_3 particles and the restraining effect of the

Fig. 9 Relative Mg to MgO X-ray peak intensities for the Al₂O₃/Mg discs.

Fig. 11 Effect of Al₂O₃ content on the bending strength of Al₂O₃/Mg plates.

Fig. 10 (a) Image of Vickers hardness test indentation of 20 vol% Al₂O₃/Mg disc. (b) High-magnification image of the area in the circle in (a) (Al₂O₃ particle size is 1 μm).

Mg matrix as a result of the excellent interfacial bonding between Mg and Al₂O₃ particles. This will occur when the Al₂O₃/Mg discs contain a sufficient amount of Al₂O₃ particles with a sufficient interparticle distance.

The solid-state reaction of Mg with Al₂O₃ particles may contribute to the excellent interfacial bonding. However, detailed observations and analysis by transmission electron microscopy are necessary to confirm this conjecture.

3.2.3 Bending strength

Figure 11 shows the effect of Al₂O₃ content on the bending strength of Al₂O₃/Mg plates. For both Al₂O₃ particle sizes, the 10 vol% plates have a higher bending strength than the 0 vol% plates. It is considered that both plates have similar fracture deflections, and that the 10 vol% plates containing Al₂O₃ particles can withstand higher compression and tension forces than the 0 vol% plate which

does not contain any particles. The 20 vol% plates have lower bending strengths than the 10 vol% plates. This is thought to be because the plate becomes harder and more brittle, making it easier for voids to form in the discs. Based on these results, it is considered that cracks generated on the specimen surface propagate more easily. This is supported by the observation of voids in the 30 vol% discs (see Fig. 3(f) and (g)) and indentation cracks were not observed after the Vickers hardness test for the 0 and 10 vol% discs, whereas they were observed for the 20 and 30 vol% discs.

The discs containing 0.3 μm Al₂O₃ particles have higher bending strengths than those containing 1.0 μm Al₂O₃ particles.

Nobre *et al.*¹¹⁾ have reported that AZ31 wrought magnesium alloys have a four-point bending strength of 200–220 MPa for a compressive strain of 2.5%. Although it is

not possible to directly compare these results with those obtained in the present study since the test pieces have different shapes and different bending test methods were used, these bending strengths are similar to those of the 0–20 vol% discs.

4. Conclusions

To enhance the mechanical properties of Mg alloys, over 10 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ powders were formed by ball milling powder mixtures of pure Mg and Al_2O_3 particles with particle sizes of 0.3 and 1 μm . The effect of the Al_2O_3 content of hot-pressed discs formed from the $\text{Al}_2\text{O}_3/\text{Mg}$ powders on the mechanical properties of the discs was investigated. The following results are obtained.

- (1) For both Al_2O_3 particle sizes, the effect of Al_2O_3 content on both the hardness and the bending strength of the $\text{Al}_2\text{O}_3/\text{Mg}$ discs exhibited similar tendencies.
- (2) The $\text{Al}_2\text{O}_3/\text{Mg}$ discs containing 0.3 μm Al_2O_3 particles had higher hardness and bending strength than those containing 1 μm Al_2O_3 particles.
- (3) The hardness of the $\text{Al}_2\text{O}_3/\text{Mg}$ discs increased sharply when the Al_2O_3 content increased from 10 to 20 vol%. It subsequently decreased at 30 vol%.
- (4) The reason for this sharp increase in hardness at an Al_2O_3 content of 20 vol% is thought to be due to Al_2O_3 particle strengthening as a result of the excellent interfacial bonding between Mg and Al_2O_3 particles. This will occur when the $\text{Al}_2\text{O}_3/\text{Mg}$ discs contain a sufficient amount of Al_2O_3 particles and have a sufficient interparticle distance.
- (5) The bending strength of the $\text{Al}_2\text{O}_3/\text{Mg}$ plates increased when the Al_2O_3 content was increased from 0 to 10 vol% and it subsequently decreased at 20 vol%.
- (6) The 10 vol% $\text{Al}_2\text{O}_3/\text{Mg}$ plates have a higher bending strength than the 0 vol% plates. It is considered that both the 0 and 10 vol% plates have similar fracture deflections and that the 10 vol% plates with Al_2O_3 particles can withstand higher compression and tension forces than the 0 vol% plates which do not contain any particles.

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