The interfacial microstructure and hardness of cladding plates produced by explosive welding between magnesium alloys having different aluminum concentrations and A6005C aluminum alloy were investigated. Further, measurements of residual stress at the interface of cladding plates were performed. In all cladding plates, the bonding interface had a wavy shape. Adiabatic shear bands were formed at the interface on the magnesium alloy side and deformation twins appeared at the interface due to the impact of explosive welding. Microstructure observation using scanning transmission electron microscope revealed that a thin interlayer was formed at the interface in all cladding plates. The thickness of the interlayer increased with an increase in aluminum concentration in the magnesium alloy, while the thickness was 1 μm or less. In the cross-section of the cladding plate, aluminum alloy showed a relatively higher Vickers hardness value compared with the magnesium alloy, and the hardness value increased when approaching the interface. However, nanoindentation tests revealed no increase in hardness was observed at the interface. Measurements of the residual stress using synchrotron radiation x-rays at the interface of cladding plates revealed a tendency for the occurrence of tensile residual stress on the magnesium alloy side and compressive residual stress on the aluminum alloy side. This might be due to a difference in the coefficient of thermal expansion between the magnesium and aluminum alloys.

Keywords aluminum, dissimilar metal joining, explosive welding, interlayer, magnesium, residual stress

1. Introduction

In terms of environmental protection, using a lightweight vehicle body leads to less CO₂ emissions. The aluminum alloys, magnesium alloys, carbon fiber composite materials, etc., which are developed to achieve weight reduction, are good candidates for new lightweight materials. Therefore, “multi-materialization,” produced by joining dissimilar materials, has received intense interest.

Magnesium alloys are the lightest of all practical alloys and have a large weight-reducing effect, so they are expected to be applied to vehicle bodies. While efforts are being made on many subjects, such as the rolling costs of magnesium alloys and their molding process, the development of a composite material (cladding plate between magnesium alloys and aluminum alloys) is drawing attention. If the cladding plate can be used as a vehicle body, a weight reduction can be expected.

Regarding the joining of magnesium alloys and aluminum alloys, various methods such as melt welding (Ref 1), diffusion welding (Ref 2), hot press (Ref 3), friction stir welding (FSW) (Ref 4, 5) have been studied. But the mechanical properties of the bonding material decrease due to the formation of brittle Al-Mg-based intermetallic compounds. Figure 1 shows the equilibrium phase diagram of the Al-Mg system (Ref 6). Magnesium and Aluminum have similar melting points and can form stable intermediate phases such as β-Mg₂Al₃ or γ-Mg₈Al₇ in their equilibrium phase. In diffusion bonding and FSW, which are solid-phase bonding the relatively high bonding strength can be obtained, but the above-mentioned intermetallic compounds are also formed by these bonding methods, which affects the mechanical properties and the bonding process time. Due to the increased bonding process time and high cost, the development of new joining methods is required.

In this research, the “explosive welding method” (Ref 7, 8), which is a type of solid-phase welding, is investigated. The explosive welding method is a method that utilizes the instantaneous high energy generated by the explosion of explosives for metal bonding and has almost no thermal effect except for local heat generation near the bonding interface (Ref 8). During the explosive welding, high-speed metal jets are generated between the base and flyer plate; this removes the
surface oxide film and the fresh surfaces are bonded together (Ref 9). There is no time for a heat transfer and large-scale melting to take place during welding, thus the number of intermetallic compounds formed during explosive welding is less than other welding method, such as melt welding. In addition, direct joining of dissimilar metals that are difficult to be welded by other welding method can be achieved using explosive welding (Ref 10). This method has already been applied in the fields of steel and aluminum alloys and is used for structural members for ships (Ref 11). Further, explosive welding of metal foils (EWMF), which joints metal foils and base metal plate through high-speed oblique impact, has received much attentions (Ref 12-14). Similar to the explosive welding of dissimilar metals, wavy interface and local molten zone which is also called vortices or eddies at the crest is obtained during EWMF (Ref 12). These zones representatively show complex microstructures such as formation of amorphous (Ref 15), nanoscale grains (Ref 16), intermetallics (Ref 17, 18), and recrystallized grains (Ref 19), which affect the bonding strength of the joint. Regarding the joining of magnesium alloys and aluminum alloys using the explosive welding method, the microstructure of the interface and mechanical properties of the explosively welded material have been reported only for specific alloy compositions (Ref 20, 21). Recently, the effects of the aluminum concentration in the magnesium alloy on interfacial microstructure, corrosion resistance and mechanical properties are studied for the first time (Ref 22), however, the detailed hardness, nanomechanical properties, and residual stress near the interface which are necessary for practical use are still lacking. The aim of this study is to evaluate the effect of the composition of magnesium alloy on the evolution of interfacial microstructure, hardness, and nanomechanical properties of explosively welded magnesium alloy/aluminum alloy cladding plates. Furthermore, residual stress states at the interface were also investigated. It is thought that the grain refinement, dislocation density increment, formation of deformation twins, etc. affect macro mechanical properties of explosive welded cladding plates. However, at the interface, they are in a nonuniform state. In this study, characterization of the entire cladding plate and the interface from the perspective of hardness and residual stress is conducted.

Explosive welding generates residual stress in the composite plate (Ref 23). The residual stress originates as a result of severe plastic deformation, local melted material during joining.

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**Table 1** Chemical compositions of the investigated alloys (mass %)

|       | Mg | Al | Zn | Si | Mn | Cu | Fe | Ni   |
|-------|----|----|----|----|----|----|----|------|
| AZ31  | Bal.| 3.0| 0.9| 0.02| 0.3| 0.002| 0.004| <0.002 |
| AZ61  | Bal.| 5.7| 0.7| 0.02| 0.3| <0.002| <0.002| <0.002 |
| AZ80  | Bal.| 8.0| 0.6| 0.03| 0.3| <0.002| 0.002| <0.002 |
| A6005C| 0.6| Bal.| 0.00| 0.6| 0.01|...| 0.1| ...  |

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**Table 2** The wavy length and the amplitude of each samples interface

| Sample     | Wavelength (mm) | Amplitude (mm) |
|------------|-----------------|----------------|
| AZ31/A6005C| 0.77            | 0.14           |
| AZ61/A6005C| 0.76            | 0.13           |
| AZ80/A6005C| 0.65            | 0.11           |

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**Fig. 1** Al-Mg binary phase diagram

**Fig. 2** Experimental setup for the explosive welding process

**Fig. 3** Schematic illustration for the specimen and measurement points of residual stress measurement
explosive welding (Ref 23, 24). The tensile pattern of residual stress at the surface is particularly undesirable, as they cause increased susceptibility to fatigue (Ref 25) and stress corrosion (Ref 26). Therefore, it is necessary to evaluate residual stresses in explosive welded multilayers. Residual stresses in engineering structures affect crack initiation, crack growth, and fracture. The exact conclusions on the state of residual stress in explosively welded multilayer structures cannot be deduced without the wide range of analyzed composite structures and the use of different methods to determine residual stresses (Ref 27, 28). In this study, the residual stress at the interface of the cladding plates with high accuracy was measured using the synchrotron radiation x-ray diffraction (XRD) method using synchrotron radiation. The $\sin^2 \psi$ method was performed to estimate the in-plane residual stress.

2. Experimental

2.1 Materials

The samples for this study were prepared from extruded materials of AZ31, AZ61, and AZ80 magnesium alloys, and A6005C aluminum alloys, with a thickness of 3 mm, a width of 130 mm, and a length of 1000 mm. Table 1 shows the chemical compositions of materials. The cladding plate was manufactured using explosive welding of magnesium alloy/aluminum alloy. Flyer and base plates were made of aluminum and magnesium alloys, respectively. As shown in Fig. 2, the base plate was located at the bottom and the explosive material was laid on the top of the flyer plate. A6005C aluminum alloy plate was placed on top of AZ31, AZ61, and AZ80 magnesium alloy plates as flyer plates. As the explosive, an ammonium nitrate...
oil-based explosive was used. The explosive was arranged in a sheet shape and detonated via a detonator so that the explosive impact wave propagated in a form close to a plane wave during the welding. The final thickness of the explosively welded cladding plate was ~5.8 mm.

### 2.2 Microstructural Characterizations

The explosively welded cladding plates were cut into small pieces, and the parallel cross-section in the joining direction was ground using emery papers of #800–#2000, and then polished with diamond paste and colloidal silica. The sample was etched with picric acid and the microstructure was observed using an optical microscope. In addition, using a focused ion beam processing device, small pieces are cut and picked up from the surface of the resin-embedded sample with an ion beam (40 kV, Ga+), fixed on a Copper mesh, and then thin-film processed to perform a transmission electron microscope (TEM) observation using JEM-2100F (JEOL). Local morphological observation of the interface of the cladding plates was performed in the scanning transmission electron microscope (STEM) mode. The Vickers hardness values were measured using an HMV-1 (Shimadzu Corporation) with a 10 g load through the bonding interface. Nanoindentation ENT-NEXUS (ELIONIX INC.) with a low load unit was used to characterize the deformation and nanomechanical properties of the specimen. A maximum load of $1.5 \times 10^{-3}$ gf with a load holding time at 1 s was used. Measured in 4 rows with 20 points in each row was selected for nanoindentation tests across the interface.

### 2.3 Residual Stress

Residual stress at the interface of the cladding plates was measured by the $\sin^2 \psi$ method using synchrotron radiation x-rays at Aichi Synchrotron Radiation Center. Applied beamline was BL8S1 (Thin film x-ray diffraction). The stress value, $\sigma$, can be obtained by measuring the diffraction angle (20) while varying angle $\psi$. $\psi$ is formed by sample surface normal $N$ and lattice plane normal $N'$. The optical system of the stress analyzer used in this research is the iso-inclination method. In this method, the setting plane of the $\psi$ angle and the counter scanning (20 scanning) plane are in the same plane. The diffraction angle is measured by aligning the $\psi$ plane to the detector scanning (20 scan) plane (diffraction surface). This is the method commonly used for residual stress measurement.

![Fig. 6 Enlarged optical microscopy images for (a), (b) AZ61 and (c), (d) A6005C of the interface in explosively welded AZ61/A6005C cladding plates](image)
The measurement surface was a cross-section parallel to the welding direction. Details of sample size, measuring direction, measuring surface, and measuring positions are shown in Fig. 3. The surface of the specimen polished with emery paper of #800 was used as the measurement surface. To select peaks for stress determination, the XRD scan was performed on the magnesium and aluminum alloys far from the interface in the range of $2\theta = 20°$–$130°$. Residual stresses estimated using the XRD method have more consistent results when performed on peaks with $2\theta$ angles greater than $90°$, multiple indices, and relatively high intensity (Ref 29). Based on these guidelines, the Al (511) and Mg (213) peaks were chosen for residual stress analysis. The measured stress direction was parallel to the welding direction. The wavelength and energy of synchrotron radiation x-ray were 0.135 nm and 9 keV, respectively.

3. Results and Discussion

3.1 Metallographic Characterization of the Interface

Figure 4 shows the cross-sectional optical images of explosively welded AZ31, AZ61, AZ80 magnesium alloys/Al6005C aluminum alloy cladding plates. The interface in all samples had a wavy shape. The asymmetrical waves are attributed to the density differences in the materials used for explosive welding. The wavelength and amplitude of each sample’s interface are shown in Table 2. The presented values are the average values obtained by measuring 10 points (waves). Further, the ratios of wave amplitude to wavelength for each cladding plate are listed in Table 2. All of them are less than the well-known Karman vortex street stable spacing ratio of 0.28 (Ref 30). Ghaderi et al. investigated the effect of welding parameters such as contact point velocity, flyer plate velocity and collision angle on the morphological characteristic of the explosively welded A1100 aluminum/ AZ31 magnesium alloy joints (Ref 30). They revealed that the wavy—waveless transition occurs depending on the collision angle and collision velocity. Compared to smooth interface, wavy interface is effective for increasing shear strength of the joints due to the increment of the interfacial contact area. Ghaderi et al. also showed the existence of eddy regions or vortices close to the ascending part of the waves (Ref 30), however, in our case, they are not observed in all cladding plates. In the cladding plates using AZ31 and AZ61 (Fig. 3a and b), adiabatic shear bands are observed at the interface on the magnesium alloy side.

Figure 5 shows the cross-section optical images of the explosively welded AZ31/Al6005C cladding plates. As mentioned above, adiabatic shear bands are formed at the interface on the magnesium alloy side (Fig. 5a, black arrows). It is known that magnesium has a lower thermal conductivity than aluminum, and transfer of heat induced by stress concentration is hardly occurred. Due to limited slip system originated from the hexagonal close-packed (HCP) structure, strain accumulation is tended to be occurred. For those reasons, it is considered
At the interface on the aluminum side, the plastic deformation twins occur due to the impact of the welding. The deformation twins were observed over the entire cross-section in the AZ31 magnesium alloy (Fig. 5b). Formation of deformation twins was suppressed in AZ80 compared with AZ31 and AZ61 because the size of ideal grain was small.

3.3 Hardness and Nanomechanical Properties of the Explosively Welded Cladding Plates

Figure 12 shows the hardness profiles of the interface for the explosively welded AZ31/A6005C and AZ80/A6005C cladding plates. In both cladding plates, the aluminum alloy showed higher hardness than the magnesium alloys, and the hardness increased as it approached the interface. Yan et al. reported that the remarkable decrease in the hardness due to over aging of
7075 aluminum alloy near the interface was observed in the explosively welded 7075/AZ31 cladding plate (Ref 36). In our case, no such decrease in hardness was seen in A6005C. In Fig. 12, the hardness of each of the AZ31, AZ80, and A6005C extruded materials is shown by the dashed line for reference. The hardness of as-extruded AZ80 magnesium alloy was higher than that of as-extruded AZ31 magnesium alloy. After explosive welding, the hardness of magnesium alloys increased in each cladding plate. In the magnesium alloys, the increase of hardness near the interface is considered to be due to the interaction of a softening caused by the adiabatic temperature rise and a strain-hardening caused by the plastic deformation during explosive welding (Ref 37). On the other hand, both shear band and twin formation in the magnesium alloy can contribute to the plastic deformation hardening. The accumulation of stress due to the difference in the coefficient of thermal expansion between magnesium and aluminum also can contribute to the hardening (Ref 38). While adiabatic shear bands were not clearly observed in Fig. 7, deformation twins were observed in the relatively small area compared to Fig. 5 and 6. Thus, it can be assumed that the strain-hardening was likely occurred in our case. After explosive welding, the hardness of aluminum alloy also increased in each cladding plate, although the hardness in each cladding plate showed a different tendency. The hardness of A6005C aluminum alloy in AZ80/A6005C cladding plate was larger than that of A6005C aluminum alloy in AZ31/A6005C cladding plate at all measurement points. Due to the difference in tensile properties of magnesium alloys (AZ31 and AZ80 magnesium alloys), the degree of strain-hardening might be changed resulting in the different hardness of A6005C aluminum alloy after explosive welding. Also, since A6005C aluminum alloy is an age-hardenable alloy, the precipitation hardening state may be different in each cladding plate.

In order to investigate the nanomechanical properties of the interface of explosively welded cladding plate, nanoindentation tests were performed for the explosively welded AZ80/A6005C cladding plate. Figure 13 shows the profiles of the nano-hardness across the interface for the explosively welded AZ80/A6005C cladding plates. Each symbol represents each
measurement line. On the A6005C aluminum alloy side, the variation of hardness was large. No increase in hardness was confirmed at the interface, which was different tendency with Fig. 12. The hardness values obtained at the interface were almost the same as that of the AZ80 magnesium side. The Vickers hardness is considered to be affected by the internal stress caused by the change in the microstructure and the plastic deformation caused by the slip line. Further, the hardness obtained by using the nanoindentation test can be influenced by the micro nano behavior of the interface, and the non-uniform hardness distribution in A6005C aluminum may confirms the nonuniformity of the interface morphology. The hardness of AZ80 magnesium alloy, A6005C aluminum alloy, and the interface was 0.87, 3.48, and 1.21 GPa, respectively. There was no significant difference in hardness and deformation behavior between the AZ80 magnesium and the interface. Thus, it was found that the γ-Mg17Al12 phase formed at the interface was likely not a significantly brittle structure as compared with the AZ80

![Fig. 10](image1)

**Fig. 10** Distributions of chemical composition near the interface obtained by line analysis for explosively welded (a) AZ31/A6005C, (b) AZ61/A6005C, and (c) AZ80/A6005C cladding plates (Ref 22)

![Fig. 11](image2)

**Fig. 11** Selected area electron diffraction (SAED) patterns for the interlayer for the explosively welded (a) AZ31/A6005C, (b) AZ61/A6005C, and (c) AZ80/A6005C cladding plates (Ref 22)

![Fig. 12](image3)

**Fig. 12** Profiles of the Vickers hardness across the interface for the explosively welded AZ31/A6005C and AZ80/A6005C cladding plates

![Fig. 13](image4)

**Fig. 13** Profiles of the nano hardness across the interface for the explosively welded AZ80/A6005C cladding plates. Each symbol represents each measurement line
element method is required. The fine neutron diffraction method and prediction by the evaluation by combining three-dimensional analysis by the method, location of the measuring points, detonation velocity the materials having a similar CTE. Accordingly, the cutting residual stress was generated. For further discussion, it is attributed to the difference in the CTE of magnesium and aluminum. It is considered that the material with a small CTE (aluminum alloy) of explosively welded cladding plates. It can be high tensile residual stress state. The Vickers hardness is considered to be affected by the internal stress caused by the change in the microstructure and the plastic deformation caused by the slip line. Further, the hardness obtained using the nanoindentation test is influenced by the micro-nano behavior of the interface.

4. Conclusive Summary

The effect of magnesium alloy composition on the evolution of interfacial microstructure, hardness, and nanomechanical properties of explosively welded magnesium alloy/aluminum alloy cladding plates was investigated. The following points can be highlighted:

1. A wavy interface was observed in all the explosively welded cladding plates. The interlayer composed of the \( \gamma-Mg_7Al_12 \) phase was formed at the interface. The higher aluminum concentration in the magnesium alloy leads to the thicker intermediate layer.

2. In the cross-section of the cladding plate, aluminum alloy showed a relatively high hardness compared with the magnesium alloy, and the hardness values increased as it approached the interface.

3. Through nanoindentation tests, no increase in hardness was confirmed at the interface. Hardness at the interface is almost the same as that on the magnesium alloy side. The Vickers hardness is considered to be affected by the internal stress caused by the change in the microstructure and the plastic deformation caused by the slip line. Further, the hardness obtained using the nanoindentation test is influenced by the micro-nano behavior of the interface.

4. The residual stress on the magnesium alloy side and the aluminum alloy side were the tensile stress and the compressive stress, respectively. It is considered that the material with a small linear expansion coefficient (aluminum alloy) restrained the contraction of the material with a large linear expansion coefficient (magnesium alloys) in the high-speed deformation at the time of the explosion.

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