Direct Welding of Metals and Ceramics by Ultrasonic Vibration

Hisashi IMAI** and Sin-ichi MATSUOKA**

This paper describes the experimental results of ultrasonically welding ceramics and metals. In comparison to other methods, ultrasonic vibration is easier and quicker for welding ceramics, such as ZrO₂, SiC, and Si₃N₄, and metals such as aluminum, magnesium, and copper. In this study, ceramics and Mg were welded under the following conditions: amplitude, 30 µm; welding pressure, 10 MPa; required duration, 1.0 s. Ultrasonic welding of the ceramics with metals was possible when the condition $E = KPn < f(P, E)$ ($E$: energy density $P$: welding pressure) was satisfied and the welding interface temperature was in the range of 300–400°C. When the ceramics were preheated, welding was possible within a short time and under low pressure, and the material had good weldability even at a high temperature (200°C). It is presumed that in this environment, oxide and organic films are efficiently removed from the bonded interfaces by the vibration of ultrasonic waves.

**Key Words:** Ultrasonic Welding, Welding Mechanism, Ceramics, Metals, Energy Density, Welding Pressure

1. Introduction

Joint bonding is an indispensable technology in nearly every field, and welding is a prime example. Moreover, joint bonding between the zygotic (complex) of metal and ceramics is critical in the field of electronics and semiconductors(1).

Ceramics have excellent physical and chemical characteristics including high strength, heat resistance, corrosion resistance, and electrical nonconductivity. Therefore, the zygotic of metal and ceramics is used in numerous fields such as precision instruments, electronics and semiconductors.

In general, solid-state bonding, brazing, or a mechanical joint is used for jointing different kinds of materials. Solid-state bonding includes friction welding with pressure, explosive welding, ultrasonic welding, and diffused welding(2). Ultrasonic welding methods make it possible to easily joint materials within a short time in any environment using basic equipment. Moreover, materials can be jointed directly without using flux or adhesive. And, since large pressure is not required, there is small deformation of the bonding material(3). However, for large materials, the state of the junction is not known, and there have been few reports on this matter(4), (5).

In this experiment, we examined direct welding metal/ceramics using ultrasonic vibration, the strength, the bonding material, the estimated temperature of the bonded interface, and the properties of the bonded interface. We also investigated the mechanism of ultrasonic welding.

2. Experiment Method and Conditions

Table 1 lists the properties of the metals and ceramics used in the experiment. There types of ceramics were selected, ZrO₂, SiC, and Si₃N₄, having normal sintering temperature and with surfaces polished to Ra: 0.1 µm using diamond slurry. The metals used were Mg, Cu, Ti, and Al which has good weldability with ceramics(6).

Figure 1 shows an outline of the ultrasonic welding. The maximum output of the ultrasonic welding

| Metal | Composition (%) | Size (mm) |
|-------|-----------------|-----------|
| Al    | 99.5 - 99.99    | 30L × 5W × 0.01-0.3t |
| Mg    | 99.0            | 30L × 5W × 0.25t |
| Cu    | 99.9 - 99.97    | 30L × 5W × 0.02-0.5t |
| Ti    | 99.5 - 99.6     | 30L × 5W × 0.2t |

Ceramic

|     | Size (mm) |
|-----|-----------|
| ZrO₂|           |
| SiC | 30L × 5W × 3t |
| Si₃N₄|           |
equipment (manufactured by CHOONPA KOGYO Ltd.) was 600 W and 1 200 W, with nominal frequency of 19 kHz and 15 kHz, respectively. The amplitude of the 600 W equipment was 30 – 35 µm (p-p) (at a no load) and the 1 200 W equipment had a wider range, from 30 µm to 70 µm (p-p) (at a no load). The area of the horn tip carved a mesh of 4 x 4 mm² on the surface of the chip, and prevented the materials from slipping. The ceramics were fixed to the anvil as shown in the figure and then the metal was attached. After a load of 80 – 480 N was applied by the horn (hereinafter, the value obtained by dividing the load in the area of the horn tip by 16 mm² is referred to as the welding pressure), ultrasonic vibrations were transmitted. The transmission time (hereinafter, this is assumed to be the required duration) ranged from 0.1 – 2.0 s. Ceramics and metal were degreased using acetone prior to the welding. The equipment used in the experiment observed the amount of electrical energy of the junction, and calculated the input energy from this value.

Moreover, a heating coil was inserted in the anvil making it possible to preheat the ceramics by heat transfer. The preheating temperature was measured at the surface using type K contact prior to welding.

Ceramics and Cu were welded using an aluminum lamina as insert material, and considering the difficulty in measuring frictional heat temperature directly on the welded surface, it was measured from the electromotive force of Cu generated when welding ceramics and Al.

Figure 2 shows an outline of the experiment. The room temperature at each welding was used as a reference and then was corrected after the welding.

The strength of the welding material was measured to evaluate the materials characteristics. Figure 3 shows an outline of the strength measurement. A shear tensile test was conducted on the welding materials and the value obtained by dividing maximum load by the actual welding area was the bond strength. Bending moment was prevented by a dummy placed between the chuck and the welding material. The actual junction area was therefore the metallic transfer area that remained on the ceramic surface after the bonding material was peeled away. In addition, the properties of the welded interface and diffusion layer and the existence of a reaction layer were investigated by SEM observation and EDX linear analysis of the welded interface.

3. Experiment Result and Consideration

3.1 Feasibility of direct welding for combination of materials

We experimented with direct welding of three kinds of ceramics and materials, and examined weldability. Table 2 shows the results, with the following signs used as indications;

○ Welding is strong (Tensile test is possible).
○ Welding is poor (Tensile test is not possible and reproducibility is low (10% or less)).
△ There is the transfer of the metal on the ceramic surface.
× Impossible to welding.

The experiment demonstrated good direct welding of aluminum and ceramics, and also confirmed the weldability of Mg/SiC and Mg/ZrO₂.

3.2 Welding strength

Even when welding is possible, the strength of the welding material is an important consideration for practical use. Figure 4 shows an example of the welding
strength of Mg/SiC under the condition of a required duration 1.0 s. Welding strength increases with an increase in the welding pressure from 6 to 12 MPa. However, the welding strength remains constant when the welding pressure reaches or exceeds 12 MPa. Under excessive welding pressure, Metal (Mg) deforms plastically, making it impossible to obtain good welding.

Figure 5 shows the welding strength of various materials. The figure shows that the materials of Mg/SiC and Mg/ZrO$_2$ do not differ significantly in welding strength. However, comparing Mg/SiC with Al/SiC, the welding strength of Al/SiC is higher. It is presumed that an excellent weld is obtained by using a soft Al material that improves strength.

### 3.3 Weldability and energy density when using insert material

In solid-state bonding using ultrasonic vibration, weldability differs greatly depending on the kind of metal and ceramics. The relationship between the weldability of Cu and ceramics and the energy density was examined using aluminum for the insert material. The welding energy is the value obtained by subtracting the no-load energy (background) from the total input energy used in the welding, and the energy density is the value obtained from dividing the junction energy by the pressurization area (16 mm$^2$). Figure 6 shows the relationship between energy density and welding pressure using varying duration and welding pressure for each bonding material (the numeral is the plate thickness) of Cu(0.2)/Al(0.2)/ZrO$_2$ (a), Cu/Al/Si$_3$N$_4$ (b) and Cu/Al/SiC (c). The figure also shows the survey results on weldability. Welding was possible even at low energy density, when the welding pressure was increased on either welding material.

Cu/Al/Si$_3$N$_4$ (b) shows the widest range of condition for weldability. Cu/Al/ZrO$_2$ (a) has higher weldability than the other two cases under low pressure and low energy density, but because the material surface shape is transformed it is not obtained. Cu/Al/SiC (c) has the lowest weldability condition in which the welding becomes possible is the smallest of all. One of the reasons for this is thermal diffusivity; ZrO$_2$: 0.022 ($10^{-4}$ m$^2$/s), Si$_3$N$_4$: 0.140 ($10^{-4}$ m$^2$/s), and SiC: 0.350 ($10^{-4}$ m$^2$/s), with ZrO$_2$ having lowest value(7). Therefore, heat loss for welded interface of Cu/Al/ZrO$_2$ is considered to be small; heat dissipation of a heat effectively does not work on Cu/Al/SiC (c), which has the highest thermal diffusivity.

The above result indicates that bonding material with sufficient bond strength is obtained if it Eq. (1), where $E$ is energy density and $P_c$ is welding pressure. The coefficient and index of each bonding material is shown in Tables 3.

$$E = KP^n < f(P,E)$$  \hspace{1cm} (1)

### 3.4 Influence of surface roughness of ceramics

Since welding materials are under the constant pressure of vibration, the roughness of the material surface becomes a problem in ultrasonic welding. Especially, the surface roughness of brittle ceramic material greatly influences the weldability. Figure 7 shows the relationship between bond strength and surface roughness on the Cu/Al/ZrO$_2$ bonding material in giving roughness to the ZrO$_2$ surface.

It can be seen in the figure that for 30 $\mu$m amplitudes, the bond strength is stable when the surface roughness $R_{\text{max}}$, is about 1 $\mu$m. However, when $R_{\text{max}}$ exceeds...
5 µm, the welding strength fluctuates and weakens. On the other hand, high bond strength is confirmed in the case of 70 µm amplitudes even if $R_{max}$ exceeds 5 µm. The welding strength tends to decrease when the amplitude is low and surface roughness is high. On the other hand, it tends to increase when the amplitude is high because there is increased entanglement of materials which suppresses the lowering of bond strength.

The welding strength is low when the surface roughness is low and the amplitude is high resulting in the destruction of metallic material. Therefore, we recommend choosing a surface roughness equivalent to the amplitude in order to obtain good welding material.

### 3.5 Temperature and joint strength on joint field side

In the ultrasonic welding, the physical welding properties and the properties of the welded interface show significant change due to friction heat that arises during welding. We examined the relationship between welding strength and friction heat for each welding material. Friction heat arising in the interface from the electromotive force affects Cu/Al, as shown in Fig. 2. Figure 8 shows the relationship between interface temperature and welding pressure when welding Cu/Al/Si₃N₄. It can be seen in the figure that the welding temperature rises as the welding time and the welding pressure increase. The temperature rise rate for Cu/Al/ZrO₂ was the highest and its weldability was the best in comparison with the ceramics welding material. It is presumed that frictional heat effectively acts on this because the thermal diffusivity rate of ZrO₂ is very small as described in paragraph 3.3, and there is little heat loss on the welding surface.

The relationship between interface temperature and welding strength for the Cu/Al/Si₃N₄ welding material is shown in Fig. 9 (the results of preheating are described later).

The same figure shows that the interface temperature is the value at which bond strength is near 0 at about 300°C or less, and there is tendency for welding strength to rise and stabilize when the welding temperature 300°C. Several factors come into play; Al softens, the adhesion between materials increases, and diffusion and reaction
Fig. 8 Relationship between welding pressures, required duration and interface temperature of Cu/Al/Si₃N₄

Fig. 9 Relationship between welding strength $\sigma_w$ and interface temperature $T$

Fig. 10 Relationship between preheating and welding area

Fig. 11 Example of welded product at heat environment

are promoted when the temperature at welding interface reaches a high value over 300°C. Because ultrasonic welding is possible at temperature below the melting point of Al, which is the insert material, it is presumed that the welding is completed before the interface temperature reaches the melting point range.

3.6 Effect of preheating ceramics

The result described in the previous section that the frictional heat occurring on the welding surface greatly influences weldability and welding strength. We then preheated the ceramics in an attempt to improve the welding and promote the formation of a reaction layer in the welded interface. Figure 9 shows that the preheated and joined welding material had higher weld strength than welded materials of normal temperature, presumably due to the following; the interatomic density of the insert material (Al) decreased due to the preheating, deformability increased, adhesion with Si₃N₄ was improved, and diffusion and reaction were promoted by the increase in friction heat.

Generating temperature was about 300°C or less, and is not considered to have had any effect. Moreover, Fig. 10 shows example results when we attempted to weld Cu/ZrO₂ and Cu/Si₃N₄ for which direct welding is difficult under ordinary temperatures for preheating ceramics. The figure also shows the relationship between junction area and preheating temperature.

A junction with high reproducibility became possible by preheating to 250°C in ZrO₂ and 300°C in Si₃N₄. One of the reasons for improved weldability is the generation of interface temperature and the softening of Cu by friction.

3.7 Thermostable strength of welded material

Since repeated thermal stress and rapid temperature rise are applied when electronic components are utilized actually used, welding require thermostable strength\(^8\). The weldability of ultrasonically welded material under a high temperature environment was investigated in this report. Cu/Al/Si₃N₄ welding material was left under a high temperature environment for 2 hours, and its peeling etc. was investigated after investigating the furnace cooling. An example is shown in Fig. 11, which is a photograph of the welding material before and after the experiment under high temperature (300°C) environment.

The observation results for environmental temperatures of 200°C, 300°C, 400°C and 600°C, verified that there was no peeling of welding material at 200°C – 400°C
and that the welding material was good. Breakage occurred not at the junction but at the base metal boundary of Cu in the stretched shearing test. The results indicate that the junction has the equivalent welding strength of base metal or over and appears to have stabilized welding strength in a high temperature environment of 200°C–400°C.

We also performed a strength comparison between room temperature and high temperature environment. Table 4 shows one example comparing the welding strength Al(0.5)/ZrO₂ and Al(0.5)/Si₃N₄ at room temperature (25°C) and at 200°C. Welding strength of about 60–70% at ordinary temperature was also maintained at 200°C for both welding materials. It is expected that the ultrasonic welding material resists rapid temperature rise and is able to maintain the good weldability in the high temperature environment.

### 3.8 Interface property of the junction

Figure 12 shows a photograph of each welded interface of Mg/SiC ultrasonic welding material (a) and Mg/Mg arc welding material (b). For welding material (b), recrystallization tends to occur due to melting from the arc heat. However, this change is not seen in the constitution of the Mg alloy in the interface of ultrasonic welding material.

Figure 13 shows an example of the SEM observation and the line analysis on the Al/Si₃N₄ welding point. The junction shows a good interface and a transition layer of several micrometers is confirmed in the region. A diffusion zone or a reactive layer may form in this part. This is similar for other welding materials(9).

Figure 14 shows X-ray diffraction result for investigating the proportion of inclusion elements in the welding interface of the Al/Si₃N₄ welding material.

This figure shows that only Si₃N₄ and Al were detected. It is presumed that the reaction of the chemical compound causing crystallization between Si₃N₄ and Al did not occur and mainly the material was welded together.

---

**Table 4** Measured values of welding strength and temperature of tensile test of welded products

| Welded products | Welding Strength | P1/P0       |
|-----------------|------------------|-------------|
|                 | P0 (Room temp.)  | P1 (200°C)  |             |
| Al/Si₃N₄       | 97.17 (MPa)      | 65.89 (MPa) | 65.89 (%)   |
| Al/ZrO₂        | 66.43 (MPa)      | 45.97 (MPa) | 69.20 (%)   |

---

![Fig. 12](image1.png)  
**Fig. 12** Cleft surface of ultrasonically welded products of Mg/SiC (a) and arc welded products of Mg/Mg (b)

![Fig. 13](image2.png)  
**Fig. 13** Scanning electron micrographs showing internal structure (a), and line analysis by X-ray micro analyzer (b) of ultrasonically welded product

![Fig. 14](image3.png)  
**Fig. 14** XRD patterns of welding interface of Si₃N₄/Al
by the diffusion of Al at Si₃N₄.

4. Conclusions

The experimental results of direct metal/ceramics welding using ultrasonic vibration and the examination of weldability of each material as well as effects and characteristics, clarified the following.

(1) Excellent weldability of Al, the Mg alloy, ZrO₂, SiC, and Si₃N₄ was confirmed. Weldability rises in ultrasonic welding when soft metallic material with a low melting point is used.

(2) The region in which junction is possible changes and the welding strength fluctuates according to the welding pressure and required duration. The optimum welding pressure and required duration must be used for each welding material in order to obtain good welding material.

(3) The relationship between energy density $E$ and joint pressure $P_c$ to obtain the welding material that has sufficient welding strength was clarified, and the line showing the critical value becomes $E = K P^n$.

(4) In material with low surface roughness, stable welding is possible even when the amplitude is small. On the other hand, good bonding material is obtained with large surface roughness to increases the amplitude.

(5) Welding material with intensity-based stabilization is obtained when the temperature of the welded interface exceeds 300°C. Weldability increases by preheating the ceramics, obtaining the bonding material with high strength.

(6) Peeling in the junction does not occur under the high temperature environment on the Cu/Al/Si₃N₄ welding material. It was confirmed that 60–70% strength was retained at 200°C or less. It is considered that the welding material has good weldability under a thermal stress environment.

(7) It was confirmed that the metal does not melt and that the bonded interface is weld in the solid phase. The results of quantitative and linear analysis indicate that a diffusion layer or reaction layer forms in the junction.

This research was supported in part by the Grant-in-Aids for Scientific Research of JSPS.

References

(1) Iwamoto, S. and Somiya, S., Joint of Metal and Ceramics, (in Japanese), (1990), pp.17–50, Uchidaroukakuhō.

(2) Japanese Society for Technology of Plasticity, Joint, (in Japanese), (1990), p.169, Corona Company.

(3) Matsuoka, S., Ultrasonic Welding of Different Materials, Journal of JSTP, (in Japanese), Vol.41, No.478 (2000), p.1069.

(4) Watanabe, T., Yanagisawa, A., Sunaga, S. and Hiraishi, M., Auger Analysis of an Aluminum/Alumina Interface Ultrasonically Welded, Journal of JILM, (in Japanese), Vol.52, No.3 (2002), pp.122–125.

(5) Matsuoka, S., Ultrasonic Welding of Ceramic/Metal, Journal of Material Processing Technology, Vol.47 (1994), pp.185–196.

(6) Matsuoka, S., Ultrasonic Welding of Ceramics-Aluminium and Its Property, Journal of JSTP, (in Japanese), Vol.28, No.322 (1987), pp.1186–1191.

(7) Nikkan Kogyo Shimbun Co., Fine Ceramics Data Book 94 Versions, (in Japanese), pp.94–97.

(8) Shiratori, M., Problems of Joints in Packaging of Electronic Devices, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol.60, No.577, A (1994), pp.1905–1912.

(9) Imai, H. and Matsuoka, S., Ultrasonic Welding of Ceramics and Metals, Lecture Proceedings of the 40th Japan Society of Mechanical Engineers Hokuriku Shinetsu Branch, (in Japanese), (2003), pp.303–304.