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Welding characteristics and structures of same and different metal specimens using ultrasonic complex vibration welding equipments

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ABSTRACT

Ultrasonic complex vibration welding of same and different metal specimens and structures of the welded area are studied using several complex vibration welding systems, scanning and transmission electron microscopes (SEM and TEM).
Ultrasonic welding can weld various metal directly using vibration and static clamping pressure. The welding area is limited very narrow layer and can weld different metal specimens which have different melting temperature and difficult to weld by usual welding methods such as resistance welding. Ultrasonic complex vibration welding of two-dimensional vibration locus could be used for joining different metal specimens at multiple positions continuously and has superior quality compared with conventional ultrasonic welding with linear vibration locus. Welding of aluminum-copper, aluminum nickel plate specimens and aluminum alloy is essential for fuel cell, multi-layer battery or EDLC capacitor electrodes for electric or hybrid automobile and other various industry fields. For large electric current devices, multiple spot or seam welding is required.
Ultrasonic complex vibration welding systems of 15 to 40 kHz were developed using (1) multiple transducers integrated with a transverse vibration disk, (2) complex vibration converter with diagonal slits. Elliptical to circular vibration loci are obtained at the welding tip and they are driven using several 500 W (1) and 2 kW (2) power amplifiers. Required vibration velocity and damage by vibration fatigue are small compared with conventional welding.
Using the ultrasonic complex vibration welding systems, aluminum, copper, aluminum-copper and aluminum-nickel plate specimens were welded directly successfully at continuous multiple positions.
Structures of these welded areas are observed using SEM and TEM. By observations of TEM images of cross sections of welded specimens, it was shown that these specimens were joined directly without any oxide, inter-metallic compound, mutual diffusion and any different structures. Required vibration velocity was one-third to quarter compared with conventional welding and weld strength near to material strength was obtained independent of specimen position and direction, and multiple or continuous welding is possible. Alumina coated aluminum alloy specimens were welded using complex vibration. The coated alumina layer was broken roughly in initial welding process and furthermore, broken into small alumina particles by ultrasonic complex vibration and finally dispersed throughout in welding specimens.

INTRODUCTION

Ultrasonic complex vibration sources and welding equipments with elliptical to circular vibration locus were developed and welding characteristics of various same and different metal specimens using the ultrasonic complex vibration welding equipments are studied.

Developed complex vibration systems are that used (1) a complex vibration source using multiple bolt-clamped Langevin type piezo ceramic (PZT) longitudinal transducers (BLTs) integrated with a transverse vibration disk, and (2) longitudinal-torsional complex vibration converter with diagonal slits driven eccentrically by longitudinal vibration source.

Ultrasonic complex vibration welding can be used for joining same and different metal and ceramics, and has superior quality compared with conventional welding with linear vibration locus. Welding of aluminum and copper, aluminum and nickel plate specimens and aluminum alloy is essential for fuel cell, battery or large capacity capacitor (such as EDLC) electrodes for electric or hybrid automobile and the other various industry fields.

Welding characteristics of ultrasonic complex vibration welding equipments developed are studied.

Conditions and structures of cross sections of (1) aluminum and copper, (2) aluminum and nickel, (3) alumina coated aluminum alloy plate specimens welded using the welding equipments are studied.

The structures of these welded areas are observed using scanning electron microscope (SEM) and transmission electron microscope (TEM).

CONFIGURATIONS OF ULTRASONIC COMPLEX VIBRATION WELDING SYSTEMS.

A. Complex Vibration Source with Six BLT Longitudinal Transducers Integrated with a Transverse Vibration Disk

The configuration of a large capacity complex vibration source with six BLT transducers using a transverse vibration catenoidal horn with a welding tip is shown in Figure 1.

The complex vibration source consists of a complex transverse vibration catenoidal horn 40 mm in diameter (SUS304B), a transverse vibration disk of (2, 1) vibration mode (JISA5056B), which is 195 mm in diameter and 25 mm in thickness, and six longitudinal vibration driving systems with BLT transducers 40 mm in diameter.

Three longitudinal vibration driving systems with two types of BLT transducers, which have normal and reverse polarity stacks of PZT rings, are installed in one side of the disk surface. These three vibration driving systems are installed in opposite side of the disk. The two driving systems (driving vibration pair) are connected in parallel and are driven in anti-phase mode (Figure 1).

The complex transverse vibration horn with a welding tip installed in the center of the disk is driven transversally by the gradient of the transverse vibration node at the center of the disk. The three driving vibration system pairs are driven simultaneously in phase difference 120° using an arbitrary wave form generator with variable phase output and three 500 W static induction transistor (SIT) power amplifiers (Figure 2).
Figure 3 shows transverse vibration amplitude distributions along the upper stainless steel catenoidal complex transverse vibration horn and the side of the disk at resonance frequency of 27.575 kHz.

The disk vibrates in transverse vibration mode. The catenoidal horn with a welding tip installed at the free end vibrates

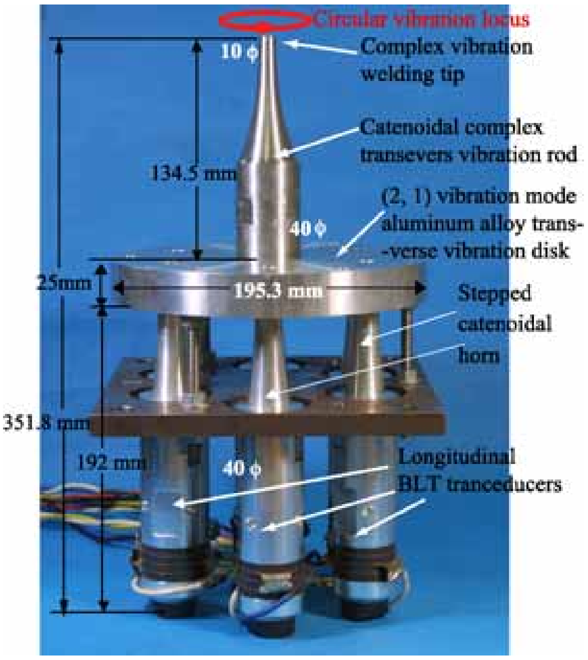

Figure 1. 27 kHz ultrasonic complex vibration system with six BLT transducers integrated using a (1, 2) transverse vibration disk.

in 2.25-wave-length transverse vibration mode and the vibration amplitude increases at catenoidal horn part. Vibration amplitude transform ration N is about 5.

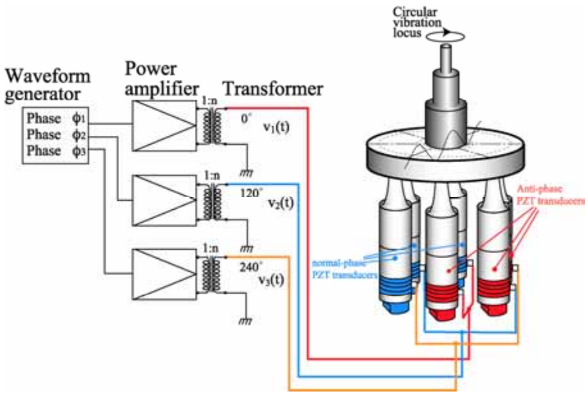

Figure 2. Block diagram of a driving system of the ultrasonic complex vibration source using a waveform generator and three 500 W SIT power amplifiers.

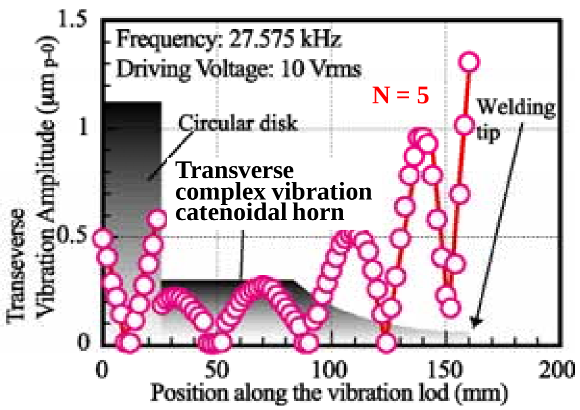

Figure 3. Transverse vibration amplitude distribution along the upper stainless steel complex vibration catenoidal horn and the side of the disk at resonance frequency of 27.575 kHz.

The admittance loop of the transverse vibration system measured from one driving longitudinal vibration pair is shown in Figure 4. The admittance loop is single loop although multiple vibration systems are connected. Quality factor is over 1,000.

The vibration locus of the welding tip at a resonance frequency of 30.520 kHz is shown in Figure 5. The welding tip vibrates in an almost circular vibration locus.

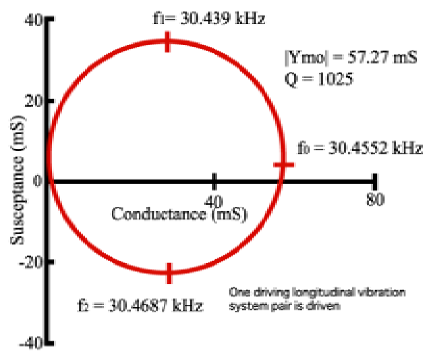

Figure 4. Free admittance loop of the 27 kHz ultrasonic complex vibration system with six BLT transducers.

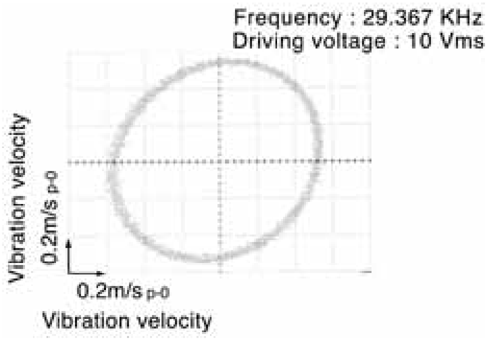

Figure 4. Vibration locus of the 27 kHz complex vibration welding tip installed at the free edge of the catenoidal transverse vibration horn. Vibration locus was measured using two laser Doppler vibrometers. Driving voltage: 10 Vrms.

B. Complex Vibration Converter with Diagonal Slits

Figure 5 shows the configuration of the 20 kHz, 2 kW ultrasonic complex vibration welding equipment with a control system. The ultrasonic welding system consists of a 20 kHz BLT longitudinal transducer (50 mm in diameter), a catenoidal horn for enlarging vibration velocity with a supporting flange, a complex vibration converter with diagonal slits and four welding tips installed in the free end of the complex vibration converter. The complex vibration converter is designed using equivalent electrical transmission line method and FEM analysis. The converter is 40 mm in diameter and made from steel, stainless steel or titanium alloy.

Twelve diagonal slits (45°, 0.5 mm in width, 10 mm in length and 3 mm in depth) were cut directly along the circumference of the converter rod using a spark machine.

Longitudinal vibration is partially converted by diagonal slits to torsional vibration. The complex vibration system is driven using a 2 kW frequency auto-tracking and constant vibration velocity control driving system.

Figure 6 shows a free admittance loop of the complex vibration system. The admittance loop is single loop since longitudinal and torsional resonance frequencies are adjusted very near. Quality factor is about 3,000.

Figure 7 shows vibration locus of the complex vibration welding tip. The welding tip vibrates in elliptical locus.

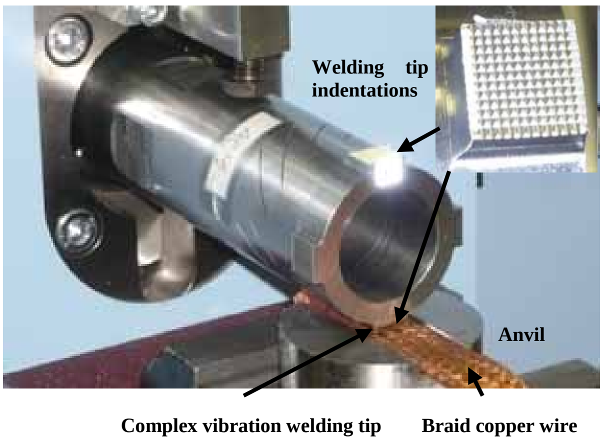

Figure 5. 20 kHz complex vibration welding system using a longitudinal-torsional complex vibration converter with twelve diagonal slits.

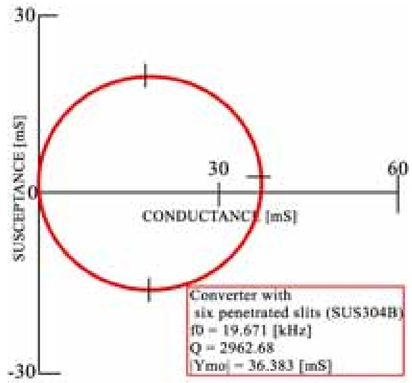

Figure 6. Free admittance loop of the 20 kHz complex vibration system using a longitudinal-torsional complex vibration converter with twelve diagonal slits.

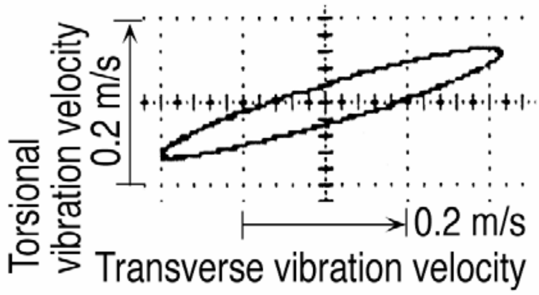

Figure 7. Vibration locus of the 20 kHz transverse-torsional complex vibration welding tip.

WELDING CHARACTERISTICS OF THE ULTRASONIC COMPLEX VIBRATION WELDING EQUIPMENTS.

Figure 8 shows the rrelationship between welding tip vibration amplitude and weld strength of 0.3-mm-thick and 1.0-mm-thick pure aluminum plate specimens welded using the 27 kHz complex vibration system with Li-Grease inserted between the welding surfaces. The aluminum plate specimens are welded successfully under vibration amplitude of 1.0 μm_{p-0} (peak-to-zero value) with weld strength almost equal to material strength, although under rather long weld time and large static pressure. The required vibration amplitude is very small compared with conventional system with linear vibration locus.

Figure 9 shows the relationship between welding time and weld strength of two lapped 1.0-mm-aluminum alloy plate specimens welded using the complex vibration system. Aluminum alloy plates are welded with weld strength over 1 kN is obtained within weld time of 0.5 s under vibration amplitude of 2.5 - 3.3 μm_{p-0}.

Figure 10 shows the relationships between vibration amplitude and weld strength of 1.0-mm-thick aluminum and copper plate specimens welded the 27 kHz complex vibration system. Static clamping force and weld time are maintained at 2.18 kN and 2.5s.

Maximum weld strength of 1 kN is obtained under vibration amplitude 1.5 to 2.0 $\mu m_{p-0.}$ The weld strength is almost equal to the material strength of the aluminum specimen. Required vibration amplitude is very small and stable welding area is very wide compared with a conventional welding system with linear vibration.

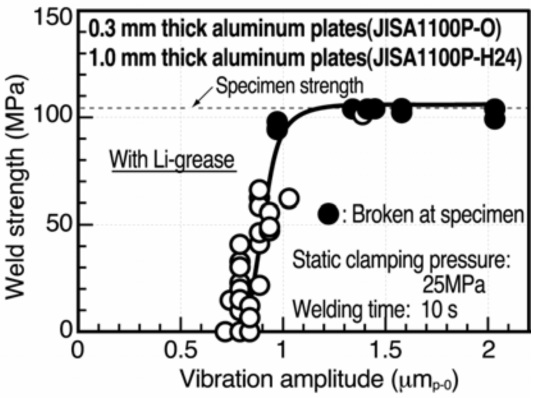

Figure 8. Relationship between welding tip vibration amplitude and weld strength of 0.3-mm-thick and 1.0-mm-thick pure aluminum plate specimens welded using the 27 kHz complex vibration system with Li-Grease inserted between the welding surfaces.

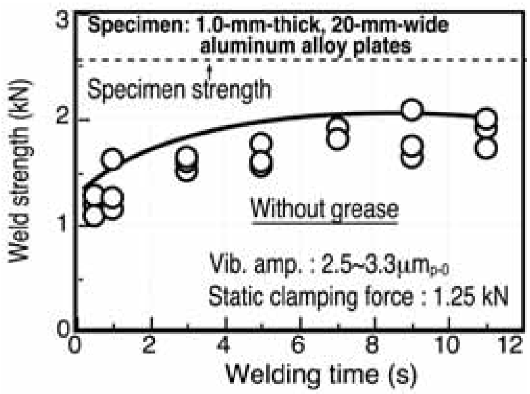

Figure 9. Relationship between welding time and weld strength of two lapped 1.0-mm-thick aluminum alloy plate specimens welded using the 27 kHz complex vibration system.

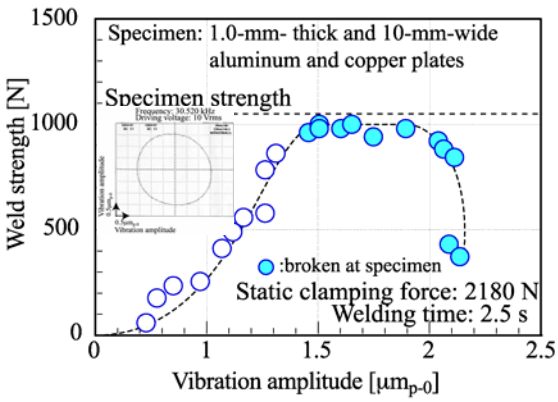

Figure 10. Relationship between welding tip vibration amplitude and weld strength of 1.0-mm-thick aluminum (JISA1100P) and copper (JISC1100P) plate specimens welded using the 27 kHz complex vibration system.

CONDITIONS OF WELDED PARTS OF METAL PLATE SPECIMENS USING THE ULTRASONIC COMPLEX VIBRATION

A. Multiple Welding of Metal Specimens

Figures 11 and 12 shows welded conditions of 0.3-mm and 1.0-mm-thick copper plate specimens and 0.3-mm-thick aluminum and 1.0-mm-thick copper plate specimens welded five and nine positions using the 20 kHz complex vibration system with 5-mm- and 10-mm-square welding tip (Figure 5).

Using complex vibration welding system, multiple welding is possible with stable and constant weld strength, and furthermore continuous seam welding is possible.

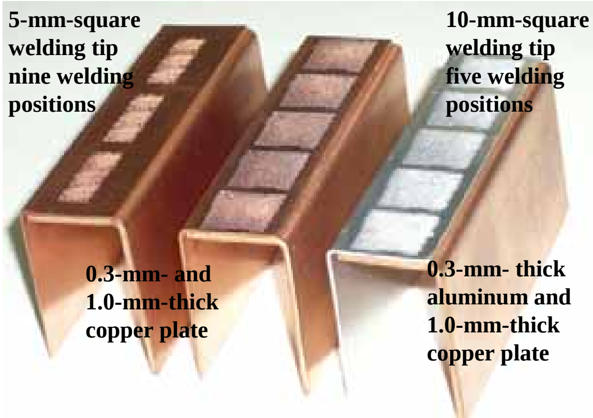

Figure 11. Conditions of copper plate specimens, and aluminum and copper plate specimens welded at five and nine positions using the 20 kHz complex vibration system.

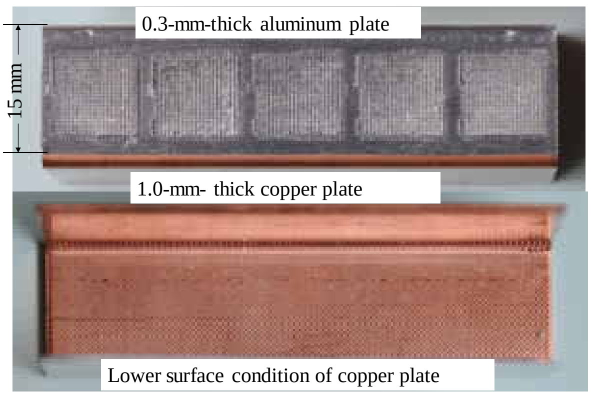

Figure 12. Conditions of aluminum and copper plate specimen welded 5 positions using the 20 kHz complex vibration system.

B. Conditions of Cross Sections of Welded Parts of Aluminum-nickel and Aluminum-Copper Specimens

Conditions of cross sections of (1) aluminum and copper, (2) aluminum and nickel, (3) alumina coated aluminum alloy plate specimens welded using the ultrasonic welding equipment are studied.

Structures of these welded areas are observed using SEM and transmission electron microscope (TEM).

Figure 11 shows SEM image of 1.0-mm-thick aluminum and copper plate specimen welded using the 27 kHz ultrasonic complex vibration equipment with six BLT transducers (Fig. 1). The aluminum and copper plate specimen is welded completely with weld strength almost equal to the aluminum specimen.

Figure 12 shows TEM image (scale; 100 nm) of cross sections of aluminum and copper specimens welded using the 20 kHz ultrasonic complex vibration welding equipment. The aluminum and copper plate specimen was welded completely with weld strength almost equal to the aluminum specimen.

Figures 13 and 14 show TEM images (scale; 100 nm and 20 nm) of cross section of aluminum and nickel plate specimen welded using the 20 kHz ultrasonic welding equipments. These specimens were joined directly without any oxides, inter-metallic compound, mutual diffusion and any different structures. These metal specimens are welded by atomic attraction force between these specimens using ultrasonic welding.

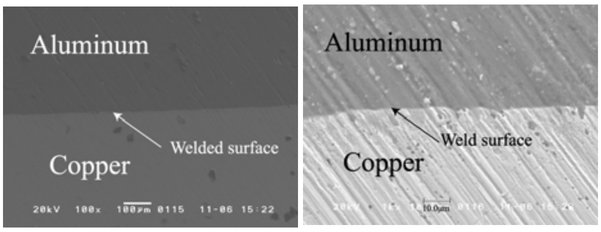

Figure 11. SEM image of cross sections parallel to welding direction of 1.0-mm-thick aluminum (JISA1100P) and copper (JISC1100P) plate specimen welded using the 27 kHz complex vibration welding equipment.

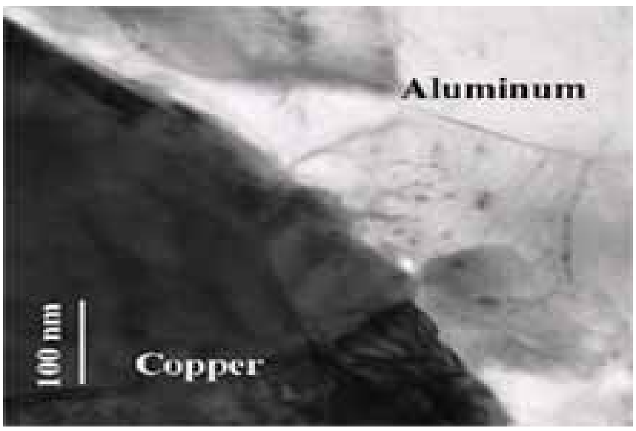

Figure 12. TEM images of cross sections of 1.0-mm-thick aluminum-copper plate specimen welded using the 20 kHz complex vibration welding equipment.

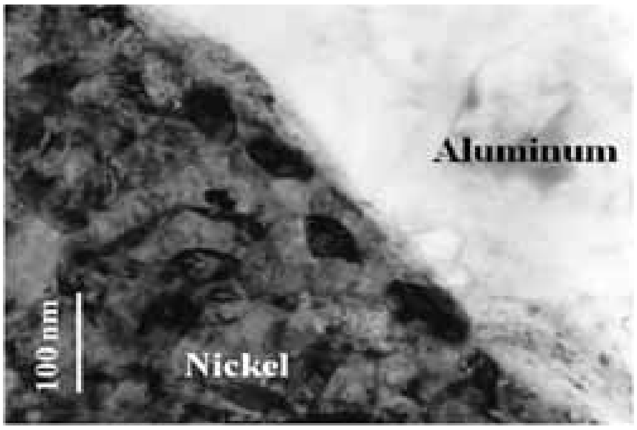

Figure 13. TEM images of cross sections of 1.0-mm-thick aluminum-nickel plate specimen welded using the 20 kHz complex vibration welding equipment.

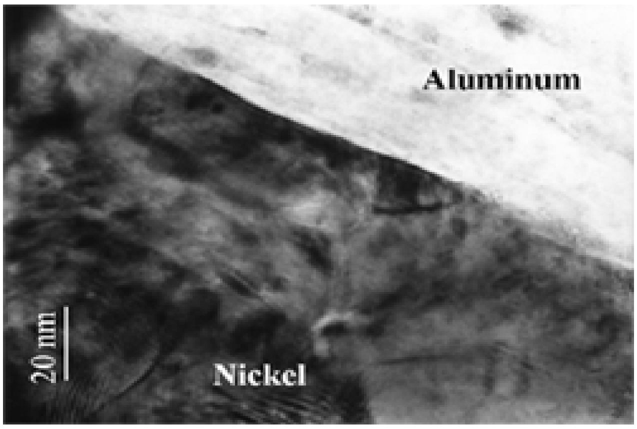

Figure 14. TEM images of cross sections of 1.0-mm-thick aluminum-nickel plate specimen welded using the 20 kHz complex vibration welding equipment.

C. Condition of Cross Sections of Welded Parts of Alumina Coated Aluminum Alloy Plate Specimens

Figure 15 shows SEM image of cross section of 1.0-mm-thick alumina coated aluminum alloy plate specimen welded using the 20 kHz complex vibration system. Thickness of coated alumina layer is about 20 μm.

It is shown that the coated alumina layer was broken roughly in initial welding process and furthermore, broken into small alumina particles by ultrasonic complex vibration and finally dispersed throughout in welding specimens. The small alumina particles are dispersed in the range from the welded layer to about 0.3 mm in thickness during welding time within 2 s.

Weld strength of the specimens is almost aluminum alloy specimen strength irrespective of the existence of the dispersed alumina small particles dispersed in the specimen.

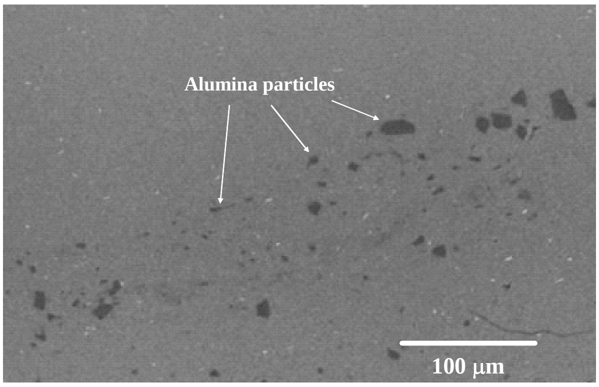

Figure 15. SEM image of cross section of 1.0-mm-thick alumina coated aluminum alloy plate specimen welded using the 20 kHz complex vibration welding equipment.

CONCLUSIONS

1. Ultrasonic complex vibration sources and welding equipments with elliptical to circular vibration locus of 15 kHz to 40 kHz were developed and welding characteristics of various same and different metal specimens were studied.

2. Developed complex vibration systems were that used (1) a complex vibration source using multiple transducers integrated with a transverse vibration disk driven by two or three power amplifier system, and (2) longitudinal-torsional complex vibration converter with diagonal slits driven by a longitudinal vibration source.

3. Welding conditions of ultrasonic complex vibration welding systems were studied and it was shown that complex vibration welding systems have superior welding characteristics. Required vibration velocity (vibration amplitude), static clamping pressure and welding time decreased due to two or three-dimensional vibration stress using welding tip vibrating in circular to elliptical locus.
Required vibration velocity for complex vibration welding was one-third to quarter compared with conventional welding using linear vibration.

4. Vibration fatigue or damage of the welding specimens decreased by smaller required vibration amplitude and furthermore, stable, uniform and large weld strength near to material strength was obtained independent of welding position and direction.

5. Using ultrasonic complex vibration welding system with circular or elliptical vibration locus, welding of multiple positions (multiple spot welding) and also continuous seam welding of same and different metal specimens become possible.

6. Welded structures were studied using SEM and TEM. Different metal specimens were welded directly without any oxides, inter-metallic compound, mutual diffusion and any different structures using the ultrasonic complex vibration welding equipments.

7. Coated alumina layer on aluminum alloy was broken to small particles and dispersed in the specimen by ultrasonic vibration.

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