Various complex vibration systems with two-dimensional vibration locus were developed for improving welding characteristics of ultrasonic metal welding. Ultrasonic complex vibration welding system could be applied effectively for joining same and dissimilar metal and ceramics, and has superior quality compared with conventional welding with linear vibration locus. Welding of dissimilar metal specimens including many metal foils such as aluminum and copper are required for electronic devices and multi-layer fuel cell, battery or EDLC electrodes for electric or hybrid automobile and other various industry fields.

Keywords: ultrasonic complex vibration welding, circular to elliptical welding tip vibration locus, two-dimensional vibration stress, various changeable welding tips, welding of many lapped electrode foils and terminals

1. Introduction

Conventional ultrasonic welding method using linear vibration locus has limited welding characteristics. For improving welding characteristics, ultrasonic complex vibration welding method using two-dimensional vibration stress was developed and proved significantly effective for various small to large welding specimens.

Ultrasonic metal welding is used for joining same and different metal materials and obtained welded part has superior mechanical and electrical characteristics. Welding mechanism is based on atomic force and welded interface has no diffusion and no inter-metallic structure.

Complex vibration converter using diagonal slits driven by a longitudinal vibration source was proposed for ultrasonic complex welding of various specimens. The longitudinal to torsional complex vibration converter vibrates in rotating circular to elliptical vibration locus at a free edge of the converter in the case where vibration phase difference between longitudinal and torsional vibrations is about 90 degrees.

The converter was designed using equivalent electrical transmission line method and FEM.

Using complex vibration, required vibration velocity becomes one-third to quarter compared with conventional welding and weld strength near to material strength was obtained independent of specimen position and direction with smaller vibration damages of welding specimens.

Furthermore, using the complex vibration welding tip with rotating circular to elliptical vibration locus, soft metal such as lead and lead/tin solder and also electric wire with insulating coating are welded successfully which are almost impossible to weld using conventional ultrasonic welding with linear vibration.

Various welding tips could be installed the free edge part using a connecting bolt due to smaller required vibration velocity. Complex vibration welding tip is easily changeable.
Welding characteristics of various metal specimens such as aluminum, copper, nickel and aluminum alloy plates and many foils were studied using 20, 27 and 40 kHz complex vibration welding systems. Many thin metal foil electrode and terminals for Li-ion battery and capacitor were welded successfully using the complex vibration systems.

2. Configuration of ultrasonic complex vibration welding system

2.1 Ultrasonic complex welding system using a complex vibration converter with diagonal slit

Complex vibration system with circular locus could be usually consisted using multiple vibration systems and amplifiers, but one-dimensional complex vibration systems with circular vibration locus could be consisted of a longitudinal-torsional vibration converter with diagonal slit part and a longitudinal vibration source which is driven by a power amplifier.

Fig. 1(1) shows 19.5 kHz, 2 kW ultrasonic complex vibration welding equipment using a complex vibration converter with a half-wavelength complex transverse vibration welding tip. The ultrasonic welding system consists of a 19.5 kHz bolt-clamped Langevin type longitudinal transducer (BLT, 50 mm in diameter), a stepped horn for enlarging vibration velocity with a supporting flange, a complex vibration converter with diagonal slits. The complex vibration converter is designed using equivalent electrical transmission line method and FEM analysis. The converter is 40 mm in diameter. Twelve diagonal slits were cut directly along the circumference of the converter rod using a spark or milling 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.

Fig. 1(2) shows schematic diagram of converter and longitudinal and torsional vibration distribution along a complex vibration converter and driving stepped horn. The converter and stepped horn vibrate 3/4 wave-length longitudinal mode and 5/4 wave-length torsional mode between free edge of converter A and nodal position of stepped horn C. Fig. 2(1) shows free admittance loops of the vibration system without welding tip and with a half wave-length complex transverse complex vibration welding tip using a power factor compensating inductance Lc. These loops are single loop due to near longitudinal and torsional resonance frequencies. Inserting inductance Lc, quality factor decreases from 1935 to 303, but motional admittance |Ymo| increases from 52.3 mS to 290.8 mS and the complex vibration system with a complex vibration welding tip could be driven effectively.

Fig. 2(2) shows vibration loci of the half-wave length complex transverse vibration welding tip. The welding tip vibrates in almost circular vibration locus during welding process.

![Diagram](image-url)
2.2 Ultrasonic complex vibration system with 20-mm-wide complex vibration welding tip

Fig. 3 (1) shows 19.5 kHz complex vibration system with 20-mm-wide, 15-mm-depth, 9-mm-height complex vibration welding tip (22 gram in weight) for welding of stacked many thin electrode foils installed at free end of complex vibration converter. This welding tip affects resonance frequency of the complex vibration system. The complex vibration converter was designed considering the welding tip weight. This non-resonant welding tip vibrates nearly as a mass but vibrates slightly transversally. Transverse resonance frequencies of the welding tip are 35.62 kHz and 44.15 kHz in the longitudinal and torsional vibration directions. The 20-mm-wide complex transverse welding tip is effective for welding of many stacked aluminum and copper foils and terminals.

Fig. 3 (2) shows free admittance loops of the converter with 20-mm-wide welding tip under no load condition and loaded by static clamping force of 1,000 N. Motional admittance $|Y_{mo}|$ were improved to 516 mS and 499.7 mS using inductance $L_c = 2.288$ mS. Using the complex vibration converter considered welding tip weight, $|Y_{mo}|$ under static pressure 1,000 N decreases only slightly. The vibration system could be driven effectively during welding processes.

2.3 Complex Vibration Welding Systems with Long and Narrow Welding Tip

Fig. 4 (1) shows 19.5 kHz hard metal 3.0-mm-diameter, 79-mm-long transverse vibration welding tip for welding of deep and narrow area. The 3.0-mm-diameter hard metal complex transverse vibration welding tip is fixed to half wave-length transverse vibration holder by shrinkage fit. The
welding tip is installed in free edge of complex vibration converter using a connecting bolt. Transverse vibration distributions measured by a laser Doppler vibrometer along half-wave transverse vibration holder and 3.0-mm-diameter, 79-mm-long hard metal rod is shown in the figure. The hard metal rod vibrates transversally in complex vibration mode with four nodal points. Free end of welding tip vibrates in circular to elliptical locus.

Fig. 4 (2) shows free admittance loops of 19.5 kHz complex vibration welding system with 3.0-mm-diameter, 78.70-mm- and 78.95-mm-long hard metal complex transverse vibration welding tip without power factor compensating inductance Lc. Resonance frequencies of complex vibration system with 78.70-mm- and 78.95-mm-long hard metal welding tip change from 19.0039 kHz to 18.9770 kHz, quality factors are 1703.9 to 2065.91 and \(|Y_{mo}|\) are 36.655 mS to 23.311 mS by 0.25-mm-length difference.

But, motional admittances could be improved by inserting adequate power factor compensating inductance LC, and the complex vibration system can be driven effectively. The complex vibration system could be driven effectively using frequency auto-tracking amplifier system but calibration and monitoring vibration amplitude of welding tip is required during welding process.

Fig. 4 (1) Transverse vibration distribution along 19.5 kHz half-wave length transverse vibration holder and 3.0-mm-diameter, 79-mm-long hard metal complex transverse vibration welding tip. (2) Free admittance loops of 19.5 kHz complex vibration welding system with 3.0-mm-diameter, 78.70-mm- and 78.95-mm-long hard metal complex transverse vibration welding tip without power factor compensating inductance Lc.

3. Welding conditions of ultrasonic welding using linear and complex vibration systems

Fig. 5 (1) shows welding characteristics of 1.0-mm-thick aluminum plates welded using a 20 kHz linear vibration welding system. Vibration amplitude were altered 1 to 13 \(\mu\)m\(_{p-o}\) (peak-to-zero value). Static clamping force are 1.0, 1.5 and 2.0 kN. Maximum weld strength obtained using vibration amplitude about 10 \(\mu\)m\(_{p-o}\). Using excess vibration amplitude, weld strength decreases due to vibration fatigue.

Fig. 5 (2) shows relationships between upper aluminum specimen length and weld strength of 0.5-mm- and 1.0-mm-thick aluminum specimen welded using a 20 kHz linear vibration welding system under same welding conditions. Weld strength obtained were changed by upper specimen length. And, in the case where upper specimen length is near to 1/4 and 3/4 longitudinal wave length, the specimen was very difficult or impossible to weld with sufficient strength.

Fig. 6 (1) shows welding condition of 1.0-mm-thick aluminum and copper plate using a 27 kHz 10-mm-diameter complex vibration welding tip of circular vibration locus. 1.0-mm-thick aluminum and copper plates are welded stably from only 1.5 \(\mu\)m\(_{p-o}\) to 2.1 \(\mu\)m\(_{p-o}\) with specimen material strength. Stable weld range is wider compared that using conventional linear vibration equipment with linear vibration locus.

Fig. 6 (2) shows welding condition of 0.3-mm-thick aluminum and 1.0-mm-thick copper plate using a 19.5 kHz 3.0-mm-diameter, 79-mm-length hard metal complex vibration welding tip of cir-
circular vibration locus. Maximum welding strength over 20 N is obtained from 0.1 s to 0.25 s welding time under 10 $\mu$m-p-w vibration amplitude and maximum strength is obtained between 0.4 s and 1.0 s. Maximum strength was obtained at wider welding condition compared with a conventional linear vibration welding system.

Using a complex vibration welding tip, required vibration amplitude and static pressure become smaller and stable welding range becomes wider. Furthermore, large and uniform welding strength is obtained independent of welding specimen direction.

Fig. 5 (1) Relationships between vibration amplitude, static clamping force and weld strength of 1.0-mm-thick aluminum plate specimens welded using a 20 kHz ultrasonic linear vibration welding equipment. Fig. 5(2) Relationship between upper specimen length and weld strength of 1.0-mm-thick aluminum plate specimen welded using a 20 kHz ultrasonic linear vibration welding equipment.

Fig. 6 (1) Welding condition of 1.0-mm-thick aluminum and copper plate using a 27 kHz 10-mm-diameter complex vibration welding tip of circular vibration locus. Fig. 6 (2) Welding condition of 0.3-mm-thick aluminum and copper plate using a 19.5 kHz 3.0-mm-diameter hard metal welding tip.

4. Welded conditions of ultrasonic complex vibration welding systems

Fig. 7 shows various non-resonant and resonant type welding tips. These welding tips are installed in the ultrasonic complex vibration welding system using a connecting bolt.

Fig. 8 shows conditions of 0.3-mm-thick aluminum and 1.0-mm-thick copper plate, and 0.3- and 1.0-mm-thick copper plate specimens welded using a 2 kW, 19.5 kHz ultrasonic complex vibration welding equipment. These specimens were welded at five positions using a 10-mm-square complex vibration welding tip.

Fig. 9 shows conditions of 0.3-mm-thick aluminum and 1.0-mm-thick copper plate welded using a 19.5 kHz 3.0-mm-diameter, 79-mm-length hard metal complex vibration welding tip of circular vibration locus. Aluminum specimens were broken at welding surface or circumference of welded area with weld strength almost material strength. Center part of welded area were welded on copper plate completely.
Fig. 10 (1) shows conditions of 30 lapped 0.02-mm-thick copper, electrode foils and Ni coated copper terminal welded using 19.5 kHz 20-mm-wide complex transverse vibration welding tip. Electrode copper foils and Ni coated copper terminal were welded uniformly with small damage and sufficient weld strength. Fig. 10 (2) shows conditions of 30 lapped 0.02-mm-thick aluminum foils and Ni coated copper terminal welded using 20-mm-wide complex transverse vibration welding tip. These specimens were welded successfully with small deformation, no damage and sufficient weld strength. Fig. 11 shows conditions of two 0.16-mm-thick, 3.0-mm-wide nickel clad copper terminals and deep nickel coated steel case bottom welded using a 19.5 kHz 3.0-mm-diameter, 79-mm-long hard metal complex transverse vibration welding tip. These two lapped terminals were successfully welded with their material strength. Required welding time is under 0.1 s. Three or more lapped terminals can be welded with sufficient weld strength. Right side specimens were welded higher welding conditions and welded area was partially colored due to temperature rise at weldment by higher welding condition.

Fig. 7 Various non-resonant and resonant type 19.5 kHz welding tips

Fig. 8 Conditions of 0.3-mm-thick aluminum and 1.0-mm-thick copper plate, and 0.3- and 1.0-mm-thick copper plate specimens welded using a 2 kW, 19.5 kHz ultrasonic complex vibration welding equipment.

Fig. 9 Indentations and broken conditions of 0.3-mm-thick aluminum and 1.0-mm-thick copper
plate welded using 19.5 kHz 0.3-mm-diameter, 79-mm-long hard metal complex transverse vibration welding tip after tensile tests.

![Welding tip indentations](image1.png) ![Anvil side indentations](image2.png)

Fig. 10 (1) Conditions of 30 lapped 0.02-mm-thick copper, electrode foils and Ni coated copper terminal.
(2) Conditions of 30 lapped 0.02-mm-thick aluminum foils and Ni coated copper terminal welded using 20-mm-wide complex transverse vibration welding tip.

![Conditions of two 0.16-mm-thick, 3.0-mm-wide nickel clad copper terminals and deep nickel coated steel case bottom welded using a 19.5 kHz 3.0-mm-diameter, 79-mm-long hard metal complex transverse vibration welding tip.](image3.png)

Fig. 11 Conditions of two 0.16-mm-thick, 3.0-mm-wide nickel clad copper terminals and deep nickel coated steel case bottom welded using a 19.5 kHz 3.0-mm-diameter, 79-mm-long hard metal complex transverse vibration welding tip.

5. Cross sections of welded specimens

Fig. 12 shows Scanning electron microscope (TEM) images of cross sections of aluminum-copper and aluminum-nickel plate specimens welded using 19.5 kHz 10-mm-diameter welding tip under sufficient welding conditions. These specimens were successfully welded under sufficient welding conditions. No diffusion area and no intermetallic structure and no specific structure are observed in welded interfaces.

Fig. 13 shows SEM image of cross section of thirty lapped 0.015-mm-thick aluminum electrode foils and 0.8-mm-thick aluminum terminals welded using 19.5 kHz 30-mm-wide complex transverse vibration welding tip.

These lapped aluminum foils and terminals were successfully welded with sufficient weld strength, small deformation and no damage.
6. Conclusions

1. Various ultrasonic complex vibration systems with two dimensional vibration locus were developed for improving welding characteristics of ultrasonic metal welding.
2. Ultrasonic complex vibration welding system using two dimensional vibration stress has superior welding characteristics and required vibration velocity and clamping force were decreased significantly compared with conventional linear vibration system.
3. Welding of same and dissimilar metal specimens including many metal foils such as aluminum and copper which are essential for various electronic devices and multi-layer fuel cell, battery or EDLC electrodes for electric or hybrid automobile and other various industry fields.
4. Complex vibration using two-dimensional and also three-dimensional vibration is effectively applied various applications of high power ultrasonics.
5. For obtaining good results using ultrasonic vibration, ultrasonic vibration systems adequate for special ultrasonic machining must be developed.

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