Configuration and welding characteristics of ultrasonic complex vibration welding systems using two-dimensional vibration stress

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Abstract. Various complex vibration systems with two-dimensional vibration locus were developed for improving welding characteristics of ultrasonic metal welding. Ultrasonic complex vibration welding system using two-dimensional vibration stress 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 are required for electronic devices and fuel cell, battery or EDLC electrodes and the other various industry fields.

1. Introduction

Ultrasonic complex vibration systems could be configured using multiple vibration systems using same and different frequencies and multiple power amplifiers, and various complex vibration systems up to 1 MHz were developed. Complex vibration converter using diagonal slits driven by a longitudinal vibration source was proposed. The longitudinal to torsional complex vibration converter vibrates in 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. Various welding tips could be installed in the free edge part with a connecting bolt. Using complex vibration, required vibration velocity becomes one-third to quarter compared with conventional welding using linear vibration and weld strength near to material strength was obtained independent of specimen position and direction, and multiple spot or continuous seam welding becomes possible using complex vibration equipment. Various dissimilar metal specimens including many metal foils such as aluminum and copper were successfully welded using ultrasonic complex vibration welding systems. These welding are essential for electronic devices and multi-layer fuel cell, battery or EDLC electrodes for electric or hybrid automobile and other various industry fields.

2. Configuration of ultrasonic complex vibration welding equipment

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

Figure 1 (a) 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.

Figure 1. (a) 19.5 kHz ultrasonic complex vibration welding equipment using a half-wave-length longitudinal mode complex vibration converter with a slit part installed a half-wave-length complex transverse vibration welding tip at a free edge (25-mm-length), (b) Schematic diagram of the longitudinal half wave-length mode converter with a slit part and longitudinal and torsional vibration distributions along the converter and a driving longitudinal vibration source.

Figure 2 (a) shows free admittance loops of the vibration system without welding tip and with a half wave-length complex transverse complex vibration welding tip of the half wavelength complex transverse vibration welding tip using a power factor compensating inductance $L_c$. (2) Vibration loci of the half wavelength complex transverse vibration welding tip under welding condition.

Figure 1 (b) 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.

Figure 2 (a) 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 $L_c$. These loops are single loop due to near longitudinal and torsional resonance frequencies. Inserting inductance $L_c$, quality factor decreases from 1935 to 303, but
motional admittance $|Y_{mo}|$ increases from 52.3 mS to 290.8 mS and the complex vibration system with a complex vibration welding tip could be driven effectively. Figure 2 (b) 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.

2.2. Ultrasonic complex vibration system with 20-mm-wide complex vibration welding tip

Figure 3 (a) 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 redesigned 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.

Figure 3 (b) 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.

2.3. Complex vibration welding systems with long and narrow welding tip

Figure 4 (a) 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.

Figure 4 (b) 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 $L_c$. 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 $L_c$, 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.

![Figure 4](image)

**Figure 4.** (a) 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, (b) 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 $L_c$.

3. **Welding conditions of ultrasonic complex vibration welding systems**

Figure 5 (a) shows welding condition of 1.0-mm-thick aluminium and copper plate using a 27 kHz 10-mm-diameter complex vibration welding tip of circular vibration locus. 1.0-mm-thick aluminium and copper plates are welded stably from only 1.5 mmp-o (peak-to-zero value) to 2.1 mmp-o with specimen material strength. Stable weld range is wider compared that using conventional linear vibration equipment with linear vibration locus.

![Figure 5](image)

**Figure 5.** (a) 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, (b) Welding condition of 0.3-mm-thick aluminum and copper plate using a 19.5 kHz 3.0-mm-diameter hard metal welding tip.

Figure 5 (b) shows welding condition of 0.3-mm-thick aluminium 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 circular vibration locus. Maximum welding strength over 20 N is obtained from 0.1 s to 0.25 s welding time under 10 mmp-o vibration amplitude and maximum strength is obtained between 0.4 s and .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.

4. Welded conditions of ultrasonic complex vibration welding systems

Figure 6 shows conditions of 0.3-mm-thick aluminium 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. Aluminium specimens were broken at welding surface or circumference of welded area with weld strength almost martial strength. Center part of welded area were welded on copper plate completely.

Figure 7 (a) 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.

Figure 7 (b) 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.

![Figure 6](image1.png)

**Figure 6.** Indentations and broken conditions of 0.3-mm-thick aluminum and 1.0-mm-thick copper plate welded using 0.3-mm-diameter hard metal complex transverse vibration welding tip after tensile tests.

![Figure 7](image2.png)

(a) (b)

**Figure 7.** (a) Conditions of 30 lapped 0.02-mm-thick copper, electrode foils and Ni coated copper terminal, (b) 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.

![Figure 8](image3.png)

**Figure 8.** 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.

Figure 8 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.

5. Cross sections of welded specimens

Figure 9 (a) shows scanning of electron microscope (TEM) images of cross sections of aluminium-copper and aluminium-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.

Figure 9 (b) shows SEM image of cross section of thirty lapped 0.015-mm-thick aluminium electrode foils and 0.8-mm-thick aluminium terminals welded using 19.5 kHz 30-mm-wide complex transverse vibration welding tip. These lapped aluminium foils and terminals were successfully welded with sufficient weld strength, small deformation and no damage.

![Figure 9](image)

(a) TEM images of cross sections of aluminum-copper and aluminum-nickel plate specimens welded using 19.5 kHz 10-mm-diameter welding tip (b) 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.

6. Conclusions

Various complex vibration systems with two-dimensional vibration locus were developed for improving welding characteristics of ultrasonic metal welding. 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. Welding of dissimilar metal specimens including many metal foils such as aluminium and copper which are essential for electronic devices and multi-layer fuel cell, battery or EDLC electrodes for electric or hybrid automobile and other various industry fields. Complex vibration using two-dimensional and three-dimensional vibration is effectively applied various applications of higher power ultrasonic.

7. References

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