Frequency Characteristics of Ultrasonic Plastic Welding*
(27 kHz to 180 kHz Ultrasonic Plastic Welding Systems)

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Welding characteristics and temperature rises at plastic welding part over frequency range from 27 kHz to 180 kHz were studied. Ultrasonic plastic welding systems of 27, 40, 67, 94, 150 and 180 kHz were developed and direct welding characteristic of lapped plastic sheets were measured. The temperature rises at welding surfaces of lapped 1.0-mm-thick polypropylene and polymethyl methacrylate plates were measured using thermocouples inserted between plate specimens. And also, temperature rise distributions in cross sections of the lapped plate specimens were measured using a thermotracer. The longitudinal vibration systems used for ultrasonic plastic welding consisted of a bolt-clamped Langevin type longitudinal vibration source using two or four piezoelectric ceramic (PZT) rings, a stepped horn and a catenoidal horn with a 4-mm- or 8-mm-diameter welding tip. Using higher frequency system, temperature rise measured at the welding part were higher. Maximum temperature rise measured using thermocouples and a thermotracer was over 350°C under excessive condition.


1. Introduction

Characteristics of ultrasonic plastic direct welding and temperature rises at plastic welding part over frequency range of 27 kHz to 180 kHz were studied. Vibration systems from 27 kHz to 180 Hz for ultrasonic plastic welding were designed and studied on their vibration characteristics.

The 94 kHz longitudinal vibration system consists of a 30-mm-diameter bolt-clamped Langevin type PZT transducer (BLT) part with four PZT rings and a stepped horn (vibration velocity transform ratio $N = 3.0$) and a catenoidal horn ($N = 3.13$) with supporting flange and with 8.0-mm-diameter welding tip. The diameter 20 mm of a catenoidal horn part for a 94 kHz vibration system is corresponding to about 0.56 wavelength, which is much larger compared with a conventional design criterion of 1/4 wavelength. Maximum welding tip vibration velocity 3.2 m/s (peak-to-zero value) was obtained using four PZT rings. Welding tip diameter of 8.0 mm is corresponding to 0.12 wavelength and vibrates only longitudinally. Radial vibration velocity of the welding tip is negligible compared with longitudinal velocity and the welding tip surface vibrates uniformly in longitudinal vibration mode$^{(1)-(9)}$.

Using 27, 40, 67, 94, 150 and 180 kHz ultrasonic plastic welding systems, welding characteristics are measured and compared. Weld strength obtained is larger as frequency of the welding system becomes higher under the same vibration condition. Required vibration velocity decreases as frequency of a welding system increases. Using 27 kHz to 150 kHz welding systems, temperature rises at welding surfaces of lapped 1.0-mm-thick polypropylene plates were measured using 0.2-mm- and 0.1-mm-diameter thermocouples (copper-constantan) inserted between welding plate specimens and also temperature rise distributions at cross sections of the lapped plate specimens were measured using a thermotracer. Maximum temperature measured was over 350°C.

2. Configurations of the Vibration Systems and Welding Specimens

Vibration systems from 27 kHz to 180 Hz for ultra-
sonic plastic welding were designed.

Configuration of the 94 kHz ultrasonic plastic welding system is shown in Fig. 1. The 94 kHz vibration system consists of a bolt-clamped Langevin type piezoelectric ceramic (PZT) transducer (BLT) of 30 mm diameter that has four PZT disks of 5 mm thickness and 30 mm outer diameter, a stepped horn (vibration velocity transformation ratio $N = 3.0$) and a catenoidal horn ($N = 3.13$), which has a welding tip of 8 mm diameter at a free edge and a supporting flange at a nodal position. The BLT transducer is integrated with a stepped horn part and a catenoidal horn are connected using a clamping bolt. The PZT position of the BLT transducer is designed as positioned at longitudinal node. The 94 kHz BLT transducer part has aluminum alloy vibration rods of 30 mm diameter (corresponding to 0.56 longitudinal wavelength) and four PZT disks of 30 mm diameter (corresponding to 0.94 longitudinal wavelength). The conventional design criteria length is under 0.25 longitudinal wavelength in diameter. The 94 kHz system designed has very large diameter compared with a conventional vibration system.

Figure 2 shows a configuration of a 20-mm-diameter 180 kHz longitudinal vibration system using two 3-mm-thick and 20-mm-diameter PZT rings. The diameter 20 mm of aluminum alloy rod part for the 180 kHz vibration system corresponds to 0.73 longitudinal wavelength. To decrease vibration loss in the connecting surfaces, uniform aluminum alloy rod connected to PZT rings, stepped and catenoidal horn parts was integrated in a body.

To increase available vibration velocity, the vibration systems used are made of high-strength aluminum alloy (super aluminum alloy, JIS A7075B). The welding tip of 94 kHz system vibrates at more than 3.2 m/s at loaded condition. The total lengths of the 94 kHz and 180 kHz systems are about 124 mm (corresponding to 2.5 longitudinal wavelength) and 90 mm (corresponding to 3.0 longitudinal wavelength). These vibration systems vibrate in higher vibration modes with 5 to 6 nodal and 6 to 7 loop positions which are numerous compared with a conventional vibration system. It is difficult to obtain a superior vibration system with high quality factor and repeatings of measurement of vibration distribution, vibration characteristics (free admittance loops) and precise adjustments are required because each vibration elements of the system must vibrates in almost same resonance frequency. All the vibration systems used have good vibration characteristics with large quality factors 188 to 894.

The vibration systems are driven at resonance frequencies using a 500 W wide-band static induction transistor power amplifier (7 – 300 kHz).

Figure 3 (a) – (c) shows configurations of the 94, 150, and 180 kHz ultrasonic vibration plastic welding systems.
The 150 kHz and 180 kHz vibration systems have almost same configuration except these PZT ring number.

The welding specimens used are 1.0-mm-thick polypropylene and polymethyl methacrylate plates with smooth surfaces. The strengths of the lapped welded plate specimens are tensile strengths in a direction of the specimen length.

3. Measurements of Temperature Rise

The arrangements of temperature measuring systems using thermocouples and a thermotracer are shown in Fig. 4 (a) and (b). Temperature rises at welding surfaces of 1.0-mm-thick polypropylene and polymethyl methacrylate plates are measured using 0.2-mm- and 0.1-mm-diameter thermocouples (T type, Copper-constantan) inserted between plate specimens and also temperature rise distributions at cross sections of the lapped plate specimens are measured using a thermotracer (TH5104) with a magnifying lens installed near the welding specimens.

4. Vibration Characteristics of the Plastic Welding Systems

Free admittance loops of the 27 kHz to 180 kHz longitudinal vibration systems measured at loaded conditions of two lapped 1.0-mm-thick polypropylene plates under static pressure 600 kPa are shown in Fig. 5. For an example, quality factor and motional admittance \( |Y_{mo}| \) of the 94 kHz system are 1562 and 30 mS without power factor compensating inductance \( L_c \). Inserting the inductance \( L_c \) (0.718 mH), quality factor decreases to 600 but motional admittance \( |Y_{mo}| \) increases to 35 mS. At loaded condition, quality factor and \( |Y_{mo}| \) decrease to 482 and 10 mS due to the loading.

Figure 6 shows radial vibration distribution along the 94 kHz vibration system. Driving frequency is 93.83 kHz and driving voltage is kept 50 Vrms constant. Radial vibrations normal to the vibration system were measured because a normal laser Doppler vibrometer could not measure in-plane vibration. Maximum radial vibration positions correspond to longitudinal nodal positions. It is shown that the PZT driving part and the flange of the stepped horn are position at longitudinal vibration nodal positions that are required to obtain maximum vibration output and to support the system without disturbing vibra-
The 94 kHz vibration system vibrates in 2.5 wavelength longitudinal vibration mode with five nodal and six loop positions.

Figure 7 shows radial vibration distribution along the 180 kHz vibration system. Driving frequency is 187.74 kHz and driving voltage is kept 50 Vrms constant. Vibration node and loops positions are not clear but it is shown that the PZT driving part and the flange of the stepped horn are positioned at longitudinal vibration nodal positions. The vibration system vibrates in 3.0 wavelength longitudinal vibration mode with six nodal positions.

Radial vibration velocity distributions measured along the side circumference of the 94 kHz and 180 kHz welding tip under driving voltage of 10 Vrms are shown in Fig. 8. Radial vibration distribution is about circular and no transverse vibration of the welding tips is observed. Radial vibration is negligibly small compared with longitudinal vibration of the welding tip which is effective for welding.

Figure 9 shows the relationships between driving voltage and longitudinal vibration velocity of the 94 kHz and 150 kHz welding tips without and with power factor compensating inductance and at no loaded condition. Driving frequencies are 93.8 kHz and 154.5 kHz. Welding tip vibration velocity of 94 kHz is 2.5 m/s at driving voltage of 80 Vrms. Using the power factor compensating inductance, maximum welding tip vibration velocity of 3.2 m/s is obtained under driving voltage of 200 Vrms at loaded condition of 1.0-mm-thick polypropylene plate welding specimens. Maximum welding tip vibration velocity of 180 kHz is about 7.5 m/s at loaded condition.

5. Welding Characteristics

Relationships between vibration velocity and weld strength of two lapped 1.0-mm-thick polypropylene plate specimens using 27 kHz to 94 kHz welding systems with an 8-mm-diameter welding tip are shown in Fig. 10. Weld strength increases as vibration velocity increases, and larger weld strength is obtained as frequency increases at the same vibration velocity.

Figure 11 shows the relationship between welding tip vibration velocity and weld strength/welded area of two lapped 1.0-mm-thick polypropylene plate specimens welded using 27 kHz to 180 kHz welding systems. Weld strength/welded area increases as vibration velocity increases, and required vibration velocity of 180 kHz sys-
tem is about 60% that of 94 kHz welding system. Maximum weld strength using the higher frequency 67 kHz to 180 kHz welding systems are higher compared with the lower frequency 27 kHz and 40 kHz, which are commercially available.

6. Temperature Rise at Welding Surfaces

6.1 Polypropylene plate specimens

Relationships between 40, 67, and 94 kHz welding tip vibration velocities and measured temperatures using 0.2-mm-diameter at welding surfaces of 1.0-mm-thick polypropylene plate specimens are shown in Fig. 12. Static clamping pressure and welding time are kept at 746 kPa and 4.0 s. Frequency becomes higher, higher temperature rise is obtained under smaller vibration velocity. Required vibration velocity of 94 kHz for temperature rise 160°C is about 80% that of 40 kHz.

Figure 13 shows the relationships between weld strength and temperature increase measured using 0.1-mm-diameter thermocouples and 27, 40, 67, and 94 kHz welding systems. Static clamping pressure and welding time are kept at 746 kPa and 4.0 s. Measured temperatures using 0.1-mm-diameter thermocouples are near to real temperature than that using 0.2-mm-diameter one because disturbance to vibration and heat conductivity are small. The required rises in temperature for a weld strength of 400 N are about 220°C for the 27 kHz and 40 kHz welding systems, but less 120°C for the higher frequencies of 67 kHz and 94 kHz systems. Using a higher frequency, the required vibration velocity and temperature rise become smaller. When the measured temperature rise is 150°C, the weld strength obtained using 67 kHz and 94 kHz welding systems is 500 N and that obtained using 27 kHz and 40 kHz welding systems is only 300 N. It seems that ultrasonic welding mechanisms may be different in the low- and high-frequency regions.

6.2 Polymethyl methacrylate specimens

Relationships between frequency, vibration velocity and temperature rises measured using 0.2-mm-diameter thermocouples of three lapped polypropylene specimens are shown in Fig. 14. Measured temperatures of welding surfaces increases as frequency increases. Measured temperatures near to the welding tip (upper part) are larger than that at lower part under these frequencies. This means that vibration condition in a welding part is not uniform and it seems that vibration is reflected at welding surfaces although specimen surfaces are smooth and vibration amplitude decreases at lower plate specimens.

6.2 Polymethyl methacrylate specimens

Relationships between frequency, vibration velocity and temperature rises measured using 0.2-mm-diameter thermocouples of three lapped polymethyl methacrylate specimens are shown in Fig. 15. Measured temperatures of welding surfaces increases as frequency increases and
Fig. 14 Relationships between 40, 67, and 94 kHz welding tip vibration velocities and temperature rise using 0.2-mm-diameter thermocouples at welding surfaces of three lapped 1.0-mm-thick polypropylene plate specimens measured using thermocouples.

Fig. 15 Relationships between 40, 67, and 94 kHz welding tip vibration velocities and temperature rise measured using 0.2-mm-diameter thermocouples at welding surfaces of three lapped 1.0-mm-thick polymethyl methacrylate plate specimens measured temperatures near to the welding tip (upper part) are larger than that at lower part. Surface conditions of polymethyl methacrylate plates are much more smooth compared with that of polypropylene plates, and vibration condition in a welding part is not uniform as polypropylene plates. Maximum temperature rise measured is 350°C under excessive welding condition that is over melting temperature.

6.3 Conditions of welded plate specimens

Conditions of three lapped 1.0-mm-thick polypropylene and polymethyl methacrylate plate specimens welded using 40, 67, and 94 kHz systems are shown in Figs. 16 and 17. Vibration velocity, static clamping pressure and welding time are kept at 2.7 m/s, 746 kPa, and 4.0 s. Welded areas are deformed and thermocouples are observed in welded areas. Thermocouples installed between welding surfaces for measuring temperature rises are embedded in specimens but not broken, and also not short-circuited by a metal welding tip or an anvil although under excessive welding conditions.

7. Temperature Rise Distributions at the Cross Sections of the Lapped Welding Specimens

Figure 18 shows the temperature rise distributions at the cross sections of two, three and four lapped polypropylene specimens welded by welding times of 4.0 s using 40, 67, 94, and 150 kHz welding systems. Vibration velocity and static clamping pressure are kept 2.7 m/s and 746 kPa constant. Temperature rises in two lapped specimens are highest at welding surface under all frequencies and temperature is higher as frequency becomes higher. In the case of three lapped specimens, temperature rise observed is highest at welding surfaces. At 94 kHz, temperature of second specimen is observed higher but it seems that temperature becomes higher at two welding surfaces and the second specimen at higher temperature deforms near to a thermotracer and the temperature rises at the two welding surfaces could not observed. In the cases of four lapped specimens, temperature rises are observed higher at upper specimens and high temperature regions extend to lower part as frequency becomes higher from 40 kHz to 94 kHz. At high frequency 150 kHz, high temperature
region is difficult to extend to lower region because high frequency vibration energy is difficult to transmit to distant area owing to small diameter welding tip and vibration stress relaxation due to small vibration amplitude\(^{(2)}\)–\(^{(4)}\).

Figure 19 shows the temperature rise distributions at the cross sections of two lapped polypropylene specimens welded by welding times of 1.0 s to 4.0 s using 40, 67, 94, and 150 kHz welding systems. Vibration velocity and static clamping pressure are kept 2.7 m/s\(_{p.0}\) and 746 kPa constant. At the same vibration velocity, temperature rises and high temperature area are higher as frequency increases.

Maximum temperature of these welding specimens measured using thermocouples are about 350°C and maximum temperature rises measured using a thermotracer are over 330°C under excessive welding conditions.

### 8. Conclusions

Vibration systems from 27 kHz to 180 kHz for ultrasonic plastic welding were designed.

Using the 27 kHz to 180 kHz ultrasonic plastic welding systems, direct welding characteristics and welding area temperature rise and temperature rise distributions in cross sections of lapped 1.0-mm-thick polypropylene plate and polymethyl methacrylate plate specimens were studied.

Temperature rises at welding surfaces of lapped 1.0-mm-thick polypropylene and polymethyl methacrylate plates are measured using thermocouples inserted between plate specimens and also temperature rise distributions at...
cross sections of the lapped plate specimens are measured using a thermotracer. In these cases, thickness of welding specimens are small compared to a longitudinal wavelength.

Temperature rise of upper welding surface near to the welding tip is higher than lower welding surfaces. Vibration condition in a welding part is not uniform and it seems that vibration is reflected at welding surfaces although specimen surfaces are smooth and vibration amplitude decreases at lower plate specimens.

Temperature rises at cross sections of welding parts are not uniform. Temperature rises in lapped specimens are highest at welding surfaces under these frequencies and temperature rises are larger as frequency becomes higher. Vibration loss at welding surfaces of lapped specimens contributes to temperature rise increase and it seems that ultrasonic welding begin usually at the welding surfaces.

Maximum temperature rise of polypropylene specimen measured using thermocouples was about 350°C. Maximum temperature rise of polypropylene specimen measured using a thermotracer was over 330°C.

As a result, the effectiveness of higher frequency for ultrasonic welding of plastic materials was reconfirmed. This system may be useful for various applications that require frequency-dependent characteristics including packaging in microelectronics.

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References


