Evaluation of welding performance of 20 kHz and 40 kHz ultrasonic metal welding

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Abstract. In this study, ultrasonic horns are designed by using vibration equations, vibration modal analysis and harmonic response analysis in order to compare welding performance when ultrasonic welding is performed at resonance frequencies of 20 kHz and 40 kHz. For the weldability evaluation of the manufactured horn for 20 kHz and 40 kHz, welding strength between Ni specimens with a thickness of 0.1 mm using tensile test are compared and analyzed. The lengths of horns with resonance frequencies of 20kHz and 40kHz were calculated as 130mm and 68mm respectively. As a result of vibration modal analysis, the optimum longitudinal vibration modes of 19,584Hz and 39,794Hz are obtained in 10th mode, and the frequency response of the two horns are 19,600 Hz and 39,800 Hz respectively. As the welding conditions are changed to welding pressure 2 bar, 3 bar and 4 bar, vibration amplitude of horn 60%, 80% and 100%, tensile strengths of welded specimens are observed. The welding strength was smaller at 40 kHz than at 20 kHz even at the same amplitude. This is because diffusion action of Ni in the weld interface is facilitated at 20 kHz than at 40 kHz.

1. Introduction
Due to recent environmental regulations, carbon emissions are controlled and interests in energy conservation are increasing. Therefore, it is important to develop low-cost and high-efficiency production technologies. Ultrasonic welding has come to the forefront as eco-friendly welding method for welding plastics and metals, which does not require special gases and welding materials used in conventional welding techniques.

Ultrasonic welding is characterized by high mechanical welding strength and almost no electrical resistance between the weld materials, because two metal surfaces are welded by physical diffusion actions removing the contaminants and deposit oxide film existed on the metal surfaces. It has been applied to the welding of secondary battery foils, can bottom, electronic and communication device parts, cell phones, speakers, vacuum glasses, and precision bonding of flip chips.

Figure 1 shows main parts of a typical ultrasonic welder. The converter or transducer converts alternating current of 50 to 60 Hz into a mechanical energy of 20 to 40 kHz. The booster amplifies the vibrational amplitude of the converter, and the horn transfers the mechanical vibration energy to the weld materials. The process of ultrasonic metal welding is such that the electric energy input through the power supply is converted into the mechanical vibration energy through the transducer, and then the vibrational amplitude is amplified by the booster. While the amplified ultrasonic vibration energy is transmitted to the weld through the horn, strong joining is achieved by the forced diffusion in the weld interfaces [1].
Many researches on the ultrasonic welding have been conducted so far. Specially, analysis and design of horns with working frequency of 20 kHz and 40 kHz, welding experiment and weldability evaluation have been widely conducted [2-7], but the study on comparing the welding performance of two horns have not been presented. It is necessary to determine the optimal frequency of the horn to improve the welding performance when welding various types of metal. However, since there is no research data on these, there are many difficulties in manufacturing and utilizing the horn.

In this study, horns with resonance frequencies of 20 kHz and 40 kHz are designed and manufactured based on the modal analysis and harmonic response analysis, and the frequency characteristics of the manufactured horns are experimentally analyzed. In additions, the welding performance and characteristics of the two horns are investigated by analyzing the welding strength of the Ni-Ni thin plate.

2. Design of horns for ultrasonic welding

2.1. Horn design process
The material of the horn is selected according to the weld material and the weight of the horn, and the strength and hardness are considered to be the most important parameters. If the material of the welding member becomes harder than the horn, it is preferable to select a material having higher hardness than the material of the weld. The shapes of the horn are step, exponential and conical, and the amplitude amplification ratio is large in this order. In general, the step type is widely used because of high amplitude amplification. However, there is a disadvantage that the stress distribution increases as the amplitude amplification ratio increases due to a radical change in diameter [8].

The first process of the horn design is to calculate the length of the horn roughly using the vibration equations, and sequentially determine the shape and dimensions of the horn based on the mode shape and natural frequency analysis. Since the performance of the horn designed through the theoretical analysis produces some errors, the design and fabrication are completed through tuning processes.

2.2. Material and shape of horns
Figure 2 shows a 2D drawing of the horn which is finally modified through vibration analysis of 20 kHz and 40 kHz horns. Table 1 shows the physical properties of titanium alloys for finite element analysis of 20 kHz and 40 kHz horns.

3. Results of vibration analysis of horns

3.1. Vibration mode analysis
The number and shape of meshes for finite element analysis are automatically generated by the analysis tool. The boundary conditions for the analysis are cylinder restraint in the fastening part which is fastened with the booster and the bolt, and the cylinder is set so that only the axial displacement is freely generated. Horns are designed and manufactured based on modal analysis and harmonic response analysis with tuning processes.
Figure 3 shows the result of the modal analysis of 20 kHz horn. In the 10th mode, the natural frequency of 19,584 Hz close to 20 kHz is obtained and the maximum amplitude occurred at the tip of the horn. Figure 4 shows the result of the modal analysis of the horn for 40 kHz. As a result, it is found that the natural frequency of 39,794 Hz close to 40 kHz is obtained in the 10th mode, and the maximum amplitude of the transverse vibration is found in the tip of the horn.

![20 kHz horn](image1)

![40 kHz horn](image2)

Figure 2. 2D Drawings of the horns.

Table 1. Mechanical properties of horn material.

| Horn frequency | Density (g/m³) | Poission’s ratio | Young’s modulus (GPa) |
|----------------|---------------|----------------|----------------------|
| 20kHz          | 4.5           | 0.34           | 116                  |
| 40kHz          | 8.14          | 0.3            | 207                  |

3.2. Harmonic response analysis

Figure 5(a) shows the result of the harmonic response of the horn tip when excited with a vibration frequency of 10 kHz to 30 kHz on the input side (left end of the horn) of the optimised 20 kHz horn. It is found that the frequency response of the horn's output surface (right end of the horn) is similar to the modal analysis result of 19,600 Hz.

Figure 5(b) shows the result of the harmonic response of the horn tip when excited with a vibration frequency of 30 kHz to 50 kHz on the input side (left end of the horn) of the optimised 40 kHz horn. The frequency response of the output of the horn (right end of the horn) is 39,800 Hz, which is similar to the result of the modal analysis.

4. Evaluation of the welding performance

4.1. Experimental method

Figure 6 shows the shape of the Ni specimen used in the weldability test using a horn of 20 kHz and 40 kHz. Test specimens of 50 mm x 10 mm x 0.1 mm are fabricated. Welding tests are carried out by overlapping 10mm width of each material. In this experiment, the welding pressure, the vibration amplitude and the welding time are selected as the welding parameters in order to evaluate the weldability of the thin Ni plate. Table 2 shows the experimental conditions for welding tests.
Seven Ni specimens are welded for each experimental condition. The welding strength is calculated by the maximum tensile force when welded Ni specimens are separated in the weld interface by using a tensile tester. In order to increase the reliability of the data, the average force of five tensile forces excluding the maximum and the minimum tensile forces was obtained.

![Image](image1.png)

(a) 9th mode – 18,024 Hz

(b) 10th mode – 19,584 Hz

(c) 11th mode – 28,159 Hz

![Image](image2.png)

(a) 9th mode – 39,373 Hz

(b) 10th mode – 39,794 Hz

(c) 11th mode – 53,401 Hz

**Figure 3.** Mode shape and natural frequency of the 20 kHz horn.

**Figure 4.** Mode shape and natural frequency of the 40 kHz horn.

![Image](image3.png)

**Figure 5.** Harmonic response analysis results of the designed horn.

![Image](image4.png)

**Figure 6.** Welding specimen and welding point.

**Table 2.** Welding conditions.

| Welding pressure (bar) | 2.0, 3.0, 4.0 |
|------------------------|---------------|
| Amplitude (%)          | 60, 80, 100   |
| Welding time (sec)     | 0.10 ~ 0.40   |
5. Experimental result and discussion

Figure 7 shows the tensile strength, i.e., weld strength, of specimens welded by ultrasonic metal welders of 20 kHz and 40 kHz. Overall tendency is that the welding strength increases as the welding time increases under any conditions, and the welding strength is smaller at 40 kHz than at 20 kHz at the same vibration amplitude. This is because the ultrasonic friction heat between the welding specimens is concentrated in the horn tip, and diffusion of Ni between the welding parts is facilitated at 20 kHz than 40 kHz.

The maximum welding strength is 226.75 N at 20 kHz under the condition of pressure of 2 bar, amplitude of 100%, and a time of 0.38 second. At 40 kHz, it is confirmed that the pressure is 2 bar, the amplitude is 100%, and the time is 0.38 second at 226.3 N. It is confirmed that the weld strength is higher at 2 bar than at 4 bar, and tensile strength increases with increasing amplitude, but there is not a tendency that the welding strength increases with increasing pressure.

![Figure 7](image)

Figure 7. Welding strength variations according to welding conditions of welding time, welding pressure, vibration amplitude, and welding frequency of 20 kHz and 40 kHz horns.

6. Summary

In this study, to develop horns with resonance frequency of 20 kHz and 40 kHz, modal analysis and harmonic response analysis are performed by finite element method. In addition, for the evaluation of the weldability of the fabricated 20 kHz and 40 kHz horns, the weld strength between Ni specimens with a thickness of 0.1 mm are compared and analysed. As for the overall tendency of welding strength according to the welding condition change, it is obvious that the welding strength increases with the increase of welding time under any welding conditions. It is confirmed that the welding strength is smaller at 40 kHz than at 20 kHz even at the same vibration amplitude. This is because the ultrasonic friction heat between the welding specimens is concentrated in the horn tip, and diffusion of Ni in the weld interface is facilitated at 20 kHz than at 40 kHz.
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