Ultrasonic Welding of Ni Thin Sheet

Dong Sam Park, Jung Ho Kim, and Jeong Seok Seo

***Abstract*—A**n ultrasonic metal welder is composed of a power supplier, transducer, booster, and a horn. Precision designing of these parts are required, since each one is affected by design parameters, such as shape, length, and mass of horn. In this study, we developed a 40 kHz band horn through vibration mode and finite element analysis first; modal analysis of designed horn resulted in a resonance frequency of 39,992 Hz—close to the intended value of 40 kHz. Using this horn, the weldability of Ni sheets was evaluated. Welding parameters of pressure, time, and vibration amplitude were considered and the correlation between the welding parameters and tensile shear strength of Ni sheets was observed. Maximum strength was 220 N under the welding conditions of 2.5 bars pressure, 80% amplitude, and 0.30 seconds welding time. It was revealed that the maximum tensile shear strength decreased in excessive welding, negatively influencing weldability.

***Keywords*—** Horn, Ni sheet, Ultrasonic welding, Weldability.

I. Introduction

MODERN microwelding techniques have attracted a great deal of attention, due to miniaturization, ultraweight reduction, and ultra-precision in various parts. These welding methods are perceived as essential production techniques in various industries, and their applications are continually increasing because of their superior precision and safety when compared to conventional welding processes.

Ultrasonic metal welding, one of these micro-welding techniques, is being widely used for vehicles, shipbuilding, and the welding of electric and electronic parts [1]. The use of this welding technique is also increasing because of the need to weld different materials for high quality/high performance requirements and new material developments in various high-tech industries [2]. The ultrasonic welding technique is highlighted as a solid-state bonding technique that can maximize the characteristics of the welded parts and products by best maintaining the fabrication materials' own properties and minimizing the occurrence of defects at welding zones.

Ultrasonic metal welding is a solid state diffusion welding method applied at the ambient or low temperature at which the welding is conducted by transferring high frequency vibration energy to particular parts under a certain pressure. Frictional energy caused by vibration is generated due to relative vertical and horizontal movements between the two welding surfaces; the vibration energy generated in the welding boundary surface removes the oxide films and contaminants dispersed throughout the boundary surface [3].

Recently, ultrasonic metal welding is applied for same/ different materials of thin sheet that are difficult to weld with ordinary methods. It is an economical and eco-friendly welding technique that does not require the use of supplementary lead or solders. Also, since the welding time is only about 1 second, it can be easily grafted onto automation processes and applied to secondary battery electrode lead bonding, heat pipe joining for solar battery panels [4], and aluminum alloy vehicle manufacturing in accordance with weight reduction regulations for transport machines, such as cars [5].

In the ultrasonic metal welding process, the electric energy that comes through the power supplier is converted to mechanical vibration energy via a transducer, and consequently, the ultrasonic energy that is formed with the amplification of the vibration amplitude is then transferred to the metal materials through the horn [6].

Fig. 1 shows the major core of an ultrasonic metal welder, which is composed of a transducer that converts a 50~60 Hz current to 20~40 kHz of electric energy; a booster and a horn that amplify the amplitude of the transducer. Finally a horn transfers the vibration energy to the metal members.

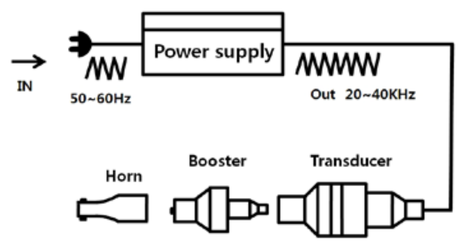

Fig. 1 Ultrasonic metal welding system

Though ultrasonic metal welding technique is quite advanced, applications are quite limited, so ultrasonic metal welding techniques that enhance the weldability of various different materials are required. In this study, we designed a 40 kHz band horn for ultrasonic metal welding using the finite element method (FEM) and performed weldability tests for Ni 200 sheets complying with welding parameters.

II. Experimental methods

A. Design of an ultrasonic horn

The horn amplifies vibrations to gain the amplitude level that

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the user desires and transfers the generated vibration energy to the welding materials. Ultrasonic metal welding horns are either of the step type, exponential type, or conical type, with high-amplitude amplification rates [7].

The materials for horns used in ultrasonic metal welders should be selected considering the materials of which the metal components are made and the weight of the horn; strength and hardness are also important variables for horn material selection. If the hardness of the metal component materials is higher than that of the horn, the horn would wear down, thus, it is preferable to select a material for the horn that has higher hardness than the materials to be welded [8].

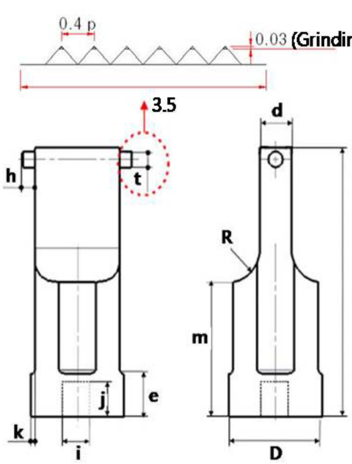
In this study, we used titanium alloy, which has excellent acoustic attributes and strength. The properties of titanium alloy are listed in Table I.

TABLE I
MECHANICAL PROPERTIES OF HORN MATERIALS

Density	4.5 g/cm^3
Poission's ratio	0.34
Young's modulus	116 GPa

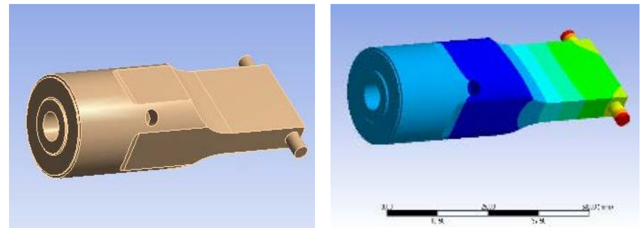
As shown in Fig. 2, the horn used in this study was designed as a half wave length horn with a D of ø24 mm, L of 67 mm, and a frequency band of 40 kHz. The tip was located at the 1/2 wavelength position, which generates maximum amplitude with longitudinal vibration. The shape of the tip was designed as cylindrical form having a diameter of 3.5 mm and a length of 3.5 mm. The surface of both tips was grinded to have a shape of quadrangular pyramid for fixing two weld materials. In order to minimize stress concentration occurring at the step area, a rounding R was applied. The R was designed to have 1/2 length with the difference between D/2 (radius of the input surface) and b [9], [10].

Fig. 3 is a drawing of the horn based on the results of 3D modeling and modal analysis with ANSYS. The horn showed a resonance frequency of 39,992 Hz which is very close to the intended frequency of 40 kHz and it was identified that the vibration with maximum amplitude occurred at the tip.



Symbol	Value(mm)
L	63
D	Ø24
d	8
R	8
i	Ø8
j	10
t	Ø3.5
h	3.5
k	1
e	10
m	31.5

Fig. 2 Dimensions of the designed horn



(a) 3D model (b) Mode shape

Fig. 3 Modeling and modal analysis of the designed horn

B. Specimen preparation

The specimen used to evaluate Ni 200 sheet weldability was composed of 99% pure Ni alloy with a thickness of 0.1 mm. The specimen produced was 50 mm in width and 10 mm in length, as shown in Fig. 4.

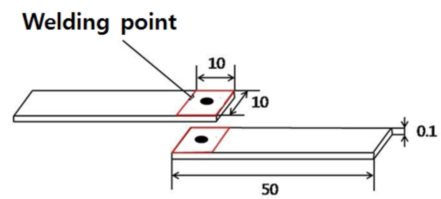


Fig. 4 A welding specimen

C. Ultrasonic metal welder

For evaluation of the weldability of the manufactured horn, an ultrasonic metal welding test was conducted. Fig. 5 is a photograph of the ultrasonic metal welder, and Table II presents its specifications.

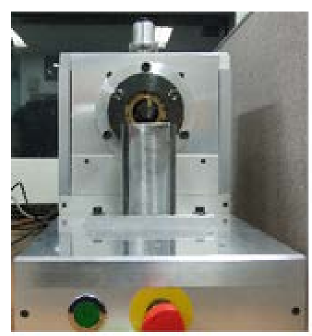


Fig. 5 Ultrasonic metal welder

TABLE II
SPECIFICATIONS OF THE ULTRASONIC METAL WELDER

Welding parameters	Ranges
power	800 W
working frequency	40 kHz
welding speed	3 m/min
pressure	0~14 MPa
vibration amplitude	7~18 ㎛

D. Weldability evaluation apparatus

The evaluation of the weldability of the Ni sheet was conducted with a tensile tester, which is able to measure tensile shear strength up to 1,000N. The tester is shown in Fig. 6, and the specifications are listed in Table III. During the test, the tensile load speed was set at 5mm/min.

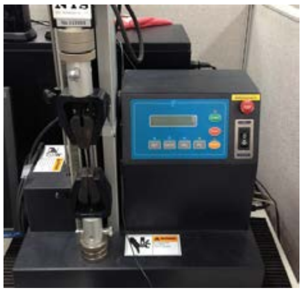


Fig. 6 Tensile tester

TABLE III
TENSILE TESTER SPECIFICATION

capacity	1 kN
maximum travel	400 mm
speed	5~500 mm/min
force resolution	1/5000 N
stroke resolution	0.005 mm

E. Welding parameters

The major parameters for ultrasonic metal welding include welding time, vibration amplitude, and welding pressure. Welding time affects the overall process, and welding pressure affects resistance when the horn contacts the member materials and then vibrates. As shown in Table IV, welding parameters were selected as 1.5 bars, 2.0 bars, and 2.5 bars for pressure, 40%, 60%, and 80% for amplitude, and the welding time from 0.10 to 0.40 seconds of interval 0.02 seconds.

TABLE IV
MECHANICAL PROPERTIES OF HORN MATERIALS

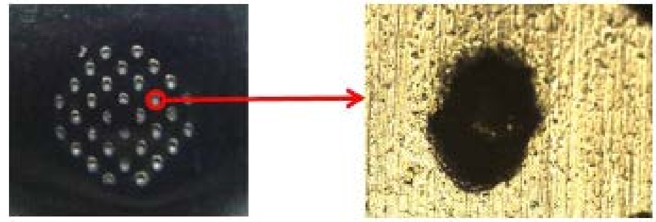
welding pressure (bars)	1.5, 2.0, 2.5
vibration amplitude (%)	40, 60, 80
welding time (sec.)	0.10~0.40

III. RESULTS AND DISCUSSIONS

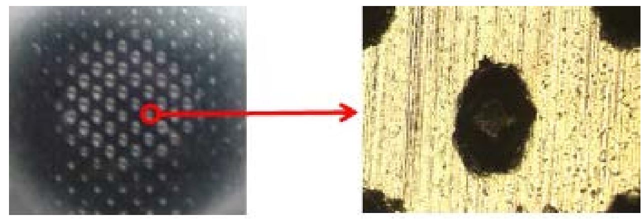
A. Welded surface

Fig. 7(a) and (b) show the indent marks on the surface of the top and bottom Ni sheets, which is caused by clamping pressure of a horn tip and an anvil.

Fig. 8 shows the welded surface in the welding area after tensile test. Indent marks generated by the horn tip is observed on the welded surface and is considerably expended. This expansion is considered to be due to the horn tip vibration and tear-off between the upper and lower welded surface of Ni sheets during tensile shear test. These indicate that the diffusion caused by ultrasonic vibration and frictional heat between two Ni sheets is generated and strong bonding is achieved.



(a) Indent marks by horn tip



(b) Indent marks by anvil

Fig. 7 Photographs showing indent marks on the surface of top and bottom Ni sheets

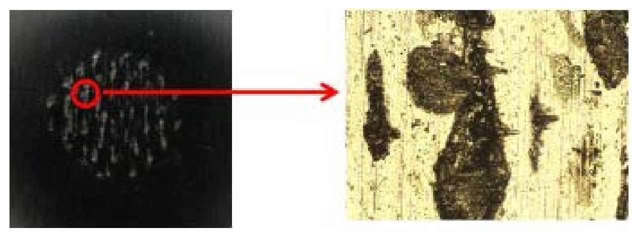


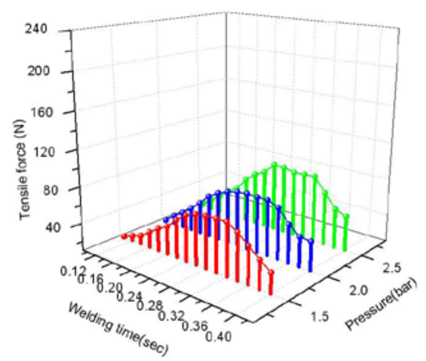
Fig. 8 Photographs showing welded surface after tensile test

B. Tensile shear strength

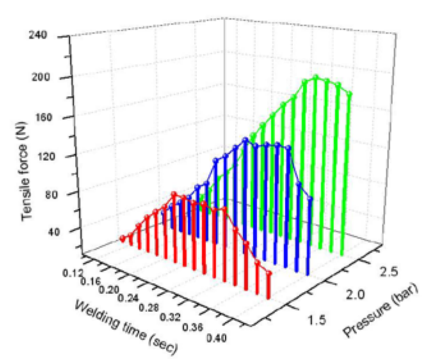
For reliable welding test, 10 sheets were welded per each experimental condition. The mean values of maximum tensile shear strengths were then measured with the tensile tester, eliminating the maximum and minimum values for the 10 sheets.

Fig. 9(a) shows the relationship between welding time and maximum tensile shear force when the pressure changes from 1.5 bars to 2.0 bars then to 2.5 bars under the experimental condition of 40% vibration amplitude. Unrelated to the welding pressure, the maximum tensile shear force increased as the welding time increased, but the maximum tensile shear force maintained a stable level when the welding time was between 0.26 sec. and 0.34 sec. Additionally, when the welding time exceeded 0.34 sec., the tensile shear force showed a tendency to decrease as the welding time increased; this was due to cracks generation on the welding surface caused by excessive welding. Changes in tensile shear force according to welding pressure were not significant, but in general, results showed that tensile shear force also increased, to some degree, as welding pressure increased.

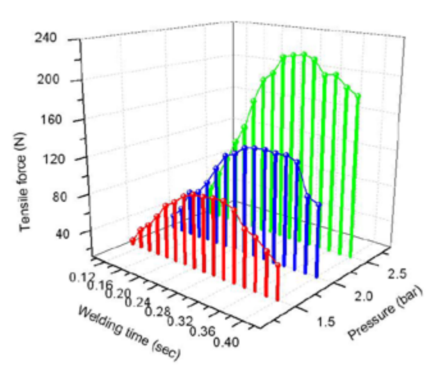
Fig. 9(b) shows the relationship between welding time and maximum tensile shear force when the pressure changes from 1.5 bars to 2.0 bars then to 2.5 bars under the experimental condition of 60% vibration amplitude. This is similar to the condition when the vibration amplitude was at 40%, and therefore, maximum tensile shear force proportionally increases until the welding time reaches 0.22 sec., but after that time, depending upon the welding pressures, each one shows a different tendency. In other words, we found that the higher the pressure, the longer the saturation period was delayed. After a certain saturation period passed, the maximum tensile shear force decreased in accordance with the welding time extension. Also, as the pressure increased, tensile shear force also increased to some degree, but after 0.22 sec., it was noted that the effect of pressure against tensile shear force became larger.



(a) Amplitude 40%



(b) Amplitude 60%



(c) Amplitude 80%

Fig. 9 Effects of the welding parameters on the tensile shear force

Fig. 9(c) shows the relationship between welding time and maximum tensile shear force when the pressure changes from 1.5 bars to 2.0 bars then to 2.5 bars under the experimental condition of 80% vibration amplitude. While the relationship is similar to the situation in the 40% vibration condition, the saturation period of maximum tensile shear force presents itself between 0.24~0.26 sec. to 0.32~0.34 sec., depending upon the pressures. Additionally, the higher the overall pressure, the larger the difference in tensile shear force.

Meanwhile, when the pressures and welding times are constant, the maximum tensile shear force of 40% vibration amplitude is less than half of that of 60% and 80% vibration amplitude conditions, so we know that it is desirable to set the vibration amplitude above 60%. There is no significant difference in tensile shear forces between the 60% and 80% amplitude, but since the saturation range appears relatively early in the 80% amplitude condition, we could conclude that the 80% vibration amplitude is desirable.

Through this experiment, we were able to determine that the most suitable welding parameters for obtaining maximum tensile force during Ni sheet ultrasonic welding include a vibration amplitude of 80%, welding pressure of 2.5 bars, welding time of 0.26 sec., and that the maximum tensile force under these conditions is approximately 220 N. However, these conditions are just for the purpose of obtaining maximum tensile force; in a case where the bonding strengths of the parts are specified, the parameters that would satisfy certain strengths could be found from the results in Fig. 9.

IV. Conclusions

A 40 kHz band horn was designed and manufactured through vibration equation and finite element analysis. Additionally, maximum tensile shear force was determined for comparative analysis using a tensile force tester to evaluate the weldability of Ni sheets depending upon welding parameters. The following conclusions were obtained.

(1) In order to design a 40 kHz horn, which generates resonance at 40 kHz vibration frequency, vibration mode analysis and FEA were conducted. The resonance frequency was found to be 39,992 Hz, which was quite close to the originally intended value of 40 kHz.

(2) When the amplitude is constant, the maximum tensile shear force increases as the welding pressure and welding time increase, but after the welding time reaches a certain period, the stabilization period appears, decreases depending upon the welding time increase.

(3) It was revealed that tensile shear force reduction after a certain welding time was due to crack generation on the welding surface.

(4) Taking into account the maximum tensile shear force and stabilization period, it was revealed that 80% vibration amplitude was the most desirable.

(5) We determined that the most suitable welding conditions for obtaining maximum tensile force during Ni sheet ultrasonic welding were 80% vibration amplitude, 2.5 bars welding pressure, and 0.26 seconds of welding time, and that the maximum tensile shear force under these conditions was

approximately 220 N.

REFERENCES

[1] Shin-Ichi Matsuoka, Hisashi Imai, "Direct welding of different metals used ultrasonic vibration," *Journal of materials processing technology*, vol. 209, no. 2, 2009, pp. 954-960.

[2] H. S. Park, W. Y. Kim and C. Y. Kang, "Welding and bonding of dissimilar metal steel/ Nonferros Metal" *Journal of the Korean Welding and Joining Society*, vol. 14, 1996, pp. 1-7.

[3] J. P. Jung, "Ultrasonic Bonding of Electronic Parts" *Proceedings of the KWS Conference 2008-Autum,* 2008, pp. 7-9.

[4] J. H. Lee, S. H. Kim, C. G. Cheon, S. U. Kim, and J. D. Kim, "Effects of welding parameters on ultrasonic bonding strength of solar collector" *Proceedings of the KWS Conference 2006 Spring*, 2006, pp. 233-235.

[5] H. T. Kim and S. C. Kil, "Trends of Welding Technologies (Aluminum Structure) " *Journal of the Korean Welding and Joining Society*, vol. 22, 2004, pp. 29-34.

[6] J. Wnek., "Ultrasonic metal welding for wire splicing and termination." Branson Ultrasonic Corp.

[7] K. H. W. Seah, S. Wong, and L. C. Lee, "Design of tool holders for ultrasonic machining using FEM," *Journal of Materials Processing Technology*, vol. 37, 1993, pp. 810 – 816.

[8] B. G. Lee., and K. L. Kim., K. E. Kim, "Design of Ultrasonic Vibration Tool Horn For Micromachining Using FEM." *Journal of Korean society Machine Tool Engineers*, vol. 17, no. 6, 2008, pp. 63-70.

[9] A. Cardoni, M. Lucas, "Strategies for Reducing Stress in Ultrasonic Cutting Systems", *An International Journal for Experimental Mechanics*, vol. 41, no. 1, 2005, pp. 11-18.

[10] E. M. Kim., H. S. Jang., and D. S. Park., " A Horn of Half-wave Design and Manufacture for Ultrasonic Metal Welding" *Journal of Korean society Machine Tool Engineers*, vol. 19, no. 6, 2010, pp. 790-796.