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ARTICLE

Evaluation of Vibration Amplitude Stepping and Welding Performance of 20 kHz and 40 kHz Ultrasonic Power of Metal Welding

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ABSTRACT

Today ultrasonic power technique is consider a mandatory technique which is always entered in many processes such as in metal and plastic welding to overcomes many issues, with aided of applying force (pressure) and supplied high frequency vibration, a solid-state weld can be generated by ultrasonic metal welding technique. That gives a technique the ability to join not only a small component, whereas also to join thicker specimens, which depends on a proper control of matching welding conditions. Therefore a welding performance can be studied and compared after designed welding horn to resonance at frequencies of 20 kHz and 40 kHz. The analyses of the designed horn are completed through use a vibration mathematical expressions, modal and harmonic analyses to ensure the weldability due to applying ultrasonic power to the working area and also to compare the performance of joint at using two resonance frequencies of 20 kHz and 40 kHz. The dimensions of the horns were determined to match the selected resonance frequencies, which the lengths were calculated as 132 mm and 66 mm respectively. The analysis of the exciting model indicates that the axial vibration modes of 19,584 Hz and 39,794 Hz are obtained in 10th mode, while the two frequency values are recorded 19,600 Hz and 39,800 Hz from the frequency response of the two horns. The weld strength between Al and Cu specimens with a thickness 0.5 mm was evaluated using a tensile test, which the analyses were obtained under using different welding pressure and varied amplitudes. The results were recorded within exciting a horn with two different resonance frequencies, show the enhancement of weld strength and quality through control of stepping amplitude, the enhancement means obtain good strength of the weld, reduce sticking horn to specimen, and lower specimen marking.

1. Introduction

Ultrasonic welding is a technique normally depends on a solid-state bonding process in which the materials are completely joint through applying high frequency in form of shear vibration to create scrubbing between intimate surfaces, and the bonding subjected to force or pressure to confirm bond. The high vibration generated will help to reform the intimate surfaces by vibration deforms and flatten surfaces, removing asperities, oxides and contaminants, and allow for increasing contact area of the weldment specimens [1],[2], this allow the technique

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to be applicable on various thinner and thicker materials [3]. Ultrasonic welding technique strongly entered in industrial and manufacturing fields to join materials with good strong and high precision [2]. Furthermore, this technique does not require any adding of filler or solder, which put this type of welding technique to be more suitable for environment specially in reducing carbon emission and controlling of energy conservation environmentally and economically [4]. The main components of an ultrasonic welding system are power supply to generate power, transducer or converter to provide vibration with specific amplitude, booster to raise displacement amplitude and horn to maximize the amplitude and to work. Also, other components such as the anvil for clamp specimens during welding and fixtures, shown in Figure 1. The horn vibrate with different vibration modes, but the tuning is focused on longitudinal mode to ensure that the horn excited at required dynamic characteristics and subsequently effect on strength and quality of weld. The mechanism of the technique is to convert 50 or 60 Hz alternating current into dynamical energy of 20 kHz or 40 kHz. An optional booster is used to raise the limited amplitude of transducer and also enclosed the welding system at nodal zone and the horn transmits the high vibrational motion through carrying ultrasonic energy to the weld materials. Sufficient amount of receiving ultrasonic energy by welded parts depend on high diffusion of material molecular at intimate surfaces [1]. Although many studies have been conducted on ultrasonic welding, using different welding frequencies, various experiments and weldability, but most of these studies pay less attention to examining welding performance between two different horns. In addition, the lack of using controls amplitude stepping for most of previous studies were issued. Therefore, it is required to examine the operating frequency of the horn to improve the performance of the weld and to enhance strength of the various bonding metals. The presented work shows a study of welding performance for join materials by ultrasonic welding technique through improve both weld strength and quality. A numerical design by finite element analysis with ANSYS code and subsequent completing experiments of an integrated welding system with exciting horn at 20 kHz and 40 kHz help to investigate the performance of weld at contact surfaces, and then to allow for study the effect of main welding parameters on welds. The weld strength is characterised experimentally in terms of the results of repeated tensile shear tests. The ability to use amplitude stepping profile is to obtain good weld strength with reasonable quality. Also, to solve several issues such as sticking horn/specimen and part marking.

2. Numerical Design of the Exciting Ultrasonic Horns

A finite element method with code ANSYS is efficiently performed help for design the main components of ultrasonic device (i.e. Horn) , which horn design must has compatibility to the requirement of high amplification and moderate clamping force in order to achieve good welding condition of specimens [5]. Vibrational characteristics such as, resonant frequency of excitation, separation of frequency, amplification of vibration displacement, uniformity of amplitude at horn tip surface, and the distribution of stresses concentration, should be carefully examined during design horn.

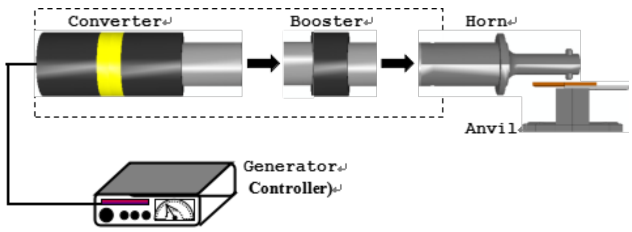

Figure 1. Main components of ultrasonic welding system

The steel is chosen as a selected material for the designing horns, because it has good acoustic properties and suitable to resist against wear. Further with low cost, the steel has good machining material and easy formation to re-shape in different forms. The selection of material depends on the type of weld, properties of weldment such as strength and hardness. It is mentioned here, that the welding member should have material harder than the material of the horn, as this recommended in welding process. Different horn profile can be designed for ultrasonic applications such as exponential, step, conical, catenoidal … etc, which the type of profile indicates the amount of amplification ratio for the horn design. High amplitude amplification is generally recommended with step profile of the horn; however unfavourable stresses should be avoided at working area as these stresses increases due to increase in amplification ratio relative to the radial change in horn diameter [8], but the stresses can be shifted back due to make some modification in the horn profile. In designing a horn, the first step is to determine a length of the horn by using a mathematical expression. Then, the horn length was identified based on relationship between wave length and resonant length. The horn length was roughly determined, and sequentially determined the shape, cross section and dimensions according to the numerical values of mode shape and analyses of natural frequency. It was noted here, that some errors were recorded by theoretical analysis of the horn. After checking all requirements of the horn design, the information of the sketch horn with

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its specification is entered as an input data to the CNC program to get the final shape of fabricated horn. The final shapes of the two dimensional sketches of two frequencies (20 kHz and 40 kHz) are shown as in Figure 2. Table 1 shows the mechanical properties of the horn material (steel alloy) for the finite element analysis of both frequencies.

Table 1. Properties of the horns material

Horn frequency (kHz)	Poisson's effect (-)	Physical density (kg/m^3)	Young's modulus (GPa)
20	0.33	7810	210
40	0.33	7850	207

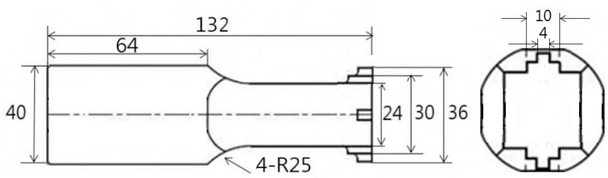

Figure 2(a). 20 kHz two dimensional sketch horn

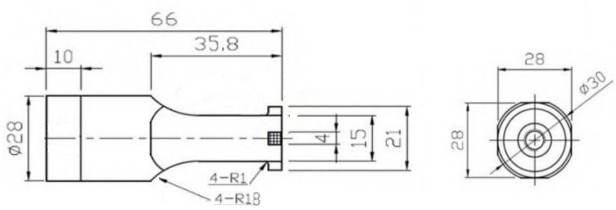

Figure 2(b). 40 kHz two dimensional sketch horn

3. Data Extraction from the Vibration Analysis of the Horns

Finite element analysis is automatically performed through setting the shape and a number of meshes for modelling and analyzing horns. The models were built through sketch the horn and define material properties then assignment the part and apply proper mesh before set boundary conditions, after that the horn restraint through connecting it with bolt, and specified the exciting movement to allow for vibrating horn axially. A high precision CNC machine is performed to design and manufacturing horns. The machine program is set based on the characteristics of the vibrational analysis of selected horn. The analyses of the vibration responses for the designed horns are shown in Figure 3, which the value of the natural frequency of 20 kHz horn is recorded to 19.895 Hz very close to 20 kHz. The frequency response of the horn was calculated at the 9th mode which picks up at the tip of the horn to ensure getting high amplitude. Whereas the vibrational response of 40 kHz horn is recorded 39.654 Hz also close to 40 kHz, which the frequency response is obtained at the 9th mode and through getting high amplitude at horn tip. The analyses of the vibration response for the exciting horn are carried out within frequency range varied from (10-30) kHz and the excitation is collected at the horn surface (horn tip). The results of analysis show an acceptable close to the numerical result of 19.980 Hz. In addition, the harmonic response was also determined at the 40 kHz horn tip, which the data were determined within the range of (30-50) kHz. Similar with the 20 kHz horn, the frequency response of 40 kHz is determined at the output of the horn, which has a value of 39.654 that is close to the result of predicted value. Figure 4 (a) and (b) plots the results of vibration response of the horn at 20 kHz and 40 kHz respectively. The analysis of simulation models shows highest value of amplitude pointed at horn tip, which the horn has good gain in providing displacement amplitude, and the longitudinal mode of vibration for the exciting horn seems to be very close to the result obtained from simulation models. The horn gain was also calculated by dividing the output amplitude / input amplitude of the horn, which the vibration amplitude recorded (17.2 micron), with horn gain 5.5 for the 20 kHz horn, and (26.0 micron), with the horn gain 4.0 for the 40 kHz respectively. However, gain may drop down due to increase coupling between vibration modes, motion distortion and loss in energy which affect on operational processes quantity and quality [8].

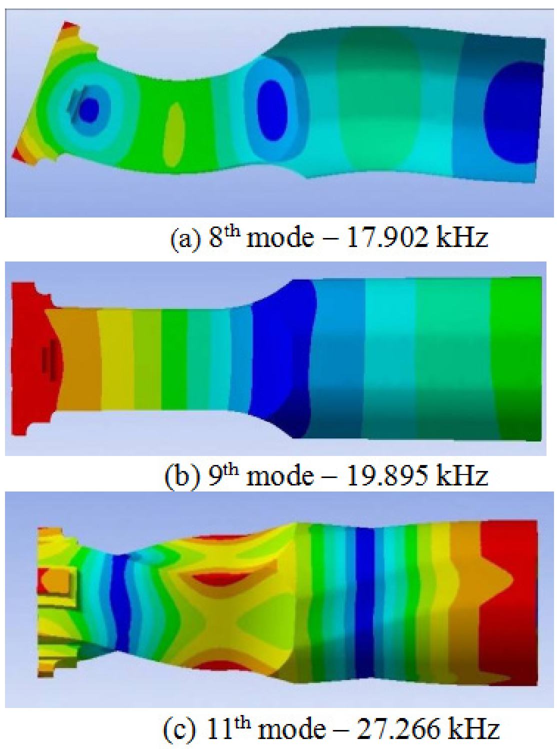

Figure 3(a). Prediction the separation frequency modes at 20 kHz

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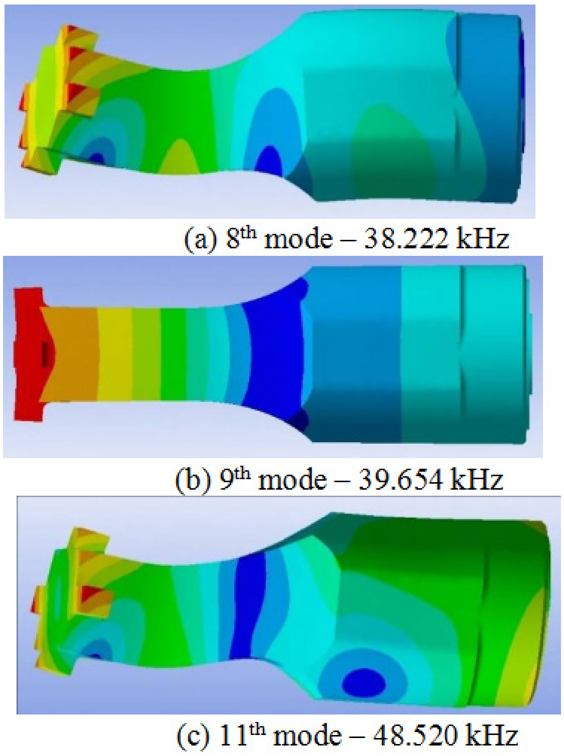

Figure 3(b). Prediction the separation frequency modes at 40 kHz

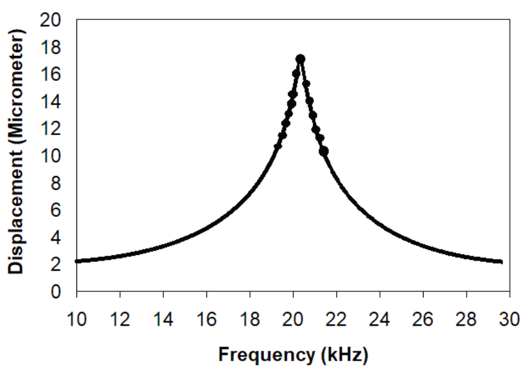

Figure 4(a). Vibration response analysis of the designed horns at 20 kHz

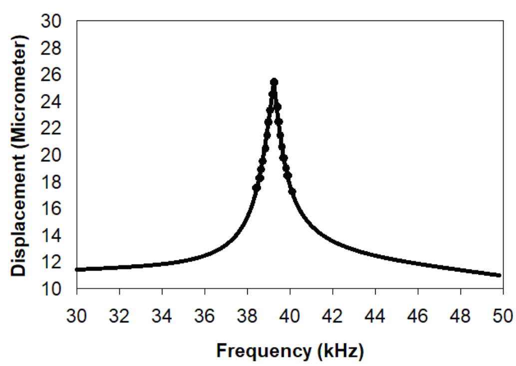

Figure 4(b). Vibration response analysis of the designed horns at 40 kHz

4. Welding System and Their Parameters

4.1 Set up of Welding Process

In order to joint specimens, welding system should be built, assembled and to work. The horn which is considered the main component of the welding system was designed precisely and accurately to produce weld according to the type and requirements of materials to be welded. First, the horn was directly connected to the transducer (sometimes adding booster between horn and transducer), which form welding stack. The transducer linked to the power supply (generator, type Sonic) to receive an alternative current from the electric main point. With 1 kW maximum capacity of ultrasonic generator the designed horns were excited at operating frequencies to provide sufficient mechanical vibration needed for welding. A tensile machine is performed to hold welding stack and to support welding specimens being sit on stationary anvil. Also, tensile machine has ability to control and measure the force applying over weldment during process, and to record the value of force by the 2.0 kN machine load cell. A computer program that equipped by tensile machine is saved the amount forces applied against the time. Horn tip is designed in the form of flatten with knurled surface to help for contact with upper specimen and avoid it from slippage during vibration, while the lower specimen is strongly held by anvil (shown in Figure 1). The aluminium and copper specimens were cut and prepared according to the ASTM and BSI Standard codes [6], [7]. Specimens dimension was set to be 50 x 10 mm for all sheets that having thickness 0.5 mm. 10 mm was set for overlap specimens to match with the dimension of horn tip, as shown in Figure 5. During the test of welded specimens' strength, the bending effect on specimens was observed and that resulted from error in measuring strength. Therefore, to avoid bend a dummy plates were added. Several trials were carried out on different welding conditions, each trial was repeated five or six times prior to get results, then the results were averaged and the standard deviation was extracted for each trial. The trials were arranged in order of welding (Al-Al) specimens and (Cu-Cu) specimens. A number of failed trials were excluded from results, because those specimens that are sticking with horn or either those trials that required more power or applied force to confirm joints. In experimental trials, input welding parameters were set to ensure good joint and to evaluate the weldability of the weld specimens, these parameters are process time, applying force and vibration amplitude.

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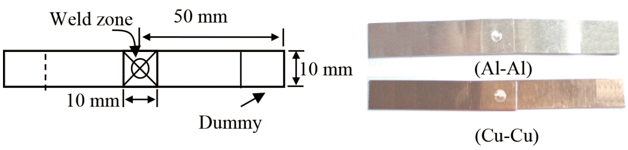

Figure 5. Specimen layout and welded coupons with welding area

4.2 Stepped Amplitude

In ultrasonic processes, generally ultrasonic amplitude apply to the process has a constant value, which its value can be pre set to higher or lower value depends on the specification of the welding system. However, an alternative technique which is presented in this work is to apply amplitude stepping. The stepping here allows the weld to be done by controlling amplitude between two different values. The digital screen of ultrasonic generator with controlling knobs allow to trigger for the transitions of the setting amplitude values, which pre setting can be made by either time period of weld process or change the energy level or power [10]. The procedure for applying stepping amplitude begin with pre set high amplitude value as this value is required to provide sufficient joints for overlapping specimens and to create a solid-state form of welding. Then, the amplitude is suddenly lowered to minimize the frictional heat between intimate surfaces and allow for high interlock atoms of materials diffusion. It was noted here, that stepping process made the samples soft, less damage and lower sticking to the horn tip. A series of experiments have been conducted on 20 kHz and 40 kHz design horns using stepped amplitude to investigate welding performance and to ensure obtained good enhancement for the both strength and quality of joining parts.

4.3 The Influence of Joining Metals by Using Constant and Stepped Amplitude

The weldability of the 20 kHz and 40 kHz designed horns was successfully done to evaluate the weld processes through which the strength between specimens were compared and analysed. Figure 6 (a) and (b) plots a relationship between the strength of the de-bonded specimens against the values of applying force, which the relations were carried out on using 0.5 mm specimens thickness that welded ultrasonically at 20 kHz and 40 kHz respectively. The welding processes were carried out through applying different constant and stepped vibrational amplitudes. For each input parameters, five tests were done, then the average values were determined with error bars, so the standard deviation indicates the variation of strength against applying force. It was noted that the welding strength is increased due to increases in clamping force and for the process time up to one second, but it was observed that excessive force may produce high friction, more heat and then suppress the relative motion between surfaces, which in turn lower weld strength [9]. Overall, the strength of weld is proportional to the time under the influence of applying clamping force, which lower values of strength were recorded with 40 kHz than 20 kHz under the common value of selecting amplitude. The reason for that either due to friction heat generated between joining specimens is concentrated at tip of the horn, also the diffusion at intimate surfaces of selected materials which is facilitated at 20 kHz compared with 40 kHz. For the welding of Al-Al specimens, the maximum strength recorded is 880 N at 20 kHz under clamping force of 680 N and vibration amplitude 17 μm, while at 40 kHz, the maximum strength was recorded 820 N under clamping force of 700 N and vibration amplitude 17 μm. Figure 6 confirms that the weld strength increased with increasing of amplitude to 26 μm. The welding strength versus clamping force tests were determined with welding of Cu-Cu specimens, which the maximum strength of 20 kHz horn was recorded 790 N at clamping force 700 N and amplitude 17 μm, and the maximum strength of 40 kHz horn was recorded 770 N at clamping force 750 N and amplitude 17 μm. Similar to the weld Al specimens, the weld strength of joining Cu-Cu specimens increased with increasing amplitude to 26 μm, but the overall that the strength of Cu stay below of Al specimens. No evidence indicates that the strength of weld increases due to increase the value of clamping force for welding material specimens. In case of setting amplitude 26 μm, despite resulting high strength, it also leads to increase in standard deviation beside leave a noticeable mark on joint specimens. During experiment, part of trials was failed due to sticking of horn tip/upper specimen. However, sticking parts become more prevalent on specimens when the welded specimens subjected to a value of clamping force above 600 N, but this result to lower in weld strength despite using constant and stepped amplitudes. Further, it was shown that the strength is significantly affected by the material properties such as hardness and roughness, as higher strength values were recorded with aluminium specimens than copper specimens.

In Figure 6, the influence of applying stepping amplitude technique is shown through indicate the weld strength values taken at different clamping forces. The advantages of changing the amplitude from higher value (26 μm) to lower value (17 μm) were clearly seen in Figure 6, through reducing the size of error bars and lower in standard deviations, and in contrast increase in weld strength, but during examine the weld strength, aluminium specimens show slightly higher values of strength compared with copper specimens under using identical parameters. Finally, it was observed that applying the stepped amplitude will improve weld consistency and reduce other issues such as sticking, part marking, tool fracture and glowering. Further, the use of stepping amplitude may enhance the quality of welding and provide proper strength for joining materials.

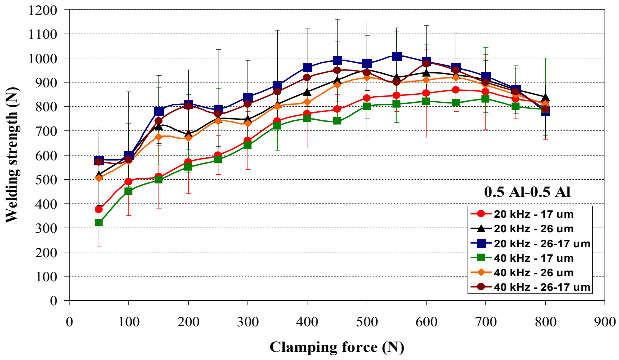

Figure 6(a). Variations of weld strength vs. clamping force for joined specimens: Al-Al for process conditions and frequency of designed horns at 20 kHz and 40 kHz

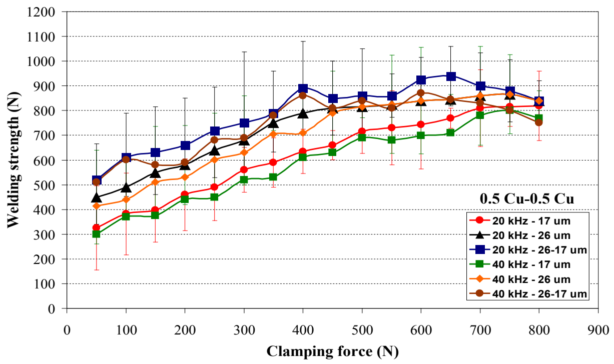

Figure 6(b). Variations of weld strength vs. clamping force for joined specimens: Cu-Cu for process conditions and frequency of designed horns at 20 kHz and 40 kHz

5. Conclusions

This work presents a design, simulation and fabrication of an ultrasonic welding system in order to study and evaluate the weldability of joined specimens through using two different horns that are excited by 20 kHz and 40 kHz. Finite element analysis is performed successfully to examine frequency response through analyses of both modal and harmonic response. The welding input parameters such as force, amplitude and specimens arrangement have a significant effect on the strength of weld, which higher strength observed for those specimens of weld aluminium to aluminium compared with slightly lower strength measured for welding copper to copper specimens. For all trials the weld strength exhibits high values due to increase in clamping force, but excess in applying force above 600 N will result to deteriorate and drop in weld strength. An evaluation of weld strength is carried out through using three amplitude values, starting from 17 micron to 26 micron for normal constant amplitude, then a comparison is done for apply stepping amplitude process of previous two amplitude values (26-17), to improve weld strength, reduce error bars and lower standard deviation. In addition, the stepping process allows for reducing specimen adhesion to the horn and lower specimen marks. According to the change in welding condition, the overall tendency of weld strength increases with the increase in clamping force during process time up to one second. The overall tendency of evaluating weldability shows that the weld strength significantly affected by welding parameters such as time and amplitude, and it have direct proportional with these two parameters, but the strength does increase due to increase in clamping force. The study confirmed that lower weld strength of joint specimens was determined by 40 kHz compared with 20 kHz, even when using the same vibration amplitude or applying stepping amplitude. The reason is related to the amount of friction heat concentration at joint, and another reason is the facility of diffusion at weld interface for the both selecting materials, means that aluminium exhibit more to diffuse than copper for the two design operating frequencies.

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