Ultrasonic spot welding of dissimilar materials: characterization of welded joints and parametric optimization

M P Satpathy and S K Sahoo

1Department of Mechanical Engineering, National Institute of Technology Rourkela, Rourkela 769008, India

E-mail: mantraofficial@gmail.com

Abstract. Material joining is one of the key manufacturing processes used to assemble metallic and non-metallic parts for several applications. But the industries are facing many difficulties in joining of thin sheets of dissimilar metals by the conventional welding process because of their differences in chemical composition, physical and mechanical properties. Thus, ultrasonic welding is a solid state joining process used for joining of small elements in microelectronics industries. In this process, acoustic horn and booster are the important assets. The accuracy and strength of the welding depend mainly on their geometry. This proposed work deals with the design and modelling of an acoustic stepped sonotrode with booster using finite element analysis (FEA). From this analysis, the actual length of the horn is obtained by gradually decreasing its theoretical length. The quality of the weld is reckoned by its weld strength and the combinations of different process parameters. These are examined using the principal components coupled with grey relational analysis approach which is showing good agreement between the predicted values with experimental results. Fractographic examination of weld zone and hardness are also used to explore the weld quality.

1. Introduction

Now-a-days there is a necessity of miniaturization, ultra lightweight and ultra-precise parts. So many researchers are looking forward to various innovative micro welding techniques, in which metals and non-metals are united together for numerous industrial applications. The major area of is the automobile industry, which enables high production rate with the use of high-performance materials. The applications are now frequently increasing because of the requirement of top-quality accuracy and safety, which can’t be obtained in traditional welding processes. In the dissimilar metal welding, two or more metals are joined together under some particular conditions. But at the same time, it is difficult to join dissimilar metals because of their differences in composition, physical and mechanical properties. However, good welds have not been noticed by the fusion welding process so far. To overcome this difficulty, a solid-state joining process born, in which the bonding between the materials can be created due to the friction, and it happens below the melting temperature of parent materials. Ultrasonic metal welding (USMW) is one of these processes.

USMW is a solid-state joining process in which the joint is created between the workpieces by the application of high-frequency ultrasonic waves under pressure. The ultrasonic welding stack is comprised of six subsystems (i) generator (ii) piezoelectric transducer (iii) booster (iv) horn/sonotrode (v) pneumatic cylinder [1], (vi) anvil. The acoustic horn and booster design is a vital part of the ultrasonic welding process and the efficiency mainly depends on its design correctness. The traditional methods for the design of an acoustic horn are based on empirical relationships which include the equilibrium of a small element under elastic action and inertia forces. But, this will take a lot of time...
and even failed, when the complicated shape is considered. To overcome this, FEM can be used as an alternative method. Sherrit et al. [2] described a new type of horn designs which are superior to other normal horn designs from a design point of view. Generally resonance frequency depends on the length of the horn and amplitude depends on the different cross-sectional area. Amin et al. [3] did their investigation on various designs of the horn, which can affect ultrasonic cutting. They stated in the different design concept of horns by computer added design procedure and used finite element analysis to validate it. Nad [4] conducted his ultrasonic machining experiment using different horns like the cylindrical, tapered and exponential type. Siddiq and Ghassemieh[5] investigated that, it is possible to join thin layers of titanium alloy with aluminium alloy by the ultrasonic welding process at low temperature, pressure, and energy consumption. The solid state welding could be applied to join nonferrous materials like aluminum with ferrous materials like stainless steel (Tsujino et al. [6]). Sooriyamoorthy et al. [7] attempted to join metal with ceramic, and it was also successful of welding of Al with Al$_2$O$_3$. Optimization of process parameters is the major step in the Taguchi method. But one major limitation of this philosophy is that it is failed while solving the multi-response optimization problem. So, to overcome this drawback, Kumar et al. [8] proposed desirability function approach in combination with Taguchi philosophy. There are also some studies that joined aluminum with copper using ultrasonic spot welding process [9]. Zhao et al. [10] reported the formation of Al$_4$Cu$_9$ intermetallic layer which is main cause of joint failure. Thus, it helps a researcher to find out the possible causes of weldment failure.

Designing of the horn for the ultrasonic welding is really a challenging task because the high-frequency vibration should precisely occur at the welding tip and the amplitude should be maximized at the welding tip. In this study, a horn with the booster is designed using FEA and performing experiments with it. The ultrasonic welding is carried out using Al and brass metals, and the effect of different process parameters on weld strength is studied. The principal component analysis is used to convert the correlated responses to uncorrelated one, and grey based Taguchi method is employed to find out the optimal parameter condition. The quality of the weld is identified by the metallographic studies.

2. Experimental Methodology

2.1 Ultrasonic horn design

In ultrasonic welding, the asymmetrical horn mostly works with the longitudinal mode phenomena. The governing equation of the horn can be derived by considering a free-free vibration in a non-uniform bar.

$$\frac{\partial^2 \xi}{\partial x^2} + \frac{1}{S} \frac{\partial S}{\partial x} \frac{\partial \xi}{\partial x} + \frac{S}{C^2} \frac{\partial^2 \xi}{\partial t^2} = 0$$  \hspace{1cm} (1)

where $\xi$ = Amplitude in $\mu$m, $S$ = Cross-sectional area in $\text{mm}^2$, $\omega$ = Angular velocity in rad/sec and $C =$ acoustic velocity in $\text{m/sec}$ passed through the material. This velocity can be found out by

$$C = \left(\frac{E}{\rho}\right)^{\frac{1}{2}}$$  \hspace{1cm} (2)

The length of the horn can be obtained by solving the Webster horn equation as shown in equation (1).

$$C = \lambda f$$  \hspace{1cm} (3)

where $\lambda =$ wavelength of ultrasound waves.

The length of the horn is the half of the wavelength of waves passing through it. Mathematically, it can be represented as

$$L = \frac{\lambda}{2} = \frac{C}{2f}$$  \hspace{1cm} (4)

The performance of the ultrasonic system is measured by its amplification ratio/gain. It represents the capability of the system to weld high thickness materials. The dimensions of the input and output
ends are fixed by the size of the booster and the specific weld tip size. The input and output diameter of the horn is 44 and 35 mm and for the booster they are 55 and 44 mm respectively. The line diagram of the horn with the booster is presented in figure 1. Mathematically the amplification ratio is represented as

\[
\frac{\xi_2}{\xi_1} = \frac{S_2}{S_1} = \left(\frac{d}{D}\right)^2
\]

where \( S_1, S_2 \) = Input and output area of the horn. \( D, d \) = Input and output diameter of the horn.

The most important factor of the horn and booster to get the accurate length. Because an incorrect design may produce infinite resistance with other elements and can damage to the system. High fatigue strength, hardness and low acoustic losses should be the criteria for the selection of any materials for the horn. If the hardness of the material is higher than the horn, then it will wear very fast. In this study, D2 steel is used as the horn material, and the titanium is used as booster material. These two materials have excellent acoustic properties and are shown in table 1.

![Figure 1. Schematic diagram of horn and booster.](image)

| Table 1. Mechanical properties of D2 steel and titanium. |
|---------------------------------------------------------|
| Property                        | D2 steel | Titanium |
| Young’s modulus (E) (GPa)       | 210      | 116      |
| Poison’s ratio (\(\nu\))        | 0.30     | 0.34     |
| Density (\(\rho\)) (kg/m3)      | 7700     | 4500     |
| Velocity of sound (C) (m/Sec)   | 5222.32  | 5077.18  |

Generally analytical techniques fail when there are a complicated contour shape and sudden increase of stress and amplitude in the system. There is two finite element analysis used for this study (i) Modal analysis, (ii) Harmonic analysis. Modal analysis has been performed to find out the natural frequency of the horn and booster without considering any load, and 20018 Hz is obtained as natural frequency. It represents the rigidity of the structure. By accurate design, it will be resonating with other parts of the machine, and this can be achieved by adjusting the length. Harmonic analysis is done to study the response of the horn under periodic loading. This is otherwise also called as dynamic loading. In this analysis, the modal frequency and the amplitude are given as the input. Then the amplitude magnification and stress concentration are obtained at the output end. From figure 2, it is clearly observed that less displacement is observed at the nodal plane and high displacement of 70 µm is at the output end. Stress is also more at the nodal plane due to a sudden change in cross-sectional area and shown in figure 3.
2.2 Experimental setup

During this investigation, the joining has been done between two materials Al and Cu alloys i.e. Al1100 and CuZn37 of 0.2-mm thin sheet. Before welding, all the materials were rubbed with P800 waterproof SiC emery paper to remove the oxide layer. All the contaminants and grease were removed from the top surface by using acetone. The size of the sheet is 20×80 mm with an overlap of 20 mm as shown in figure 4. The Al1100 sheet is placed on the top of CuZn37 (brass) sheet. All the spot welding experiments have been performed with a Telsonic® lateral drive welding machine at a constant power of 3 kW and a frequency of 20.0 kHz. Figure 5 shows the complete setup of welding machine. The flat welding tip and a rigid anvil with serrations were implemented for the experiments. A universal testing machine was used to find out the weld strength with a displacement rate of 1 mm/min.

2.3 Domain of experiment

A lot of screening tests conducted prior to this study and based on that six process parameters were selected as the design variables. Taguchi’s L27 orthogonal array design with 5 replicates for each test condition was applied to determine the optimal results from a finite set of data. At the optimum condition of the input factors, micro-hardness and microstructural analysis are performed. Based on the parameter settings available in the system and the idea of the screen test; the domain of experiment has been chosen. The design of experiments is given in table 2.

| Table 2. Process parameters with their levels. |
|-----------------------------------------------|
| Parameters | Unit | Terms | Level 1 | Level 2 | Level 3 |
| Amplitude | μm | A | 54 | 60 | 68 |
| Weld pressure | bar | WP | 2 | 3 | 4 |
| Weld time | Sec | WT | 0.2 | 0.4 | 0.6 |
3. Data analysis and optimization
Experimental data have been normalized first to eliminate the ignorance of some factors. There are three different types of normalization procedure like LB (lower-the-better), HB (higher-the-better) and NB (nominal-the-best). For all the responses like tensile shear strength, T-peel strength and weld area, HB criteria have been chosen. After normalization, the correlation between three responses has been checked by using Pearson coefficients, and it is found that the correlation exists among the responses. These responses are converted into uncorrelated one with the help of Principal component analysis (PCA) and are shown in table 3.

Table 3. Principal component analysis results.

|      | $\Psi_1$ | $\Psi_2$ | $\Psi_3$ |
|------|----------|----------|----------|
| Eigenvalue | 2.546    | 0.389    | 0.064 |
|        | 0.585    | -0.518   | -0.624 |
| Eigenvector | 0.608    | -0.229   | 0.760 |
|        | 0.537    | 0.824    | -0.181 |
| AP | 0.849    | 0.13     | 0.022 |
| CAP | 0.849    | 0.978    | 1.000 |

The individual grey relational coefficients of the three principal components and consequently overall grey relational grade have been calculated using equation (6). The results are shown in table 4.

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k)$$

(6)

Table 4. Grey analysis results.

| Sl no. | Individual grey coefficients | Overall grey relational grade | $\gamma_i$ |
|--------|-------------------------------|-------------------------------|-----------|
|        | G1   | G2   | G3   | G1   | G2   | G3   | G1   | G2   | G3   | G1   | G2   | G3   | G1   | G2   | G3   | G1   | G2   | G3   |
| 1      | 0.3609 | 0.8206 | 0.7020 | 0.6278 |
| 2      | 0.3609 | 0.8200 | 0.7005 | 0.6271 |
| 3      | 0.3608 | 0.8208 | 0.7028 | 0.6281 |
| 4      | 0.7206 | 0.9995 | 0.8289 | 0.8497 |
| 5      | 0.7204 | 0.9988 | 0.8260 | 0.8484 |
| 6      | 0.7207 | 0.9998 | 0.8296 | 0.8500 |
| 7      | 0.6168 | 0.6349 | 0.5785 | 0.6100 |
| 8      | 0.6164 | 0.6343 | 0.5817 | 0.6108 |
| 9      | 0.6168 | 0.6348 | 0.5792 | 0.6103 |
| 10     | 0.4655 | 0.4714 | 0.6161 | 0.5177 |
| 11     | 0.4656 | 0.4716 | 0.6146 | 0.5173 |
| 12     | 0.4655 | 0.4714 | 0.6170 | 0.5180 |
| 13     | 0.9995 | 0.8136 | 0.9937 | 0.9356 |
| 14     | 0.9999 | 0.8133 | 0.9991 | 0.9374 |
| 15     | 0.9993 | 0.8138 | 0.9904 | 0.9345 |
| 16     | 0.4850 | 0.5041 | 0.3339 | 0.4410 |
| 17     | 0.4848 | 0.5040 | 0.3348 | 0.4412 |
| 18     | 0.4849 | 0.5040 | 0.3343 | 0.4410 |
| 19     | 0.5626 | 0.3544 | 0.9744 | 0.6305 |
From the overall grey relational grade value, the main effects plot can be obtained. All the input variables are varied in 3 levels. For each parameter, the over desirability values of a particular level are averaged. Then the difference between the highest and lowest value gives the rank of each parameter. The highest rank signifies that the weld strength is greatly affected by it. All these values are given in Table 5, and main effects plot is showing in figure 6.

**Table 5.** Main effects on overall grey relational grade.

| Factors       | Levels | Difference | Rank | Optimum level |
|---------------|--------|------------|------|---------------|
| Amplitude     | 0.696  | 0.592      | 0.549| 0.147         |
| Weld pressure | 0.632  | 0.787      | 0.707| 0.155         |
| Weld time     | 0.654  | 0.602      | 0.725| 0.123         |

![Main Effects Plot for S/N ratios](image)

**Figure 6.** Main effects plot for the overall grey relational grade.

4. Results and discussion

4.1 *FEM results for the welding stack*

From the dynamic analysis, it has been observed that the input amplitude is modified by the booster, and again it is also amplified by the horn to create a good weld between the sheets. According to the design of both elements, at each stage the amplitude is increased by 1.5 times. Thus, at the end of horn nearly 70 µm amplitude is obtained which is just 2.25 times of the input amplitude. This value is quite close to the theoretical value. Also at the nodal position of the booster and horn, i.e. at 60 mm and 183 mm, the amplitude becomes zero. These variations in amplitude with the length of welding stack are given figure 7. Likewise, figure 8 shows the Von Mises stress distribution along the length of the horn. It increases with the gradual decrease in the dimension, and it is maximum at the suddenly changing section. Thus, a stress of 117.90 MPa and 324.63 MPa are observed for booster and horn
correspondingly. The 4.5 mm radius of curvature is also applied at that section to lower the stress concentration. These results are then validated by FEM analysis and are given in Table 6. From the data shown in the table, signifies that there are 2.4% and 4.76 % errors in the length calculation of both systems. Similarly, 5% and 4.45 % errors are obtained while calculating the magnification ratio.

| Sl No. | Factors                  | Theoretical calculated horn | Theoretical calculated booster | FEM Analysed horn | FEM Analysed booster | % error in horn | % error in booster |
|--------|--------------------------|-----------------------------|-------------------------------|------------------|----------------------|----------------|-------------------|
| 1      | Frequency (kHz)          | 20                          | 20                            | 20               | 20                   | 0              | 0                 |
| 2      | Total length (mm)        | 130                         | 127                           | 126              | 120                  | 2.4            | 4.76              |
| 3      | Diameter ratio           | 1.25:1                      | 1.25:1                        | 1.25:1           | 1.25:1               | 0              | 0                 |
| 4      | Amplification factor     | 1.5                         | 1.5                           | 1.58             | 1.57                 | 5              | 4.45              |

Table 6. Comparison between theoretical and FEM analyzed horn and booster.

![Figure 7. Amplitude variation with length.]

![Figure 8. Stress distribution with length.]

4.2 Confirmatory test results

Based on table 5, the rank of each process parameter is given. The highest rank parameter contributes most of the responses. So weld pressure is the most important parameter. The optimal condition of parameters is A1WP2WT3. On this condition, high weld strength was obtained. The predicted values for the above optimal condition are given by the PCA based grey Taguchi analysis. The lap joints were performed with the predicted parameters and corresponding S/N ratio is also found out. It is then compared with the predicted parameter results. Table 7 shows the results of the confirmatory experiment. It is observed that the confirmatory test results show a fine agreement with predicted results as the percentage of error is 0.816%.

| Sl No. | Factors                  | Prediction | Experiment |
|--------|--------------------------|------------|------------|
|        | Factors level            | A1WP2WT3   | A1WP2WT3   |
| 1      | S/N ratio                | -4.738     | -4.777     |
| 2      | Overall grey relational grade | 0.5795 | 0.5768 |
| 3      | Error between S/N ratio  | 0.816%     |            |

Table 7. Confirmatory test results.
4.3 Metallographic studies

After the tensile test, a scanning electron microscopy (SEM) is employed to observe the fracture surfaces of the weld coupons. Figure 9 shows the microscopic features such as the plastic flow of the metal in the weld zone of Al-Brass specimens at 3 bar pressure, 0.6 Sec welding time and 54 µm vibration amplitude. The fracture surface of the Al side is shown in figure 9 (a). It is observed that due to the lower hardness of Al than brass, it is severely deformed, and thus less brass is located on it. But as the brass is harder than Al, so it undergoes less deformation, and there is no improvement of weld area which affects the weld quality. It is represented in figure 9 (b). In the meantime, in the weld zone, the hardness of both the materials increases due to increase in temperature, and it is the major cause of strain hardening. For this purpose, Vaiseshika microhardness tester with a load of 100gm and holding time of 15 sec was used and figure 10 shows the microhardness of the material in the parent zone as well as in the weld zone.

![Figure 9](image)

**Figure 9.** Fractographic study of weld coupons (a) Al side, (b) brass side

![Figure 10](image)

**Figure 10.** Microhardness variation with length.

5. Conclusions

- The modal analysis has been done to find out the natural frequency of the horn as 20007 Hz, which is quite close to the operating frequency of 20 kHz. These are obtained by adjusting the length of the horn and booster to 126 mm and 120 mm respectively. 2.4 % and 4.76 % errors are noticed while adjusting it.
- The harmonic analysis also has been performed to find out the amplitude and stress distribution in the horn. The magnification factors obtained from this analysis are 1.58 and
1.57. These values are very close to magnification given by the commercial horn. 5 % and 4.45 % errors are found out during this analysis. This is due to the limitations of the FEM or measurement errors in the real system. To encounter the danger of stress concentration, the radius of curvature of 4.5 mm is given to the corners.

- In addition to it, the multi-objective optimization problem has been solved by finding an optimal parametric combination in which appreciable weld strength is obtained. PCA has been implemented to eliminate the correlation between the responses, and grey based Taguchi method is used to find out the optimal sequence of input parameters.
- The confirmatory test also shows an error of 0.816%, which shows a good agreement with the predicted results. From the weld quality studies, the mechanism of plastic deformation and the effect of hardness due to the temperature of the welding zone have been uncovered effectively.

References

[1] Bakavos D and Prangnell P B 2010 Mechanisms of joint and microstructure formation in high power ultrasonic spot welding 6111 aluminium automotive sheet Mat. Sci.Eng. A 527(23): 6320-6334.
[2] Sherrit S, Askins SA and Gradziol M 2002 Novel horn designs for ultrasonic/sonic cleaning, welding, soldering, cutting and drilling Proceedings of the SPIE Smart Structures Conference 4701 353.
[3] Amin S G, Ahmed MH M and Youssef H A 1995 Computer-aided design of acoustic horns for ultrasonic machining using finite-element analysis J. of Mat. Proc. Tech. 55(3-4): 254-60.
[4] Nad M. 2010 Ultrasonic horn design for ultrasonic machining technologies Applied and Computational Mechanics 4: 79-88.
[5] Siddiq A and Ghassemieh E 2011 Fibre embedding in aluminium alloy 3003 using ultrasonic consolidation process-thermo-mechanical analyses Int J. Adv Manuf Technol. 54(9-12): 997-1009.
[6] Tsujino J, Hidai K, Hasegawa A, Kanai R, Matsuura H, Matsushima K and Ueoka T 2002 Ultrasonic butt welding of aluminum, aluminum alloy and stainless steel plate specimens Ultrasonics 40(1-8): 371-374.
[7] Sooriyamoorthy E, John SP and Kalakkath P 2011 Experimental studies on optimization of process parameters and finite element analysis of temperature and stress distribution on joining of Al-Al and Al-Al2O3 using ultrasonic welding Int J. Adv Manuf. Technol. 55(5-8): 631-640.
[8] Kumar P, Barua PB, Gaindhar J L 2000 Quality optimization (multi-characteristics) through taguchi's technique and utility concept Qual. Reliab Eng Int.16(6): 475-85.
[9] Matsuoka S-, Imai H. 2009 Direct welding of different metals used ultrasonic vibration. J Mater Process Technol 209(2): 954-60.
[10] Zhao YY, Li D, Zhang YS. 2013 Effect of welding energy on interface zone of Al-Cu ultrasonic welded joint. Sci TechnolWeld Joining 18(4): 354-60.