Parametric Investigation on Microstructure and Mechanical Properties of Ultrasonic spot welded Aluminium to Copper sheets

Mantra Prasad Satpathy¹, Kasinath Das Mohapatra*, Ananda Kumar Sahoo² and Susanta Kumar Sahoo³

¹School of Mechanical Engineering, KIIT University, Bhubaneswar, 751024, Odisha
²³Department of Mechanical Engineering, National Institute of Technology Rourkela, Rourkela 769008, India

*Corresponding Author E-mail: kitu.kasinath1@gmail.com

Abstract. Ultrasonic welding is one of the promising solid state welding methods which have been widely used to join highly conductive materials like aluminum and copper. Despite these applications in the automotive field, other industries also have a strong interest to adopt this process for joining of various advanced alloys. In some of its applications, poor weld strength and sticking of the workpiece to the tool are issues. Thus, an attempt has been taken in the present study to overcome these issues by performing experiments with a suitable range of weld parameters. The major objectives of this study are to obtain a good joint strength with a reduced sticking phenomenon and microstructure of Al-Cu weld coupons. The results uncovered the mechanical strength of the joint increased up to 0.34 sec of weld time and afterward, it gradually decreased. Meantime, the plastic deformation in the weld zone enhanced the formation of an intermetallic layer of 1.5 μm thick, and it is composed of mainly Al₂Cu compound. The temperature evolved during the welding process is also measured by thermocouples to show its relationship with the plastic deformation. The present work exemplifies a finer understanding of the failure behavior of joints and provides an insight of ultrasonic welding towards the improvement in the quality of weld.

1. Introduction

The invention of Ultrasonic metal welding (USMW) was in the 1950s. Meanwhile, this technique has been continuously applied in various sectors such as an automobile, electrical and electronics, manufacturing and aerospace industries. Due to the high thermal and electrical conductivity nature, aluminum and copper are used in electric power industries to transmit power efficiently. Due to the friction, an interface temperature is developed between the sheets, and that is capable of softening the overlapping zone. Thus, the plastic deformation occurs in the weld area, and the two materials are joined [1]. Zhang et al. [2] accomplished various tests by taking different ultrasonic energy values in order to measure the temperature at the weld center. He concluded that the softening of the material is achieved when the peak temperature is above 500°C, to boost the joining of aluminium sheets. Recently, USMW is tried to join thin sheets of aluminium with other lightweight materials in the structural automotive and aerospace application [3]. This process is also being used to accumulate secondary aerospace structures such as helicopter access doors: These doors can sustain loads of about 5 to 10 times the design load without the weld failure in air load tests as described by American welding society [4]. Meantime, there is a necessity to understand the influences of various welding parameters on the mechanical strength of welds during the USMW process. Most of the literatures [5]
reported about the ability of the USMW process to weld metals like titanium, steel, nickel, copper and their dissimilar combinations with other non-metallic materials. Kodama [6] performed experiments using soft materials like aluminium, copper, brass and gold. The study also investigated the various parameters like specimen roughness, hardness, dimensions, coefficient of friction and anvil geometry on the bond strength. The results showed that the good strength could be obtained when the amplitude of vibration was reduced with the increase of frequency of vibration. Hetrick et al. [7] also demonstrated the ultrasonic welding process as a low heat producing process. For this reason, the issues like part distortion and the degradation of Al alloy property can be eliminated. Barnes and Pashby [8] reported that USMW could be used in aerospace and automotive sectors for joining of lightweight structural components.

A large number of studies have examined the joint strength by considering one or two of the parameters as constant. However, a good result can be obtained by varying these control parameters simultaneously to study the joint strength and quality. The majority of studies had also not considered the effect of dissimilar material combination and the effect intermetallic compounds (IMCs) on the weld strength. Therefore, in this study, an attempt has been taken to weld the dissimilar materials such as AA1100 aluminium alloy with UNS C10100 copper along with the investigations of the effects of various process parameters like weld time, weld pressure and vibrational amplitude on T-peel failure and tensile shear loads along with the generation of temperature during joining.

2. Experimentation

In this study, the welding experiments have been conducted between commercially available 0.45 mm thick sheets of aluminium (AA1100) and copper (UNS C10100) (further it is abbreviated as 0.45Al-0.45Cu combination). Sheets were sheared to a rectangular shape of 100 mm length and 20 mm wide with an overlapped area of 20 × 20 mm² for the lap welding. Meantime, the sheet hardness also has a vital role in deciding the quality of the joint [9]. As the top specimen (i.e., on the sonotrode side) is more subjected to the impact of ultrasonic energy, thus, a softer material, i.e., AA1100 (45 HV) is selected for all the experiments. Moreover, it can be more plastically deformed than the relatively harder material, i.e., UNS C10100 (72 HV) (i.e., on the anvil side). The configuration is shown in Figure 1. The mechanical and thermal properties of weld specimen are presented in Table 1.

![Figure 1. Schematic diagrams for testing of weld coupons.](image)

**Table 1.** Thermal and mechanical properties of weld materials

| Materials                  | AA1100  | UNS C10100 |
|----------------------------|---------|------------|
| Ultimate tensile strength (Pa) | 135.5E6 | 302.1E6    |
| Brinell Hardness (BHN)     | 32      | 70         |
| Yield strength (Pa)        | 115.2E6 | 251.5E6    |
| Thermal Conductivity (Wm-1°C-1) | 220    | 391        |

The welds are produced by a Telsonic® ultrasonic lateral drive spot welder (Figure 2) with a flat serrated weld tip size of 11 mm × 9 mm on time control mode. For achieving a good weld, there is a need to select proper process parameters with suitable operation levels in such a way that the required quantity of ultrasonic energy can be transmitted to the weld zone. Therefore, from various literature
studies and screening tests, three process parameters like weld time (WT), vibration amplitude (A) and weld pressure (WP) have been selected. In the current analysis, WP, WT and A are varied in three, seven and four levels respectively. These factors with their levels are represented in Table 2. The full factorial design of experiment has been employed in this study to record the influence of each process parameters on the outputs like T-peel failure and tensile shear loads. Thus, a total of 84 numbers of experiments are executed using this design. For better accuracy of results, each experiment has been replicated six times, and a total of 504 samples are prepared. Out of which 252 samples each are employed for tensile shear and T-peel tests.

Prior to welding, the face of weld strips are cleaned by swabbing with acetone and was dried by hot air to get rid of any contaminants and oxides. The interface temperature was analyzed by embedding 0.1 mm K-type thermocouples near to the periphery of the weld spot. The implanted position of the thermocouple is illustrated in Figure 3. This temperature measurement is essential to provide an insight to predict the formation of intermetallic phases. The T-peel failure load and tensile shear tests were carried out using the fully computerized universal testing machine (UTM) INSTRON® 1195. This UTM is equipped with 10 kN load cell with a constant crosshead speed of 2 mm/min to avoid any type dynamic stress effect on the joint.

Table 2. Experimental domain for Ultrasonic metal welding of 0.45Al-0.45Cu weld coupons

| Amplitude (µm) | Weld time (Sec) | Weld pressure (MPa) |
|----------------|-----------------|---------------------|
| Level 1        | 47              | 0.26                | 0.26                |
| Level 2        | 54              | 0.28                | 0.34                |
| Level 3        | 60              | 0.30                | 0.42                |
| Level 4        | 68              | 0.34                | ...                 |
| Level 5        | ...             | 0.36                | ...                 |
| Level 6        | ...             | 0.38                | ...                 |
| Level 7        | ...             | 0.41                | ...                 |

Figure 3. Weld samples with positions of thermocouples for temperature measurement.
The metallographic specimens were prepared from the weld coupons by cutting in the transverse cross-sections and followed by polishing with different grades of emery paper and diamond paste. The microstructural examinations were performed using scanning electron microscope (SEM) (JEOL®, JSM-6480LV).

3. Results and Discussion

3.1. Interface temperature analysis

Figure 4 represents the peak temperatures at each condition of process parameters. It can be noticed that the temperatures rise very quickly up to 0.28 sec for all the vibration amplitudes and then these increasing rates gradually slow down. The maximum temperature of 292.78 °C is observed at the weld time of 0.41 sec, vibration amplitude of 47 μm and weld pressure of 0.34 MPa. However, this interface temperature value is increased to 303.83 °C, 314.39 °C and 328.98 °C with the increase in vibration amplitude to 54 μm, 60 μm, and 68 μm respectively. It can be observed that most of the frictional works are performed at the weld interface, and this is originated from the scrubbing motion of the sheets. Thus, increasing in amplitude value means the increasing the degree of scrubbing motion and finally, it leads to rise in temperature.

![Figure 4](attachment:image.png)

Figure 4. Weld interface temperatures for 0.45Al-0.45Cu weld coupons at different vibrational amplitudes.

3.2. Analysis of weld area

Figure 5 illustrates the graph between different input parameters with weld area for the weld coupons of 0.45Al-0.45Cu. Similar to previous analysis, these tests are also conducted using four amplitude settings comprising of 47 μm, 54 μm, 60 μm and 68 μm. The weld area instigates to rise and reaches the peak value of 67.19 mm² at maximum weld pressure of 0.34 MPa, vibration amplitude of 47 μm and weld time of 0.41 sec. Similarly, the weld area exhibit higher values of 69.63 mm², 72.52 mm² and 79.19 mm² respectively when the vibration amplitude values are increased to 54 μm, 60 μm, and 68 μm respectively. This nature of the graph is obvious because the highest weld time results in less oxidation and a higher rate of heat generation during welding. Furthermore, on the increase of
vibration amplitude, the rate of plastic deformation in the mating surfaces rises, and it leads to the dense distribution of micro-bonds in the interface.

3.3. Fractographic analysis

The microscopic photograph of 0.45Al-0.45Cu is illustrated in Figure 6. From these figures, it can be observed that no appreciable deformation takes place in the copper materials. Meanwhile, it is believed that the inter-metallics formed between the weld coupons affect the joint strength. From this figure, some micro cracks are noticed on the aluminium side at the higher level of weld time due to its higher ductility and lower hardness properties. Furthermore, the inter-granular cracking is the other reason for reducing the joint strength. Once again, when the weld pressure is too high, then the relative motion between the sheets disappears, and the sticking may happen. Likewise, the weld time also plays a crucial role in getting good weld strength. With less weld time, the interatomic diffusion will not be complete, and it results in lower weld strength with voids in the interface region. From the weld quality studies, it is confirmed that the strength of a joint depends on the specific values of input parameters.

Figure 5. Weld areas of 0.45Al-0.45Cu weld coupons at different vibration amplitudes.
Figure 6. Fractured surfaces of ultrasonic welded specimens (a) Al side, (b) enlarged portion of figure “a” (c) Cu side and (d) enlarged portion of figure c.

4. Conclusions

The present study deals with the extensive analysis on every aspect of USMW of Al-Cu dissimilar materials. This study includes the exploration of input parameters of the welding process on the outputs like T-peel strength failure loads, tensile shear and weld area with providing information during the process. The following conclusions can be extracted from this research:

- At various input parameter, AA1100 and UNS C10100 sheets are welded successfully.
- The interface temperature of 328.98 °C achieved during welding is the highest among all the observed results. It is obtained at weld pressure of 0.34 MPa, vibration amplitude of 68 μm and weld time of 0.41 sec. Initially, the temperature profile suddenly increases up to 0.28 sec, but as the relative motion between the sheets vanishes, the temperature comes to a steady state. Due to the sudden increase of interface temperature, the oxide film on the weld surface ruptures and extensive plastic deformation occurs.
- The maximum weld area of 79.19 mm$^2$ is obtained at a weld time of 0.41 sec, vibration amplitude of 68 μm, and weld pressure of 0.34 Mpa. It is because of denser micro-bonds formation at the highest vibration amplitude.
- From the fractographic study of weld surfaces, it is observed that for Al-Cu weld specimens, the number of scratch marks increases and it leads to the formation of cracks around the weld zone.

References

[1] Janaki Ram G D, Robinson C, Yang Y and Stucker B E 2007 Use of Ultrasonic Consolidation for Fabrication of Multi-Material Structures Rapid Prototyp. J. 13(4): 226–235.
[2] Zhang C Y, Chen D L, and Luo A A 2014 Joining 5754 Automotive Aluminum Alloy 2-Mm-Thick Sheets Using Ultrasonic Spot Welding Weld. J. 93(4): 131-138.
[3] Komiyama K, Sasaki T and Watanabe Y 2016 Effect of Tool Edge Geometry in Ultrasonic Welding J. Mater. Process. Technol. 229: 714–721.
[4] O’Brien R L 1997 Jefferson’s Welding Encyclopedia, American Welding Society.
[5] Seo J S, Jang H S and Park D S 2015 Ultrasonic Welding of Ni and Cu Sheets Mater. Manuf. Process. 30(9): 1069–1073.
[6] Kodama M 1989 Ultrasonic Welding of Non-Ferrous Metals Weld. Int. 3(10): 853–860.
[7] Hetrick E, Jahn R, Reatherford L, Skogsmo J, Ward S, Wilkosz D, DEVINE J, Graff K and Gehrin R 2005 Ultrasonic Spot Welding: A New Tool for Aluminum Joining Weld. J. 84(2): 26–30.
[8] Barnes T A and Pashby I R 2000 Joining Techniques for Aluminium Spaceframes Used in Automobiles: Part I—solid and Liquid Phase Welding J. Mater. Process. Technol. 99(1): 62–71.
[9] Yang J W, Cao B, He X C and Luo H S 2014 Microstructure Evolution and Mechanical Properties of Cu-Al Joints by Ultrasonic Welding Sci. Technol. Weld. Join. 19(6): 500–504.