Characterisation of Ultrasonic Welding of Al-Al with Dry, Methanol and Acetone Medium Between the Weldments

Abhyuday Singh Thakur, Parth Dasadiya, Akshay Nair, Harshvardhan Deshmukh, Vishvesh Badheka

Abstract*: The ultrasonic welding method is a solution to join alloys that have high thermal conductivity. In this study, the ultrasonic welding method was applied on Al 6061 T6 aluminium alloy and the effects of different lubricants at the interface were examined. A feasibility test was performed initially by varying parameters like pressure, amplitude, delay time, weld time, hold time, power, force, energy and stroke while keeping other parameters constant. The results of the test helped in setting up the actual parameters of the study. A comparative study amongst two different interface lubricants namely methanol and acetone was performed and compared with dry welding conditions. The lubricants were applied at the faying surface to better understand the effects of friction and relative motion between the foils. The highest tensile strength was observed in case of methanol (151.15 MPa), followed by acetone (145.26 MPa) and dry condition (98.05 MPa). In the case of methanol, lubrication increased the inter-metallic temperature leading to deformation at the surface allowing proper mixing of metals and thus, enhancing strength. Next, a microstructure analysis was performed indicating plastic deformation and grain refinement more in case of lubricants. Lastly, a fractographic image analysis was done to observe the various fractures visualized during tensile testing.

Index Terms*: Aluminium Alloy, Fractographic Image Analysis, Lubrication, Microstructure Analysis, Tensile Strength, Ultrasonic Welding.

I. INTRODUCTION

Ultrasonic welding is a solid state welding process or friction welding where amalgamation through simultaneous application of localised high frequency vibratory energy applied to work pieces being held together under pressure to create a solid state weld. Since, in this process no melting occurs it is an advantage over other solid state welding processes. It can join dissimilar metals (like Al to Cu) from thin sections to thicker sections, providing strong joints with good thermal and electrical conductivity. Odour and fumes generated are negligible as arcs and sparks are not generated. With less energy input (i.e., without heat of fusion) and the non-essential requirement of flux/consumables results in reduction of cost and work time. In this process, generally the thinner sections are placed next to welding tip and thicker sections of weldments to anvil side overcoming the limitation of thickness. This welding process uses high-frequency vibration to weld metals at reasonable amount of pressure [1]. Also, the process doesn't require any cleaning methods before the welding process.

II. THEORY

For complex welding to be carried out, the ultrasonic welding is considered one of the best techniques. In this method, the parts are jammed between the anvil and the horn or sonotrode (welding tip) to a transducer generating (generally 25 kHz ~ 30 kHz) from high frequency electrical energy to amplification of vibratory motions being emitted. This results in the melting of parts between the interface due to generation of high heat and friction, making it a contact thus, creating a joint. It is faster than other conventional process by means of drying time between the parts i.e., long period of time to dry or cure the welds. This process can be automated making the joints precise and clean rarely requiring machining. Lower thermal input on parts enables multiple welding to be carried out on them. Likewise, it is reported that when friction stir welding (FSW) employed to weld Al alloys then brittle and bulk inter-metallics (IMCs) are formed with micro cracks at the interface zone [2].

Increase in the demand of Aluminium alloys for the joining processes has been an interesting area for the development in the effort to reduce weight with optimum economics in automobile sector is a vital solution i.e., Ultrasonic Welding can be an effective method than resistance welding which is studied with set of observations being carried out in Al-Al samples. Higher thermal conductivity, electrical conductivity and large coefficient of thermal expansion rate may result in higher input of power consumption and the tendency to have cracks in the joint. Mechanical test by testing the strength of the joint has been examined in the study of lap joint of Aluminium to Aluminium (1mm thickness). The butt welding of 10mm thick aluminium sheet has also been studied.

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Ultrasonic welding between Aluminium and Copper has also been studied. Further, Ultrasonic Consolidation (UC) is a process which is also an additive manufacturing process which joins metals to make objects from 3-D model data, usually layer upon layer. The coefficient of friction of Al alloys is further reported to decrease when lubricants like ethanol methanol and acetone is arranged to adhere to the friction surfaces during welding of alloys. Ultrasonic welding is used to weld the joining of A6061 aluminium alloy for automobiles.

Unfortunately, joining of these alloys by traditional fusion welding process produces bulk and brittle inter-metallic compounds (IMCs), average strength and high degree of distortion [3]. The coefficients of friction on metal surfaces are also observed minimal when lubricants are at the faying surfaces. Vibration energy and weld time are the two key factors in UW. Hence, ultrasonic welding is a short weld time and low energy consumption technique. In the present study, we investigated ultrasonic welding process under effects of possibilities of joining and properties occurring at joining interface under the influence of lubricants applied at faying surface.

III. EXPERIMENTAL WORK

A. Material Specification

If Aluminum having grade of Al 6061T6 having Brinell Hardness No. of 95, was selected as our welding sample. Chemical composition and mechanical properties are as listed below in Table 1 respectively.

Table I Chemical composition and mechanical properties of Al 6061T6

Component	Wt.%	Mechanical Properties	Metric System
Al	95.8-98.6	Ultimate Tensile Strength	310 MPa
Cr	0.04-0.35	Tensile Yield Strength	276 MPa
Cu	0.15-0.4	Elongation at break	17%
Fe	Max. 0.7	Modules of Elasticity	68.9 GPa
Mg	0.8-1.2	Ultimate Bearing Strength	607 MPa
Si	0.4-0.8	Poisson's Ratio	0.33
Ti	Max.0.15	Fatigue Strength	96.5 MPa
Zn	Max.0.25	Shear Modulus	26 GPa

B. Specimen Dimensions

Fig. 1 shows the specimen, which was prepared by cutting 1mm thick sheet having dimension 100mm * 25mm. overlapping length of lap joint was kept around 20mm.

C. Experimental Set-up

Experimental setup shown in Fig. 2 was used during ultrasonic welding. This ultrasonic welding facility was provided by Roop Telesonic Ultrasonix Ltd., GIDC, Gandhinagar.

Ultrasonic welding machine comprised of the following components:-

1. Ultrasonic generator – Series SG-22, 3000W, 20 kHz. This composnent is used to generate electrical signal having 20 kHz frequency and passes it to the piezoelectric transducer.

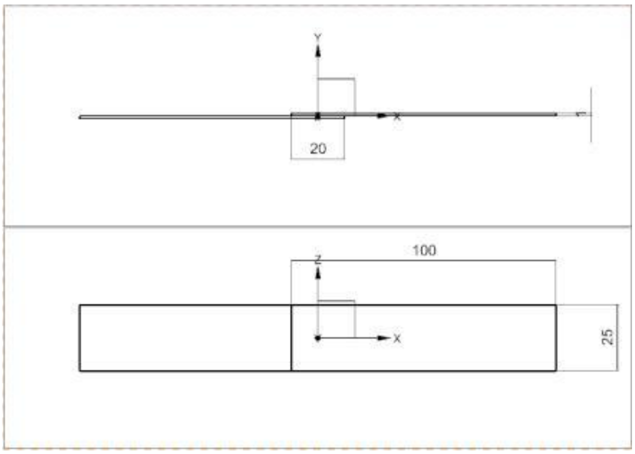

Fig. 1 Dimensions of Al 6061 T6 specimen

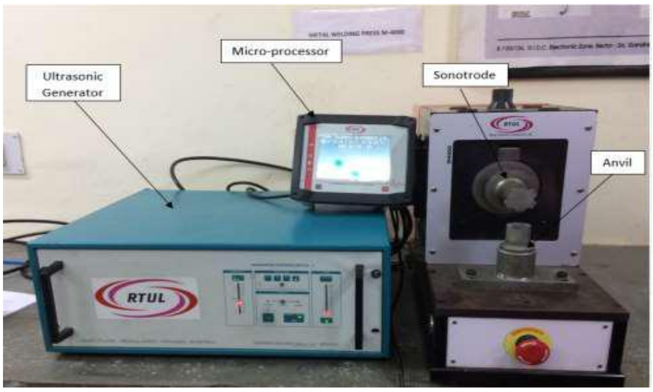

Fig. 2 Ultrasonic Welding Experimental Set-up

2. Piezoelectric transducer (converter) –This component uses piezoelectric material to convert electrical signals into mechanical vibrations.
3. Microprocessor – It is used to set the value of input parameters and also to display output parameters after a particular weld.
4. Pneumatic press – Model M4000 (max. capacity = 4000N). It is used to apply force on the weld specimen during a weld.
5. Booster – Booster is used to amplify the mechanical vibrations. In our case, the booster used had an amplification of 1.5x. However, amplification from 0.5 to 2.5 were also available.
6. Sonotrode – It is the main tool for this welding process through which pressure is applied. The sonotrode used in the study was made up of stainless steel and had six differently knurled tips.

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IV. PROCEDURE

The experiments were carried out using an ultrasonic welding machine with the power 1308W, frequency 20 kHz, net energy 2460W.s, force 3241N, pressure 5bar, and amplitude 30µm.

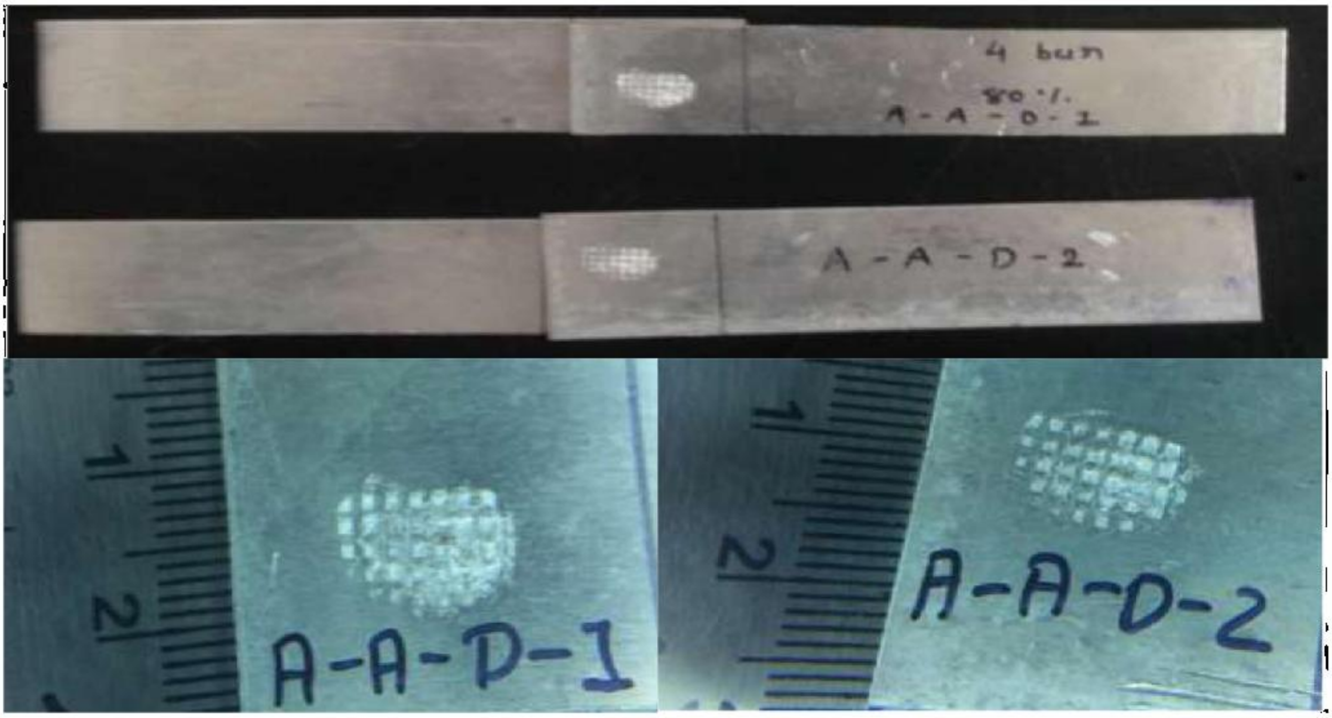


Fig. 3 Images of Al-Al ultrasonic welded with Dry condition and their magnified images

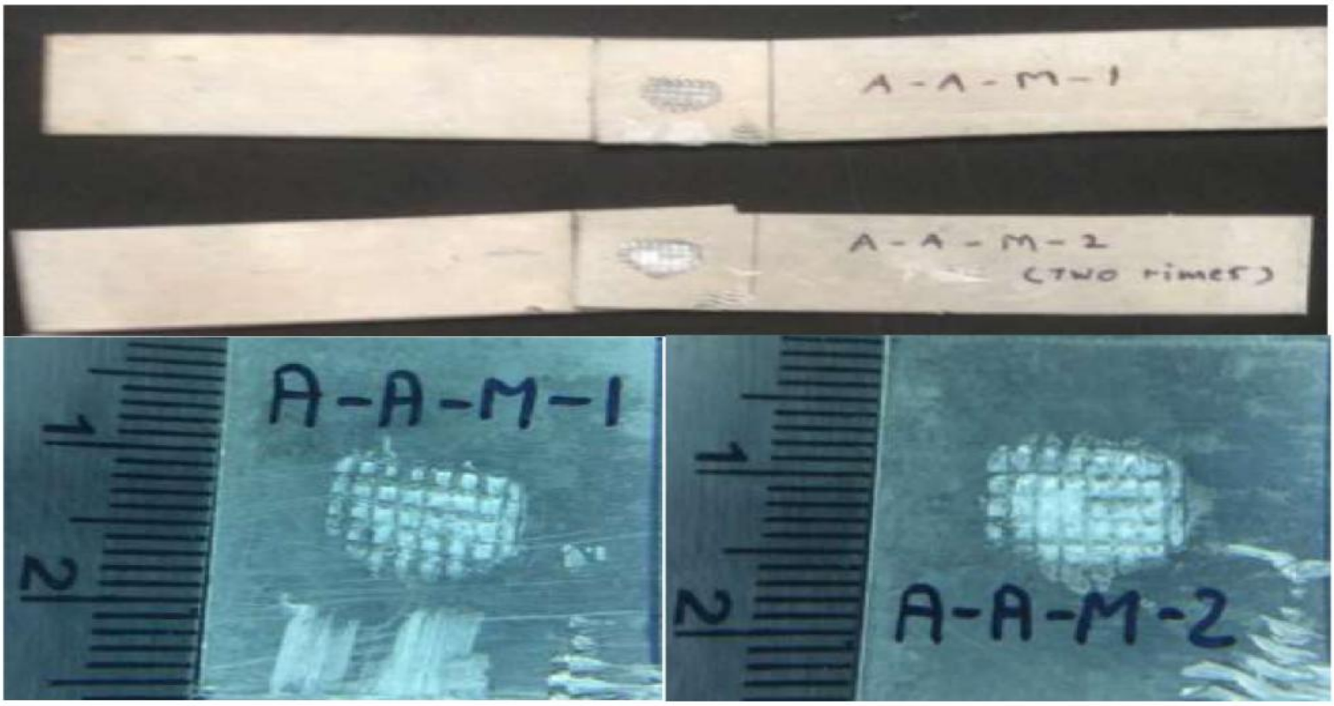


Fig. 4 Images of Al-Al ultrasonic welded with methanol at interface and their magnified images

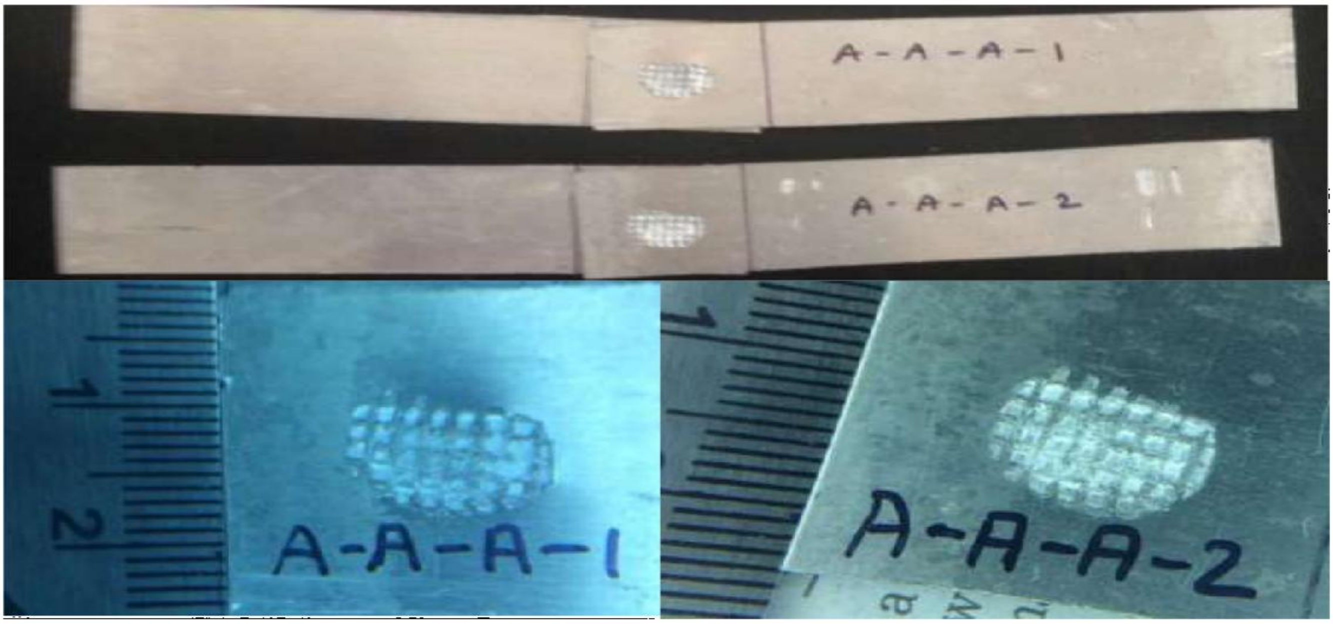
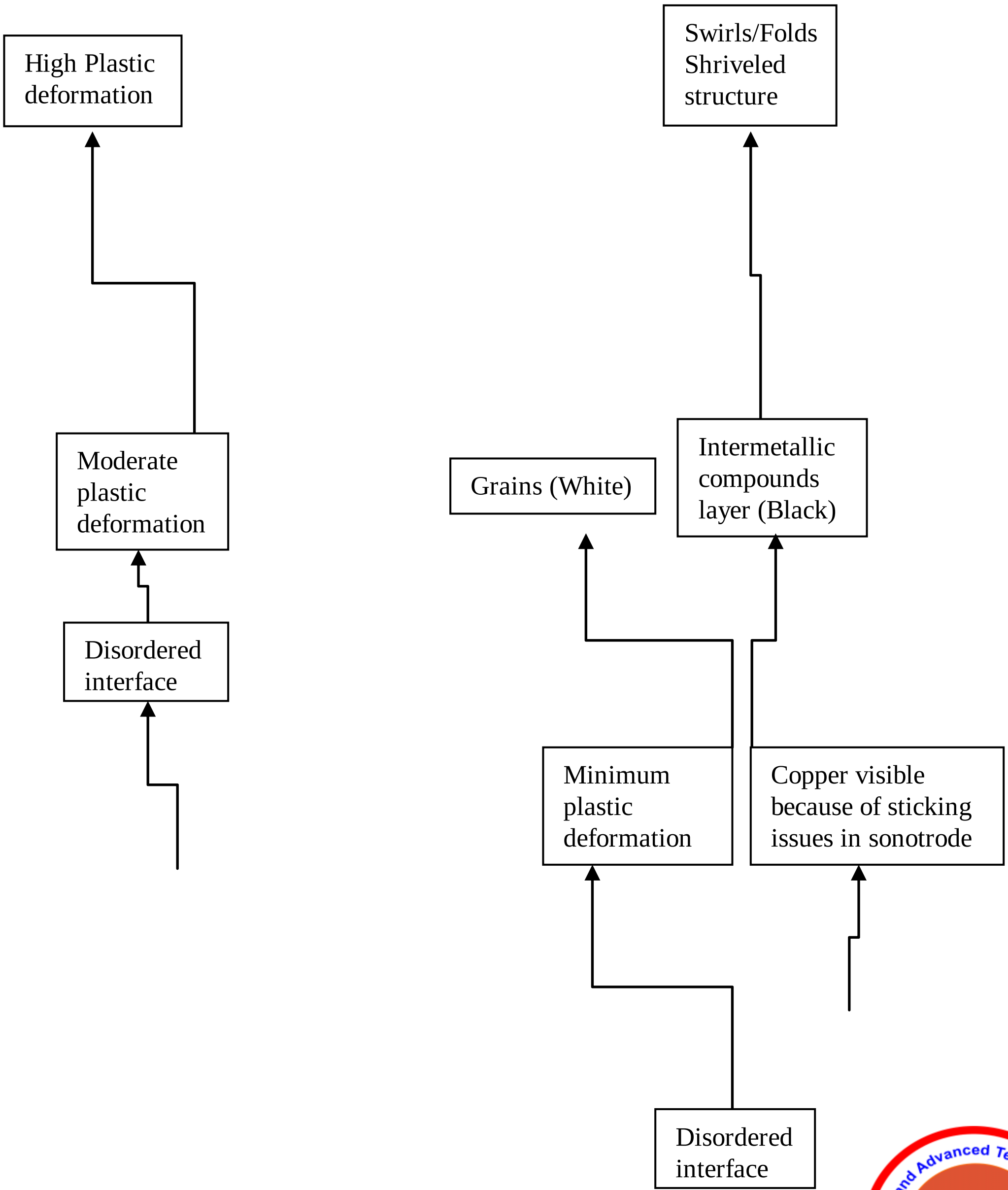


Fig. 5 Images of Al-Al ultrasonic welded with acetone at interface and their magnified images



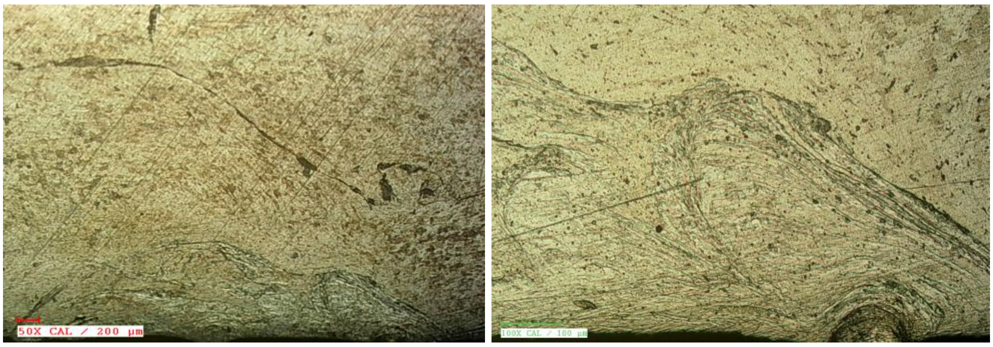


Fig. 1 Cross sectional view of microstructures of Methanol conditions under magnification of 50X (Left) & 100X (Right)

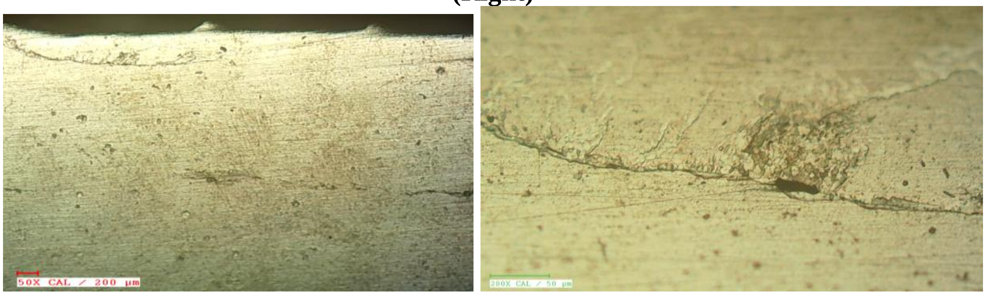


Fig. 2 Cross sectional view of Microstructures of Acetone Condition under magnification of 50X (left) & 200X (Right)

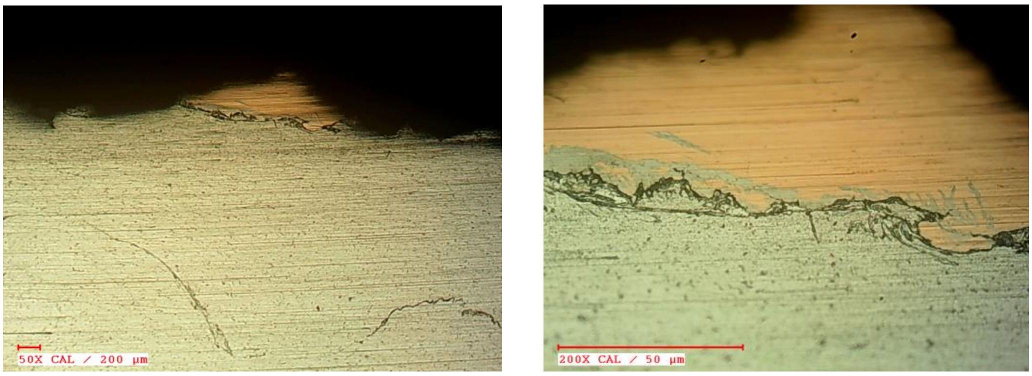


Fig. 3 Cross sectional view of Microstructures of Dry condition under magnification of 50X (left) & 200X (right)

The direction of ultrasonic vibration was so arranged so that it was perpendicular to the longitudinal direction of the two joined specimens. The upper hone (sonotrode) of ultrasonic welding machine which is fitted with a surface machined joining attachment is lowered onto the foils to be joined which are fixed on surface machined and anvil. Thus, required pressure is applied to produce joining after the required application time over an area of 11x8 mm^2. All the data presented is for welds produced in 1mm thick Al6016 aluminium alloy with no cleaning and surface preparation prior to joining [4]. Methanol and acetone were applied at the faying surfaces to reduce the coefficient of friction of Al alloys during the welding process. The whole weld area was scanned by cutting out the weld into two halves and examining the cut cross section. For lubrication condition, acetone and methanol were applied on the bottom specimen and the gap was ultimately filled by it due to capillary effect. Then the foils were joined by pressing and adjusting by applying pressure between the foils. The welded joints were sectioned across their center parallel to the direction of vibration and perpendicular to the longitudinal direction of the foils to be joined and weld interface microstructure were characterized.

A. Feasibility Trials

Initially, certain trials were carried out to obtain a set of parameters which are feasible. These sets of parameters were obtained by changing any one parameter and keeping other constant. Set of parameters those were selected for actual trials are highlighted in table 2.

Table II Feasibility test taken for Al-Al Ultrasonic Welding

Top metal	Down Metal	Pressure (bar)	Amplitude (µm)
Al	Al	5	30

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Delay Time (s)	**Weld Time (s)**	**Hold Time (s)**	**Max. Power (W)**
1	2.5	1	1620
Net Energy (W.s)	**Max. Force (N)**	**Stroke (mm)**	
3643	3231	19.32	

From the above tabulated trial, the set of parameters were chosen for our actual trials as it was the optimal solution. The selection was based on visual inspection of surface and strength.

Table III Output variables for Al to Al welds under Dry, Methanol and Acetone lubrication conditions

Sr. no.	Stroke (mm)	Max. Power (W)	Net energy (J)	Max. Force (N)
AAD1.	19.36	1142	2383	1923
AAD2.	19.48	1351	2627	1945
AAM1.	19.36	1386	2768	1937
AAM2. (2 times)	19.36	1196	2622	1947
AAA1.	19.32	1305	2497	1927
AAA2.	19.44	1259	2592	1989

A. Aluminium to Aluminium Ultrasonic Welding

The ultrasonic welding was carried out using output variables as tabulated in table 3 which gives variables for dry, methanol and acetone conditions. Fig. 3, 4 and 5 shows ultrasonically welded samples for three different surface conditions i.e. dry, methanol and acetone and their respective magnified view for welded area.

B. Tensile Testing of Welded Specimens

The tensile test was carried out on the universal testing machine (20 TON), CMT-5205 at IIT Gandhinagar keeping the strain rate constant as 0.1 mm/min.

Table IV Tensile testing results of Al-Al joint

Sample No.	Max. Power (W)	Net Energy (J)	Tensile Strength (MPa)
4.D	1351	2627	98.05
4.M	1386	2768	151.15
4.A	1305	2497	145.26
Sample No.	**Upper Yield Strength (MPa)**	**Lower Yield Strength (MPa)**	**Max. Force (N)**
4.D	20.64	20.59	2451.27
4.M	31.77	31.69	3778.82
4.A	34.41	34.38	3631.38

V. RESULTS

A. Tensile strength in Dry, Acetone, Methanol lubrication conditions

The results in Table 4 depict the tensile strength observed under dry, methanol and acetone lubrication medium conditions on the surface. The order of the tensile strength is: - Methanol > Acetone > Dry.

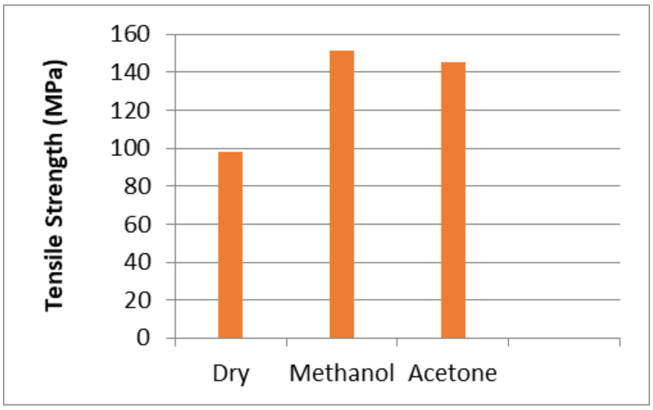

Fig. 4 Tensile strength of Al-Al weld with different surface conditions

From chart shown in Fig. 6, we can see that ultrasonic welded joints with methanol as lubricant shows more promising results compared to dry and acetone conditions. Hence, the results indicate that that use of lubrication has increased the tensile strength of the weld compared to dry condition as the relative motion increases the interface temperature resulting in interface strength enhancement [5, 6]

B. Microstructure Analysis

Microstructure analysis was first sectioned by cutting the specimen according to the standards. The sectioned specimen was polished with the help of emery paper. The emery paper was of different grades starting with fine to coarse grades. Next, the specimen was dipped in the etchant Kellers etch (190ml distilled water, 5ml nitric acid, 3ml hydrochloric acid (HCl), 2ml hydrofluoric acid) immersed for 30 seconds. Then it was cleaned by distilled water for further shine and clear appearance. It was then observed under optical microscope (Range 50X-1000X).

The images were taken in 50X, 100X and 200X. For better visuals, we have taken the selected magnifications as mentioned for specified samples. From Fig. 7, Fig. 8 and Fig. 9, we can observe that when welding with methanol as lubricant, the plastic deformation is highest as shown in Fig. 7. Moderate deformation is visualised in acetone as a lubricant (Fig.8). In the dry condition, less plastic deformation is observed as shown in Fig. 9. Copper is visible in the structure as the sonotrode grips have a problem of sticking metals which made the visibility of copper in welding zone.In acetone conditions, the level is moderate for the plastic deformation.

The shrivelled structure (swirls/cortices) or folded grain structure in the methanol condition shows plastic deformation due to high temperature achieved in the interface. Several complex features like swirls, holes, vortices can be observed from the microstructures, which can be caused by several reasons like the collapse of the crest of the macroscopic interface waves during forging stage resulting in swirls at the interface. Majorly swirls reported arise due to intercalation of the two foils occurs due to interface folding at an intermediate land scale [4,7]. Also, slight inter-metallic compound layers are observed under dry and acetone conditions at metal to metal interface.

C. Fractographic Analysis

The photograph of fractured surface during tensile testing is observed below in the photographs showing the breakage of welded joint.

As we can observe from the fracture surface of dry condition as shown in Figure 10, in which the nugget pull out is observed showing nugget strength but not the foils which have been joined. In methanol condition as shown in Figure 11, the nugget has not been pulled out as it remains within the foil but the tensile test confirms the highest strength in methanol condition. In acetone condition as shown in Figure 12, we could see a partial nugget pull out which may or may not get pulled out which couldn't be taken out in tensile testing machine as the necking started and the load applied was stopped. Thus, it may show equivalent strength to that of methanol condition. In methanol condition, the defect is interfacial defect whereas in acetone and dry condition the defect is nugget pull out.

VI. CONCLUSIONS

In this study, ultrasonic welding of Aluminium alloy in which the effects of welding under dry condition, acetone as a lubricant, methanol as a lubricant between the weld interface was conducted for which investigation with the examination of joint strength by tensile testing , microstructure analysis and fractographic analysis was carried out. The results obtained can be summarized as follows:-

- The weld strength of joint is increased when lubricant is applied. Within the scope of present tests, the order of tensile strength can be reported as Methanol (151.15 MPa)> Acetone > Dry Condition.
- Microstructure analysis shows plastic deformation which is related to the increase in temperature and coefficient of friction as reviewed from studies. Also, some intermetallic compounds are found in dry and acetone conditions at metal to metal interface.
- Fractographic analysis also reports the interfacial defects in methanol, in spite of high strength in methanol lubrication condition at the interface during tensile test. Whereas defects like nugget pull out were observed in acetone although the tensile strength was close to the methanol lubrication condition. In dry condition, a complete nugget pull out was observed.
- The main reason for achieving the highest joint strength is because of the lubricant, as it increases the relative motion between the two foils due to which plastic deformation occurs and so the weld strength was maximised in case of lubricants applied at the weld interface. Relative motion between the foils increases the interface temperature, thus, resulting in uniform mixing of alloys at the interface and thus resulting in highest strength in tensile testing.

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REFERENCES

1. Lienert, T., et al., ASM Handbook, Volume 6A, Welding Fundamentals and Processes. system, 2011. 286: p. 287.
2. Patel, V., S. Bhole, and D. Chen, Ultrasonic spot welded AZ31 magnesium alloy: microstructure, texture, and lap shear strength. Materials Science and Engineering: A, 2013. 569: p. 78-85.
3. Zhao, Y., D. Li, and Y. Zhang, Effect of welding energy on interface zone of Al–Cu ultrasonic welded joint. Science and Technology of Welding and Joining, 2013s. 18(4): p. 354-360.
4. Watanabe, T., et al., Ultrasonic welding of Al-Cu and AI-SUS304. Study of ultrasonic welding of dissimilar metals (1st Report). Welding international, 1999. 13(11): p. 875-886.
5. Hiraishi, M. and T. Watanabe, Improvement of ultrasonic weld strength of Al–Mg alloys by alcohol adhesion–ultrasonic welding of Al–Mg alloys. Welding international, 2004. 18 (5): p. 357-363.
6. Watanabe, T., et al., Ultrasonic welding of heat-treatable aluminium alloy A6061 sheet. Welding International, 2009. 23(9): p. 633-639.
7. Bakavos, D. and P. Prangnell, Mechanisms of joint and microstructure formation in high power ultrasonic spot welding 6111 aluminium automotive sheet. Materials Science and Engineering: A, 2010. 527(23): p. 6320-6334.
8. Yang J, Cao B. Investigation of resistance heat assisted ultrasonic welding of 6061 aluminum alloys to pure copper. Mater Des. 2015;74:19–24.10.1016/j.matdes.2015.02.028
9. Koellhoffer S, Gillespie JW, Advani SG, et al. Role of friction on the thermal development in ultrasonically consolidated aluminum foils and composites. J Mater Process Technol. 2011;211:1864–1877.10.1016/j.jmatprotec.2011.06.011
10. Patel VK, Bhole SD, Chen DL. Improving weld strength of magnesium to aluminium dissimilar joints via tin interlayer during ultrasonic spot welding. Sci Technol Weld Join. 2012;17:342–347.10.1179/1362171812Y.0000000013
11. Bloss MC. Ultrasonic metal welding: the weldability of stainless steel, titanium, and nickel-based superalloys. Columbus (OH): The Ohio State University; 2008.
12. Yang JW, Cao B, He XC, et al. Microstructure evolution and mechanical properties of Cu–Al joints by ultrasonic welding. Sci Technol Weld Join. 2014;19:500–504.10.1179/1362171814Y.0000000218
13. Kim TH, Yum J, Hu SJ, et al. Process robustness of single lap ultrasonic welding of thin, dissimilar materials. CIRP Ann Technol. 2011;60:17–20.10.1016/j.cirp.2011.03.016
14. De Vries E. Mechanics and mechanisms of ultrasonic metal welding. Columbus (OH): The Ohio State University; 2004.

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