Ultrasonic welding aluminium alloy 7075 to titanium alloy Ti-6Al-4V: parameter optimization and mechanical property

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Abstract. The demand for lightweight materials has increased for automobile and airplane industry. Traditional fusion welding techniques always generate brittle intermetallic compound (IMC). Ultrasonic spot welding (USW) is a promising technique to joint dissimilar metals and suppress IMC formation. This study aims to investigate the role of process parameters as well as surface roughness on the joint shear strength of titanium alloy Ti-6Al-4V and aluminium alloy 7075. Process parameters namely penetration depth, welding time and pressure were varied and the joint shear strength obtained was investigated. Results obtained were indicative that penetration depth and pressure should be used with highest values and surface roughness with lowest. In summary, optimal parameters are USW penetration depth 0.7 mm, welding time 1.8 s, pressure 0.7 MPa and surface roughness of AA7075 0.1457 Ra µm and Ti-6Al-4V 0.0651 Ra µm (both ground by P1200 SiC paper) in this study.

1. Introduction
Lightweight materials, such as titanium alloy and aluminium alloy, have high ratio of strength to weight, which can reduce weights of automobiles and airplanes with sufficient mechanical properties and thus can improve fuel economy, reduce CO₂ emissions and save overall cost. Welding titanium alloy and aluminium alloy is necessary but difficult due to their inherent different properties. For example, the melting points of Al and Ti are 660 °C and 1668 °C, respectively. The difference brings problems to concurrently melting of base materials. The density of Al and Ti are 2.70 g/cm² and 4.51 g/cm², respectively. At high temperature, Al liquid tends to float upon Ti liquid. Thermal conductivity of Al and Ti are 247 W/(m·K) and 11 W/(m·K), respectively. The difference of thermal conductivity leads to melting volume difference and cooling rate difference during welding.

Besides the above problems, the often observed intermetallic (IMC) which is hard and brittle also increase the dissimilar welding difficulty. As fusion welding, laser welding, laser roll welding, and arc welding always generate brittle intermetallic compound (IMC), such as Ti₃Al₅, Ti₅Al, TiAl and Ti₃Al₅, at the joint interface due to high reaction rate of liquid phase. Casalino et al. [1] suggest IMC mostly made of Ti₃Al₅ is formed in laser butt joining of T40 and 5754 Al alloy. Ozaki et al. [2] observed Ti₅Al₈ and TiAl during laser roll welding of commercial pure titanium H4600 to A5052 aluminium alloy. As a subdivision of both liquid-phase welding and solid-state welding, diffusion bonding produces IMC at interface of Al/Ti alloy dissimilar joining. Sohn et al. [3] identified Al₅Si₁₂Ti₁ and Al₁₂Si₃Ti₅ in diffusion bonding of commercial pure Ti to 1050 Al using an Al-10.0wt.%Si-1.0wt.%Mg filler at 620°C. Friction stir welding (FSW) is a solid state welding, whose process temperature is lower than that of the fusion welding. However, IMCs still occasionally form in FSW of Al/Ti and their alloys. Choi et al. [4] investigated FSW of pure Ti and pure Al. They concluded that the
formation order of the Ti and Al intermetallic compound layer is TiAl₃, TiAl and Ti₃Al. The formation of TiAl₃ is attributed to the lowest free energy of formation of TiAl₃, and the formations of TiAl and Ti₃Al are attributed to the Al diffusion from the TiAl₃. Because IMC can deteriorate the quality of welded joint, the formation of IMC should be prevented or, at least, its thickness should be kept to the lowest possible value. Some works suggest that acceptable joint strength can be achieved in the condition that IMC layer thickness is less than 10 µm [5].

Ultrasonic spot welding is a promising technique in the dissimilar joining of Al/Ti and their alloys. In ultrasonic welding process, processing parameters and welded materials play an important role in controlling the formation of IMC of Al/Ti and their alloys. Zhang et al. [6] investigated aluminium alloy AA6111–TiAl6V4 dissimilar joint using high power ultrasonic spot welding (USW). No visible intermetallic compounds were found, even using transmission electron microscopy. However, they also claimed that by prolonged isothermal heat treatment at high temperature, IMC can be made to form in Al–Ti USW. Wang et al. [7] investigated USW of AA 5754 and Ti64. Using pure Al interlayer, TiAl₃ was identified by XRD. However, using same USW parameters without Al interlayer, no IMC was found by XRD. Sridharan et al. [8] claimed that bond formation occurred without any intermetallic formation. Zhang et al. [9] observed no obvious intermetallic reaction layer in the AA2139–TiAl6V4 welds by USW, even using transmission electron microscopy. According to Zhang et al. [6], no visible IMC formation is due to kinetics of the process rather than solubility limit effects alone. The inter-diffusion rate of Al-Ti system and energy barrier of IMC nucleation are both important to IMC nucleation speed. However, inter-diffusion in the Al–Ti system has a relatively high activation energy, the ultrasonic welding energy input is low, and the welding time is short, all of the factors limited the growth of IMC layer. The objective of this paper is to investigate effects of process parameters on mechanical property of shear strength of USW joint.

2. Experimental procedure

2.1. Materials

The materials used in this research were Ti-6Al-4V in dimension of 1mm×10mm×48mm and Aluminium Alloy 7075 (AA7075) - T6 in dimension of 1.02mm×10mm×48mm. The true stress-strain curve of the received Ti-6Al-4V sheet is in figure 1(a). The yield strength, ultimate tensile strength and maximum strain are about 1000 MPa, 1100 MPa, and 0.1 for Ti-6Al-4V alloy, respectively. AA7075 is solution heat treated and artificially aged (T6) with chemical composition shown in table 2. The true stress-strain curve of the received AA7075-T6 is in figure 1(b).

| Table 1. Chemical composition of base material AA7075-T6. |
|------------------|---|---|---|---|---|---|---|---|
|                | Al | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti |
| Bal.            | 0.07 | 0.29 | 1.6 | 0.03 | 2.5 | 0.19 | 5.70 | 0.02 |

Figure 1. True stress-true strain curve obtained at strain rate 10⁻³ s⁻¹: (a) T-6Al-4V, (b) AA7075.
2.2. Ultrasonic spot welding (USW) process
AA7075-T6 with dimensions of 1mm×10mm×48mm was welded on top of the Ti-6Al-4V with dimensions of 1.02mm×10mm×48mm. The overlap length was about 15 mm. The schematic diagram is shown in figure 2. Because of the existence of oxide films of AA7075 and Ti-6Al-4V, such as Al₂O₃ and TiO₂, faying surfaces were gradually sanded to grit number of P1200 by SiC paper to remove the oxide film and reduce surface roughness. Faying surface were washed by ethanol before USW. USW process was performed on ultrasonic metal welding SPM 4200 (serial no. NP-M-20-4200) manufactured by Guangzhou SUNTOP Ultrasonic Co Ltd. The welding power of the machine is 2.2kW and the vibration frequency is 20kHz.

![Figure 2. A schematic diagram of ultrasonic spot welding (USW) of AA7075 and Ti-6Al-4V.](image)

After preliminary experiments, a DOE screening, using 13 different group of process parameters and repeating 3 times for each group, was randomly conducted to study the USW factors. DOE screening parameters are shown in table 2. The USW factors are pressure, welding time and penetration depth. The factor pressure is the pressure of compressed air, which is used by the USW machine to drive the sonotrode downward. The factor welding time is the vibration time during welding process. The factor penetration depth is the maximum depth that sonotrode tip can penetrate into the soften aluminium. To analyse effect of welding time, 15 samples were welded by USW process. Holding pressure at 0.7MPa and penetration at 0.7mm, 5 levels of welding time from 1.4s to 2.2s with 0.2s increment were used to join AA7075 plate to Ti-6Al-4V plate.

Effect of surface roughness on weld shear strength in USW process were analysed. AA7075 plate and Ti64 plate were gradually ground to different roughness with grit size P400, P800 and P1200 SiC papers. Then plates were welded by USW process at pressure 0.7MPa, penetration depth 0.6mm, and welding time 1.6s.

2.3. Tensile shear test
Tensile shear test was conducted on INSTRON 5982 machine with a constant speed of 1mm/min. A typical test sample after welding and a typical test sample in tensile shear test are shown in figure 3. AA7075 plate and Ti64 plate were attached to each sample to ensure the applying force was parallel to ultrasonic welded surface. The red rectangular area was taken as weld area and was measured for every sample. Shear strength was calculated as shear force divided by the red rectangular area.

![Figure 3. Sample for tensile shear test.](image)
3. Results and discussion

3.1. Mechanical shear tests
Tensile shear strengths of USW samples are presented in Table 2. For each USW parameter, 3 samples were welded. Their tensile shear strengths were marked as shear strength 01, strength 02 and strength 03. There were 13 different groups of USW parameters, thus 39 weld joints in total were shear tested.

Table 2. DOE screening of USW parameters on joining Ti-6Al-4V and AA7075-T6.

| Pressure, MPa | Welding time, s | Penetration depth, mm | Shear strength 01, MPa | Shear strength 02, MPa | Shear strength 03, MPa |
|--------------|-----------------|-----------------------|------------------------|------------------------|------------------------|
| 0.5          | 0.8             | 0.6                   | 10.21                  | 4.04                   | 0                      |
| 0.5          | 0.8             | 0.7                   | 0.03                   | 8.98                   | 7.13                   |
| 0.5          | 1.1             | 0.5                   | 0.03                   | 0                      | 0                      |
| 0.5          | 1.4             | 0.5                   | 13.06                  | 0                      | 0                      |
| 0.5          | 1.4             | 0.7                   | 0                      | 8.96                   | 7.27                   |
| 0.6          | 0.8             | 0.5                   | 2.7                    | 0                      | 0                      |
| 0.6          | 1.1             | 0.6                   | 14.25                  | 6.19                   | 4.75                   |
| 0.6          | 1.4             | 0.7                   | 7.75                   | 8.91                   | 15.04                  |
| 0.7          | 0.8             | 0.5                   | 0                      | 0                      | 0                      |
| 0.7          | 0.8             | 0.7                   | 9.34                   | 5.66                   | 6.66                   |
| 0.7          | 1.1             | 0.7                   | 11.43                  | 12.81                  | 12.99                  |
| 0.7          | 1.4             | 0.5                   | 8.8                    | 0                      | 0                      |
| 0.7          | 1.4             | 0.6                   | 10.94                  | 6.31                   | 6.07                   |

USW pressure, welding time and penetration depth all have positive effects on weld shear strength within the studied range. Based on statistical results of shear strengths in DOE screening, effects of USW parameter on shear strength are analysed by MINITAB and results are shown in figure 4.

Figure 4. Processing parameters effects on shear strength of USW joint: (a) Shear strength vs. pressure and welding time, (b) Shear strength vs. penetration and welding time, (c) Shear strength vs. penetration and pressure. (d) Main effects plot for shear strength by fitted means.
3.2. Effect of pressure

In the studied pressure range, from 0.5MPa to 0.7MPa, shear strength increase as pressure increase while holding penetration depth and welding time constant. During USW process, ultrasonic vibration frequency and vibration distance is determined by USW machine and should no vary. If pressure is increased, the friction force at the interface of AA7075 and Ti64 will be increased, leading to the increase of input vibration energy at the surface. With little energy dispersed into atmosphere, the increased vibration energy transforms into higher material temperature. The strengths of interface materials are reduced due to temperature increase. With higher pressure and reduced material strength, plastic deformations of interface materials happen more easily to form intimate contact between metallic surfaces which leads to a solid state bond and joint strength increase.

Because 0.7MPa is the maximum value that can be achieved at present lab condition, the analysis of shear tests of DOE screening samples leads to the conclusion that the optimal welding pressure is 0.7 MPa for present ultrasonic welding.

However, it should be noted that too high pressure would lead friction force too large, causing relative friction motion in the specimen, or even reduces the effective amplitude. The bonding area is reduced and weakens the contact interface surface for the material being crushed. [10]

3.3. Effect of penetration depth

In the studied range of penetration depth from 0.5mm to 0.7mm, shear strength increase as penetration depth increase while holding pressure and welding time constant. During USW process, sonotrode sinks into softened AA7075 plate. Penetration depth prevent sonotrode go too deeply into welded plate by limiting sonotrode downward length. Sonotrode teeth may not firmly hold AA7075 plate if penetration depth is small. When penetration depth is reached in middle of USW process, the sonotrode stops moving downward. The pressure on AA7075 plate would be released gradually due to softening effect, causing an effect similar to gradually decreased pressure, and thus reduced joint shear strength. In this point of view, a penetration depth that is large enough is crucial to a good USW bonding. However, AA7075 cross-section area would be decreased with a large penetration depth, causing the decrease of load bear ability of welded AA7075 plate. AA7075 plate may even be broken into pieces with too large penetration depth.

At the penetration depth of 0.5mm, samples generally yield low shear strengths due to not sufficient penetration depth. Despite of two samples that yield 0.03MPa and 2.7MPa (relatively low comparing with shear strength of other samples), 11 samples out of 15 test samples are not welded with penetration depth of 0.5mm. According to analysis of figure 4, shear strength increase as penetration depth increase within the studied range. Preliminary experiments showed that AA7075 would be broken into pieces when penetration depth is higher than 0.7mm. Thus, the penetration depth of 0.7mm is the applicable highest value. The optimal value of penetration depth is 0.7mm for present USW process.

3.4. Effect of welding time

In the studied range of welding time from 0.8s to 1.4s, shear strength increase as welding time increase while holding penetration depth and pressure constant. Enough welding time should be used in USW process, to break surface oxides and bring Ti and Al alloys surfaces into intimate contact to form metallurgical bond. Sufficient welding time also promote elements diffusion across interface of dissimilar Ti and Al alloys.

Since shear strength increase as welding time increase, and 1.4s has no reach the machine limit, a further analysis of variance (ANOVA) is conducted focusing on welding time, while holding pressure at 0.7MPa and penetration depth at 0.7mm. The ANOVA experiments and their results are shown in table 3 and in figure 5. The data of welding time of 0.8s and 1.1s are from previous DOE screening analysis.
Table 3. ANOVA analysis of USW\(^a\) welding time on joining Ti-6Al-4V and AA7075-T6.

| Welding time, s | Strength 01, MPa | Strength 02, MPa | Strength 03, MPa |
|----------------|------------------|------------------|------------------|
| 1.4            | 18.06            | 14.76            | 10.21            |
| 1.6            | 14.58            | 12.34            | 12.05            |
| 1.8            | 20.72            | 12.40            | 13.08            |
| 2.0            | 5.83             | 14.9             | 14.19            |
| 2.2            | 16.26            | 3.65             | 20.69            |

\(^a\) other process parameter were 0.7MPa pressure and 0.7mm penetration depth.

In figure 5, beyond the DOE screening studied range from 0.8s to 1.4s, in higher welding time range from 1.4s to 2.2s, average shear strength gradually increase as welding time increase and approximately reach a stable value as welding time is higher than 1.4s. The highest shear strength and highest average shear strength are taken from samples with welding time of 1.8s. At higher welding time, such as 2.2s, shear strength of weld is also high. However, at such high welding time, USW welds may be re-broken by the ultrasonic vibration, leading to a decrease in shear strength of weld. Based on the ANOVA analysis, the optimal welding time is 1.8s for present ultrasonic welding.

3.5. Effect of surface roughness

The surface roughnesses of AA7075 and Ti-6Al-4V ground by P400, P800 and P1200 grit size SiC papers are present in figure 6. As increase of grit number of SiC paper that is used for AA7075 or Ti-6Al-4V, the surface roughness decrease. Using SiC paper with the same grit number to grind AA7075 and Ti-6Al-4V, the obtained roughnesses of AA7075 and Ti-6Al-4V are different. With higher hardness and lower "spring back" effect during grinding, Ti-6Al-4V is ground to a lower roughness than that of AA7075 under the same grinding condition. The studied roughness range of Ti-6Al-4V is from 0.0651 Ra \(\mu\)m to 0.2264 Ra \(\mu\)m, while the roughness range of AA7075 is from 0.1457 Ra \(\mu\)m to 0.5211 Ra \(\mu\)m.

Figure 6. Surface roughnesses of AA7075 and Ti-6Al-4V plates which are finally ground by P400, P800 and P1200 grit size SiC papers.
The grit number of SiC paper that are used on AA7075 or Ti-6Al-4V, the corresponding roughness obtained, and the shear strength of USW welds manufactured by AA7075 and Ti-6Al-4V plates with corresponding surface roughness are shown in table 4. For un-welded samples, their strength is noted as 0MPa.

| Grit number,  | AA7075 roughness, Ra µm | Grit number, Ti-6Al-4V roughness, Ra µm | Shear strength, MPa |
|---------------|-------------------------|-----------------------------------------|---------------------|
| 1200          | 0.14565                 | 400                                     | 0                   |
| 1200          | 0.14565                 | 400                                     | 9.7                 |
| 800           | 0.20635                 | 1200                                    | 0.0651              | 29.93                |
| 400           | 0.52105                 | 1200                                    | 0.0651              | 25.76                |
| 400           | 0.52105                 | 800                                     | 0.10295             | 0                   |
| 400           | 0.52105                 | 400                                     | 0.2264              | 0                   |
| 1200          | 0.14565                 | 1200                                    | 0.0651              | 26.65                |
| 800           | 0.20635                 | 400                                     | 0.2264              | 0                   |
| 400           | 0.52105                 | 400                                     | 0.2264              | 0                   |
| 400           | 0.52105                 | 1200                                    | 0.0651              | 0                   |
| 1200          | 0.14565                 | 1200                                    | 0.0651              | 26.13                |
| 800           | 0.20635                 | 800                                     | 0.10295             | 0                   |
| 800           | 0.20635                 | 800                                     | 0.10295             | 0                   |

The grit number of SiC paper that are applied on AA7075 plate surface.

The contour plot of shear strength with respect to surface roughnesses of AA7075 and Ti-6Al-4V are shown in figure 7. It can be concluded from figure 7 that shear strength of USW joint increases as the roughness of AA7075 or Ti-6Al-4V decreases. Within the studied roughness range, smallest roughnesses of AA7075 and Ti-6Al-4V should be used to get the highest shear strength of USW joint. It is supported by the surface roughness analyses that faying surfaces with low roughness is good for robustness of USW joint. The reason may be that low roughness reduce the amount of material deformation needed to form metal to metal contact and adhesion, which is a key factor for atomic diffusion during USW process.

![Figure 7. Effects of surface roughness of AA7075 and Ti-6Al-4V on shear strength of USW weld.](image)

4. Conclusion
A DOE screening utilizing 13 different groups of process parameters on USW AA7075 and Ti-6Al-4V for 3 process parameters (pressure, penetration depth, and welding time), a further ANOVA analysis on welding time, and a DOE screening of surface roughness of AA7075 and Ti-6Al-4V were carried out. 3 times repetition was used for the analyses. Tensile shear tests were conducted. There was a big
variability of shear strength of samples in tensile shear tests. The greatest shear strength observed is about 20.7 MPa. The tensile shear strengths are all much less than the ultimate tensile strength of both parent materials (Ti-6Al-4V around 1100 MPa and AA7075 around 650 MPa). The analyses of DOE screenings and ANOVA indicate that the following combination of USW process parameters should yield the highest strengths: USW penetration depth 0.7mm, welding time 1.8s, pressure 0.7 MPa and surface roughness of AA7075 0.1457 Ra µm and Ti-6Al-4V 0.0651 Ra µm (both ground by P1200 SiC paper).

5. References
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