Modeling and optimization of tensile shear strength of Titanium/Aluminum dissimilar welded component

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Abstract. Titanium was successfully welded to Aluminum using laser welding. Laser welding parameters ranges combinations were experimentally determined using Taguchi approach with the objective of producing welded joint with acceptable welding profile and maximizing the tensile shear strength. Tensile shear strength of dissimilar Al/Ti was evaluated as a response function of the selected laser welding parameters and statistical model was developed to describe it. The result indicates that the developed model can predict the responses satisfactorily. Tensile strength of the joints was found to be same as Al base metal. Furthermore the microstructure and microhardness of the joint have been studied.

1. Introduction

Because of its superior mechanical and metallurgical properties, titanium is used in wide range of engineering and manufacturing applications. On the other hand titanium and its alloys are costly which limits its applications. Moreover, in dissimilar welding titanium forms a brittle intermetallic phase exhibit inferior mechanical properties [1,2]. Many solid-state welding methods for joining these dissimilar materials such as pressure welding [3], diffusion bonding [4] and friction welding [5,6] processes have been studied. Wilden et al. [8] instigated diffusion bonding of pure Al with pure Ti. Selected mechanical testing results of joints showed that diffusion bonding was a suitable process for high strength applications. Laser welding affords a high aspect-ratio bead, low distortion and excellent mechanical properties, which make it possible to be applied in dissimilar welding. The high potential of laser welding technologies has been proven through successful applications in the automotive, aeronautics and aerospace industries [7].

Statistical techniques and Design of Experiment (DOE) are widely used to optimize process parameters. Many researches were applied to optimize process input parameters [8,9,10 and 11]. Taguchi method is DOE technique which used to optimize welding parameters. This method was applied to reduce the number of experiments without disturbing the results [9], due to that the optimization of process parameters can improve quality characteristics and the optimal process parameters; the optimal combination of the process parameters can then be predicted. This work concerns with the effects of welding parameters on the tensile shear strength of titanium/aluminum dissimilar joints and the prediction of the optimal combinations of the selected welding factors. This method was applied to reduce the number of experiments without disturbing the results [9], due to that the optimization of process parameters can improve quality characteristics and the optimal process parameters; the optimal combination of the process parameters can then be predicted.
The objective of this study is to optimize the maximum shear strength of Ti/Al-welded components, through minimizing the laser power and maximizing welding speed in order to optimize the cost and increase the production rate. Additionally the developed models are subjected to ANOVA analysis to test significance on individual model coefficients. The microstructure in the welded zone has been evaluated. Also the microhardness variation in the welded zone and their affect on the tensile strength has been investigated.

2. Experimental design and procedure
Two plates of dissimilar materials mentioned above with their chemical compositions and mechanical properties presented in Tables (1 to 2) are welded together using the CO$_2$ laser welding process. Lap joint design was applied to join the plates of aluminum and titanium with dimensions of (160 x 80 x 1.5 and 160 x 80 x 1) mm respectively. The titanium plate was positioned above the aluminum plate in direct contact with laser beam during the welding process. A heterogeneous single pass was carried out to join the two plates. Pilot experiments were applied to determine the input welding parameters range. The pilot experiments were carried out by changing one parameter at a time to identify the operating range of the welding parameters under the study.

Table 1: Chemical composition of the Aluminum 5251 H22 and the Titanium G2 (wt %)

| Material | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | H  | C  | O  | N  | Al  | Ti  |
|----------|-----|-----|-----|-----|-----|-----|-----|----|----|----|----|-----|-----|
| Al 5251  | 0.407 | 0.509 | 0.154 | 0.154 | 2.152 | -   | -   | -  | -  | -  | -  | Bal. | 0.147 |
| Ti G2    | -   | 0.3 | -   | -   | -   | -   | 0.015 | 0.1 | 0.25 | -  | 0.03 | 0.1 | Bal. |

Table 2: Mechanical and physical properties of the materials

| Grade    | Tensile Strength, [MPa] | Yield Strength [MPa] | Elongation % | Hardness Brinell [HB], max | Elastic Modulus [GPa] | Thermal Conductivity W/m. °C | Melting Point °C | Thermal Expansion µm/m/°C | Density Kg/m$^3$ |
|----------|-------------------------|----------------------|--------------|-----------------------------|-----------------------|-------------------------------|------------------|----------------------------|-----------------|
| Al 5251  | 190                     | 120                  | 6            | 56                          | 70                    | 134                           | 650              | 25                         | 2690            |
| Ti G2    | 344                     | 275                  | 20           | 14.5                        | 105                   | 16.4                          | 1665             | 9.36                       | 4510            |

The criterion for identification of the operating range of the welding parameters was the approval by visual inspection of the welded joints under the principle of absence of observable welding defects and the presence of a good weld seam. The selected welding parameters for these dissimilar materials are presented in Table 3. The same table shows welding input variables and experiment design levels. The welding experiments were carried out following the Taguchi design matrix generated by Design Expert V7 software, presented in Table 4, in random order. An L16 orthogonal array with three columns and 16 rows was used. Sixteen experiments were required to study the welding parameters using an L16 orthogonal array. Tensile shear strength testing of the jointed specimens was carried out and the results are presented in Table 4. Since the thicknesses of the sheets are not the same, the ultimate tensile shear strength is obtained by dividing the force at fracture of the specimen by the length of the weld line (14 mm) and termed as resistance (N/mm).
Table 3: Process parameters and design levels used

| Variables       | Code | Unit | Level 1 | Level 2 | Level 3 | Level 4 |
|-----------------|------|------|---------|---------|---------|---------|
| Laser Power     | P    | kW   | 0.9     | 1.05    | 1.20    | 1.35    |
| Welding Speed   | S    | mm/min | 1600   | 1767    | 1933    | 2100    |
| Focus           | F    | mm   | -1.0    | -0.67   | -0.33   | 0.00    |

Table 4: Welding input variables, experiment design levels and tensile shear strength.

| Std | Run | P, kW | S,  mm/min | F, mm | Shear St, N/mm |
|-----|-----|------|-----------|-------|----------------|
| 1   | 4   | 0.9  | 1600      | -1    | 135            |
| 2   | 5   | 0.9  | 1767      | -0.67 | 172            |
| 3   | 12  | 0.9  | 1933      | -0.33 | 164            |
| 4   | 1   | 0.9  | 2100      | 0.00  | 181            |
| 5   | 13  | 1.05 | 1600      | -0.67 | 130            |
| 6   | 6   | 1.05 | 1767      | -1.00 | 137            |
| 7   | 3   | 1.05 | 1933      | 0.00  | 164            |
| 8   | 16  | 1.05 | 2100      | -0.33 | 147            |
| 9   | 14  | 1.2  | 1600      | -0.33 | 120            |
| 10  | 11  | 1.2  | 1767      | 0.00  | 84             |
| 11  | 7   | 1.2  | 1933      | -1.00 | 99             |
| 12  | 9   | 1.2  | 2100      | -0.67 | 112            |
| 13  | 2   | 1.35 | 1600      | 0.00  | 38             |
| 14  | 8   | 1.35 | 1767      | -0.33 | 98             |
| 15  | 15  | 1.35 | 1933      | -0.67 | 135            |
| 16  | 10  | 1.35 | 2100      | -1.00 | 143            |

Samples for tensile shear testing were cut as shown in Fig 1 (a, b) and prepared from the tensile shear testing. The achieved results, presented in Table 4, were performed in random order to avoid any systematic error and they were tested at room temperature (20 °C). It was noted that during the test the fracture occurred within the welding pool regardless of the input welding parameters. The rupture of the joint was brittle-like fracture, implying that the welding process caused the ductility of the alloy to deteriorate at the WZ.
3. Development of a Mathematical Model for Tensile Strength

3.1. Analysis of the result

The raw data, the average tensile shear strength test results are shown in Table 4. To analyze the effects of the welding parameters in detail, ANOVA was conducted; these results are shown in Table 5. The ANOVA results are presented in Table 5; the $F_v$ is used to test the significance of a factor by comparing model variance with residual (error) variance, which is calculated by dividing the model mean square by the residual mean square. As mentioned in the previous chapter the high $F_v$ value for a parameter means that the effect of the parameter on the characteristics is large. The average tensile shear tests appear to be mainly affected by the laser power and focus position as shown in Table 5. The result in Table 5 shows that the highest $F_v$ value in the process was obtained for laser power ‘$P$’ equal to 29.20. The $F_v$ value for the focus position ‘$F$’ was equal to 1.0, which indicates that the ‘$F$’ has a relatively small effect on the process. The $F_v$ value for the welding speed ‘$S$’ was not available in the ANOVA analysis, which indicates that the speed has an insignificant effect on the process. Adequate Precision compares the range of the predicted values at the design points to the average prediction error. For this model it was equal to 10.595, as shown in Table 5. Other adequacy measures $R^2$ and Adjusted $R^2$ are presented in the same table. All the adequacy measures indicate that an adequate model has been obtained. The final mathematical model for predicting the tensile strength of a dissimilar joint in terms of coded factors and actual factors as determined by Design Expert software are shown below in Eqs. 1 and 2.

![Schematic diagram illustrating the (a) Center-line welding lap-join, (b) Tensile shear sample](image)
Table 5: ANOVA for tensile strength response

| Source   | Sum of Squares | df | Mean Square | F Value | p-value  |
|----------|---------------|----|-------------|---------|----------|
| Model    | 16250.2       | 3  | 5416.74     | 16.3743 | 0.0002   |
| P        | 9660.44       | 1  | 9660.44     | 29.2026 | 0.0002   |
| F        | 331.202       | 1  | 331.202     | 1.00119 | 0.3368   |
| PF       | 6258.58       | 1  | 6258.58     | 18.9191 | 0.0009   |
| Residual | 3969.69       | 12 | 330.807     |         |          |
| Cor. Total | 20219.9    | 15 |            |         |          |

R-Squared = 0.8037

Adj. R-Squared = 0.7546

Adeq. Precision = 15.079

Final Equation in Terms of Coded Factors:

Tensile Strength = 128.65 - 32.97*P - 6.10*F - 35.60*P*F

...(1)

Final Equation in Terms of Actual Factors:

Tensile Strength = 465.375 - 304.741*P + 343.792*F - 316.445*P*F

...(2)

3.2. Validation of the model

Fig. 2 shows the actual response versus the predicted response for tensile shear testing result. From this Fig., it can be seen that the model adequately describes the response within the limits of the factors being investigated herein, as the data points are close to the diagonal line. Furthermore, three extra confirmation experiments were carried out using different test conditions, which are presented in Table 5 along with the resulting percentage error. It can be noticed that the average percentage error is almost 11%. The obtained tensile shear stress after laser welding is greater than the base metals value certainly comparing to the aluminum side.

Fig. 2: Predicted Vs Actual for developed tensile shear strength model.
3.3. Effect of process parameters on the response:

1) Laser Power: It is evident from the results that the laser power is the most significant factor associated with the response, as shown in a contour graph in Fig. 3. The highest tensile strength value was 181 MPa, observed to be at a laser power of 0.9 kW as presented in Table 7.12.

2) Focus point position: The results indicate that the focus point position has also has a significant effect on the tensile strength of the laser-welded joint, as shown in Table 4. The model developed indicates that there is an interaction between the two welding parameters (the welding speed and the focus position) as exhibited in Fig. 4.

3) Welding speed: From the ANOVA analysis it can be seen that the welding speed has no obvious effect on the response within the parameter range domain applied. By changing the welding speed the response will not be affected. The relationship between the welding speed and laser power is exhibited in 3D graph Fig. 5 at focus position $F = 0.0$ mm.

Table 5: Confirmation experiments of the tensile shear strength compared with model results.

| Exp. No | $P$, kW | $S$, mm/min | $F$, mm | Tensile strength, MPa | $|E\%|$ |
|---------|---------|-------------|---------|----------------------|------|
|         |         |             |         | Actual               | predicted |      |
| 1       | 1.00    | 1600        | 0.00    | 139                  | 160   | 13.1 |
| 2       | 1.10    | 1800        | -1.00   | 157                  | 134   | 17.2 |
| 3       | 0.90    | 2100        | 0.0     | 186                  | 191   | 2.6  |

Fig. 3: Contour graph shows the effect of welding parameters At $S = 2100$ mm/min.

Fig. 4: Interaction between the laser power and focus at $S = 2100$ mm/min.
4. Microharness and Microstructure Studies

4.1. Microstructure of dissimilar jointed materials

The welded specimens were prepared for microhardness and microstructure studies by polishing successively in 120, 240, 600, 800 and 1200 SiC paper polishing, followed by a final disc polishing using 3 μm, 1 μm diamond suspension and finished with a SiO₂ suspension to a mirror-like surface aspect. The titanium side of the weldment was etched in Reagent consisting of (10 ml HF and 5 ml HNO₃ in 85 ml of water), and the rest of the regions of the weldment were etched with Keller’s reagent (1% HF, 1.5% HCl, 2.5% HNO₃ and H₂O solution).

Different grain textures can be clearly observed in Figs. 6 (a-d) between the upper weld and the lower weld due to the diversity of heat transfer direction. When welding started but before penetration, heat transfer occurred along cross-direction and depth direction, consequently generated the columnar grains whose orientation was perpendicular to the boundary between the fusion zone and the HAZ in titanium plate as it exhibited in Fig. 6 (a). No obvious second phase was observed in the WZ at upper part of welding pool and just the solidification crystals were apparent. Optical microscopy micrograph shows that the HAZ in the vicinity of molten boundary of titanium consists of mainly α martensite exhibited in Fig. 6 (a). The circular α in the HAZ was attributed to rapid cooling of the weld metal. The base metal of aluminum 5251 H22 is exhibited in Fig. 6(b). The laser titanium–aluminium dissimilar joining resulted in a complex and heterogeneous microstructures composed of columnar grains and “white solute bands” in the base of welding pool. The welding zones in aluminium are partially melted zones due to the presence of low fusion point elements (magnesium) at the grain boundaries. The Al5251 WZ, HAZ and BM are exhibited in Fig. 6(c, d). It is well established that the microstructure of the joints affect the tensile strength critically. The influence of the heat inputs on the microstructure can be observed on the grain size variation with different heat inputs in Figs. 6(a-d). The higher the heat inputs and greater dwelling time at liquid temperature could accelerate the growing of the grain size and deteriorate the tensile strength of the weldment.
Fig. 6 (a) TiG2 WZ and HAZ    Fig. 6(b) Al5251 BM    Fig. 6 (c) Al5251 BM, HAZ and WZ    Fig. 6 (d) Al5251 BM, HAZ

Figs. 6 (a, b, c and d): The microstructure of lap weld Al5251 to Ti G2 joint.

4.2. Microhardness of dissimilar jointed materials

The specimens selected for microhardness studies were based on heat input calculation. Vickers microhardness measurements with a 50 g loading force test were applied to the selected specimens shown in Fig 7. For each specimen three different positions were subjected to the study (BM, HAZ, and WZ) for each plate of the dissimilar joint as presented in Table 6 and exhibited in microhardness profile of the dissimilar joint Fig. 7. The data on the liquid titanium to liquid aluminium interaction during high solidification rate key-hole laser welding is very limited. In the HAZ of the titanium side, the microhardness increase (232 – 287 HV) and further increase in WZ up to (280- 349 HV), as presented in Table 6, this could be related to the to the quenching effect resulting in a martensitic α microstructure.

Table 6: Microhardness test result of dissimilar nonferrous to nonferrous materials

| Sp No. | Al 5251 H22 | Ti G2 |
|--------|-------------|-------|
|        | BM   | HAZ  | WZ   | WZ   | HAZ  | BM   |
| 3      | 95.45| 104.2| 379.61| 347.98| 232.7| 226.69|
| 8      | 96.34| 103.1| 210.2 | 348.65| 263.45| 242.75|
| 15     | 99.7 | 94.72| 149.11| 280.71| 261.58| 245.9 |
| 16     | 98.81| 83.85| 194.29| 327.44| 286.99| 262.41|
Compared to the hardening effect evident in the weld–aluminium interfaces by intermetallic compound generation, the titanium–weld interfaces were not expected to be the weakest point of the assemblies. The fracture was mostly occurring at the aluminum WZ and referring to the microstructure transformation during the welding process which is evident from the microhardness result measured and presented in Table 6 and Fig 7 microhardness profile. The fracture could be interpreted by losing the ductility of aluminium and due to the brittle components formed during the solidification stage in WZ at aluminium side.

![Microhardness vs. Heat input at Different Locations](image)

Fig. 7: The Microhardness profile of the dissimilar joint (Al 5251 / Ti G2).

5. Conclusion
- The dissimilar joint between aluminum alloys (Aluminum 5251H22 and titanium G2 alloys were successfully welded by CO$_2$ laser welding with a single pass and without filler material using the overlap joint design.
- A high-quality joint with high tensile strength was achieved by applying the Taguchi optimization technique. The obtained tensile shear strength values in the optimization step reached up to 186 N/mm when joining Al–Ti. The achieved tensile shear strength was almost same as the Al base metal values. The tensile shear tests indicate that fractures are mostly occurs at the aluminum WZ or HAZ which could be referring to the microstructure transformation accorded during the welding process that was evident from the microhardness result presented in Table 6 and microhardness profile shown in Fig 7.
- The model developed for the considered Al–Ti joints can adequately predict the response within the factors domain.

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