Original Article

Influence of friction stir welding parameters on metallurgical and mechanical properties of dissimilar AA5454–AA7075 aluminum alloys

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\textbf{Abstract}

Friction Stir Welding (FSW) is a solid-state welding process used for welding similar and dissimilar materials. FSW is especially suitable to join Al alloys sheets, and this technique allows different material couples to be welded continuously. In this study dissimilar joints between aluminum alloy (AA5454) and aluminum alloy (AA7075) produced by friction stir welding, to optimize these parameters and determine which of them is significant by using Taguchi L16 optimization method. Seven parameters at two levels were selected in this study. The selected parameters are tool rotational speed, traverse speed, pin profile (based on taper angle), the ratio between shoulder diameter (D) and pin diameter (d) (D/d ratio), tool tilt angle, plunge depth, and base metal location (weld location). The ultimate tensile strength (UTS) and ductility are considered as the mechanical properties of the dissimilar joints. Then, mathematical models are built for ultimate tensile strength and ductility as a function of significant parameters/interactions using response surface methodology. In addition, the microstructures of the optimum joint and the weakest joint are studied using optical microscopy. The results of this work showed that the rotational speed, traverse speed, D/d ratio and plunge depth are significant parameters in determining UTS (mean, signal to noise ratio (S/N)) at different confidence levels, but pin profile, location of base metal and tool tilt angle are insignificant parameters at any confidence levels. The traverse speed has the highest contribution to the process for UTS about 18.5% and 16.9% for S/N ratio and mean, respectively. The accuracy of the models according to the UTS is 97.6% and 99.5% for mean and S/N ratio, respectively. The maximum joint efficiency, compared to the strength of the AA5454, is 85.3%.

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1. Introduction

From the previous studies, it is clear that all the optimization studies of FSW parameters investigate only two or three variables with neglecting the effect of other variables. It is relatively not effective on studying the process. The thesis is focused on studying most of FSW parameters together by Taguchi method. The process a rotating FSW tool is plunged between two clamped plates. The frictional heat causes a plasticized zone to form around the tool. The rotating tool moves along the joint line. Then, a consolidated solid-phase joint is formed [1,2]. FSW being a solid-state process eliminates many of the defects associated with fusion welding techniques such as shrinkage, solidification cracking and porosity. The welding temperature is approximately between 70 and 90% of the melting temperature of a material to be welded. The mechanism of the FSW is thermo-mechanical which needs three elements to complete the process [3]. These elements are heat generation, plastic deformation and forging. The heat is produced by the friction action between the material and the tool of the FSW. The tool used in the process is a cylindrical tool consisting of a shoulder and a probe [4–6]. Then, the plasticized metals are forged by the shoulder of the tool. The base materials must be fixed and clamped before welding to prohibit the material from moving during the process. Formation of friction stir processing zone is influenced by material flow behavior under the action of rotating tool [7,8]. However, material flow behavior is mainly affected by tool geometry and welding parameters. The process parameters are classified as welding process parameters and tool design parameters. The welding process parameters are tool rotational speed, traverse speed, dwell time, plunge depth, axial force, and tool tilt angle. The tool design parameters are pin profile, shoulder diameter, the ratio between shoulder diameter and pin diameter. When welding dissimilar materials, there are another two process parameters: tool offset and base metal location in a joint (weld location) [9,10]. Recently, joining dissimilar materials by the FSW method has become a very hot issue. The dissimilar materials can be dissimilar aluminum alloy [11,12], or aluminum alloy to copper [13], aluminum alloy to stainless steel and steel [14], etc. At the condition of aluminum alloys, from previous studies, all the studies of the optimization of FSW parameters on similar or dissimilar joints of aluminum alloys (by Taguchi methods or full factorial design) investigate only two or three parameters. The results of the most studies show that the rotational speed or the traverse speed or both are the significant parameters of FSW [4,5,8,10,11] but some studies show that the pin profile [7] or axial force [5,8,10] is the significant parameter. The studies show that the parameters of FSW may be significantly affected in the process due to many reasons or conditions such as selected parameters; levels of the parameters; the number of parameters and joint conditions (material, similar or dissimilar joint, material thickness). The optimal levels of the process parameters from the previous studies (aluminum alloy joint) can be summarized as follows: With 3 mm thick plate, 1000–1225 rpm – rotational speed and 17–35 mm/min – traverse speed. With 5 mm thick plate, 900–1600 rpm rotational speed, 28–160 mm traverse speed and 2.5–7 KN axial force. With 6 mm thick plate, 1100–2000 rpm rotational speed, 22–68 mm/min traverse speed and 4–6 KN axial force. [5,6,8,9,12]. Most of the studies have been used a pin length smaller than the thickness of a material to be welded about 0.1–0.5 mm. The ratios between shoulder diameter and pin diameter are between 3 and 4. At 3 mm and 6 mm thick plate, the diameters of the shoulder and the pin are 18 mm and 6 mm, respectively. The study of the interactions between the process parameters shows that the interaction variables have a little contribution to the process. For example [13], the interaction parameters included rotational speed/traverse speed, rotational speed/axial force and rotational speed/traverse speed have a contribution to the process about 2.5%.

The aim of this work is to study the effect of process parameters on the mechanical properties of dissimilar joints between aluminum alloy (AA5454) and aluminum alloy (AA7075) produced by friction stir welding, to optimize these parameters and to determine which of them is significant by using Taguchi optimization method. Experimental work was carried out to produce friction stir welding joints between AA5454 and AA7075 at different levels of process parameters (tool rotational speed, traverse speed, pin profile (based on taper angle), the ratio between shoulder diameter (D) and pin diameter (d) (D/d ratio), tool tilt angle, plunge depth, and base metal location (weld location)). The ultimate tensile strength and ductility are considered as the mechanical properties of the dissimilar joints.

2. Theory of experimental design

Taguchi L16-orthogonal is employed for experiments. L16 (2^{15}) has 16 rows corresponding to the number of tests with 15 columns at two levels. The plan of experiment is made of 16 tests in which the first column is assigned to rotational speed (rpm), the second column to traverse speed (mm/min), the fourth column to D/d ratio, the fifth column to pin profile (based on taper angle), the eighth column to plunge depth, twelfth column to tool tilt angle, eleventh column to location of base metal (lower metal (LM), AA5454- based on tool rotation direction) and the remaining are assigned to the interactions as shown in Fig. 1 [14]. Tests are replicated, resulting in a total of 48 tests, to allow the analysis of variance and signal to noise ratio calculation. Seven factors are used at two levels. Table 1 indicates the factors studied and the assignment of the corresponding levels. S/N ratios are calculated from the measured values. In this study, the experimentally observed

![Fig. 1 – Linear graph for L16-OA.](image-url)
Table 1 – Control variables and corresponding levels.

<table>
<thead>
<tr>
<th>Control variables</th>
<th>Level 1</th>
<th>Level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational speed (rpm)</td>
<td>1000</td>
<td>1225</td>
</tr>
<tr>
<td>Traverse speed (mm/min)</td>
<td>17</td>
<td>21</td>
</tr>
<tr>
<td>Pin profile based on taper angle (°)</td>
<td>0° Cylindrical profile</td>
<td>17° Tapered profile</td>
</tr>
<tr>
<td>D/d ratio</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Tilt angle (°)</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Location of base metal (LM) based on tool rotation direction (°)</td>
<td>-360° Retreating side</td>
<td>+360° Advancing side</td>
</tr>
<tr>
<td>Plunge depth (mm)</td>
<td>0.1</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 2 – Chemical composition of the base metals used in the second process.

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical composition (wt.%)</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cr</td>
<td>Cu</td>
</tr>
<tr>
<td>AA7075</td>
<td>0.28</td>
<td>1.59</td>
</tr>
<tr>
<td>AA5454</td>
<td>0.20</td>
<td>0.04</td>
</tr>
</tbody>
</table>

UTS values and ductility values is the higher the better [15–18]. The related equations are as follows:

\[ S/N = -10 \log \left( \frac{1}{n} \sum y_i^2 \right) \]  \( (1) \)

where \( n \) is the number of observations, and \( y \) is the observed data.

3. Experimental procedures

3.1. Base metals

The base metals used in this study are AA5454 and AA7075 of similar plate thickness of 3.5 mm. The chemical composition and the mechanical properties of the base metals are given in Table 2.

3.2. FSW tools

The tool parameters selected in this study on the Taguchi array L16 are pin profile and diameter ratio between shoulder diameter (\( D \)) and pin diameter (\( d \)) (\( D/d \) ratio). Two levels of each parameter are used which mean that the array of the tool parameters on the L16-OA contains four different tools. The pin profile was designed based on the taper angle of the pin (0°–cylindrical pin, 0°–tapered pin). The D/d ratio is determined by dividing the diameter of the shoulder to the diameter of the pin at mid-length. The diameter ratios used in this array are 3 and 4. Simple drawing for the four tools is shown in Fig. 2 and the dimensions are summarized in Table 3.

3.3. Friction stir welding procedures

The experimental joints were carried out by using a WMW HECKERT vertical milling machine. A butt joint form was used in the aluminum/aluminum joints. The direction of the weld line is perpendicular to the rolling direction of the plates [19,20]. The butt sides of the plates were cleaned and

Table 3 – Specifications of the FSW tools used in the first process.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Tool 1 (T1)</th>
<th>Tool 2 (T2)</th>
<th>Tool 3 (T3)</th>
<th>Tool 4 (T4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>18</td>
<td>16</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>Concavity angle (°)</td>
<td>10°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taper angle (°)</td>
<td>17</td>
<td>17</td>
<td>0° Cylindrical</td>
<td>0° Cylindrical</td>
</tr>
<tr>
<td>At shoulder</td>
<td>(A) a</td>
<td>(A) a</td>
<td>(X) a</td>
<td>(X) a</td>
</tr>
<tr>
<td>At mid</td>
<td>Φ 6</td>
<td>Φ 4</td>
<td>Φ 6</td>
<td>Φ 4</td>
</tr>
<tr>
<td>At end</td>
<td>Φ 5</td>
<td>Φ 3</td>
<td>Φ 5</td>
<td>Φ 3</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>From shoulder surface</td>
<td>3.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Drawing symbols.
machined using the milling machine to produce a smooth surface and to make suitable butt joints. The base metals were clamped and supported by a steel backing plate. The plates were fixed by two clamps. Positions and number of clamps are selected after many experimental runs. Fig. 3(a) and (b) shows the milling machine and the experimental setup, respectively. The rotational and traverse speeds were calibrated and verified by using a digital tachometer. Before every experiment, the values of the parameters corresponding to trial number are adjusted. Then the rotating tool is plunged at the interface of the two plates, till the shoulder sinking into the metals by the value of the plunge depth. After that the traverse speed was applied. Before the tool reaching the end of the work piece, it is released from the metals. Fig. 4 shows the clamping position and specimen location related to clamping position.

3.4. The analysis of specimens

3.4.1. Tensile test
Transverse tensile specimens are used to evaluate the strength of the dissimilar joints. The transverse direction is perpendicular to the welding direction. A universal testing machine was used to perform the tensile test. The tensile specimens were cut by using a wire cut machine according to ASTM B557 [22,23] and the dimensions of the tensile specimens are shown in Fig. 5.

3.4.2. Metallography
Microstructure specimens were cut from a welded part in the transverse direction of the weld. The specimens had a preparation according to ASM-9 Metallography and Microstructures [24–26]. The microstructure specimens are examined by using an Olympus optical microscope (OM).
4. Results and discussions

4.1. Experimental results analysis of L16-OA

Table 4 illustrates the results of the experiments for UTS and ductility according to L16-OA. The results of S/N ratio and mean for UTS and ductility are given in Table 5.

4.1.1. Analysis of variance for L16-OA

Table 6 gives a conclusion of the effect of the process parameters, interactions, and its contribution on UTS and ductility[27–29]. It can evaluate the efficiency of using L16-OA to study seven parameters at two levels by evaluating the degree of statistical errors obtained from ANOVA tables. For UTS, the errors are 0.782% and 1.347% for S/N ratio and mean, respectively. For ductility, the errors are 11.7% and 12.9% for S/N ratio and mean, respectively. With these errors, the use of L16-OA to study a process have seven parameters with two levels is very efficient. It means that the process is not affected by any other parameters or interaction variables out of these screen parameters in mean and S/N ratio of UTS under this process condition [30,31]. With these results obtained from ANOVA tables about the process, it can build strong mathematical models [32–35].

ANOVA for L16-OA results of mean and S/N ratio shows some results:

A – For ultimate tensile strength

A.1 – Based on S/N ratio

- Rotational speed, traverse speed, D/d ratio and plunge depth are significant parameters at 95% confidence level (C.L.). Pin profile, location of base metal and tilt angle are insignificant parameters at any confidence levels [36,37].
- X1.X5 and X3.X6 are significant interactions at 95% confidence level. Only X2.X5 is significant interaction at 90%...
I, insignificant at any confidence levels (90%, 95%, 99%). X1, rotational speed (rpm); X2, traverse speed (mm/min); X3, D/d ratio; X4, pin profile (based on taper angle); X5, plunge depth (mm); X6, tilt angle; X7, location of base metal (based on tool rotation direction).

- The traverse speed and D/d ratio and the interactions of X1.X5 and X3.X6 have the highest contribution to the process and totally contribute about 73.94% for S/N ratio to overall contributions. The traverse speed has the highest contribution to the process about 18.577% as in references [21] 33% and [4] 35% but the traverse speed in some previous processes of joining aluminum alloys has the highest second contribution to the process as in references [22] 28.3%, [8] 13.40%, [10] 29.8%, and [11] 32.24%. The D/d ratio has the second highest contribution to the process about 12.702%

- Some of the previous processes of joining aluminum alloys show that the rotational speed has the highest contribution to the process instead of traverse speed and D/d ratio as 67% [22], 68.13% [8], 53.55% [10] and 41.25% [11]. The change in contribution percentage of parameters to the process depends on the levels of its parameters, the other parameters applied in this process and the process condition [23].

- It can ignore the effect of the insignificant parameters and the insignificant interactions when performing the process or develop a mathematical model for the response, especially if the parameters have a very low contribution to the response. It can neglect the effects of pin profile, location of base metal, tilt angle and the interactions of X1.X2, X1.X7 and X4.X6 which totally have a contribution of 6.8% to the system output [41].

- The optimum levels of the process parameters which can be used to obtain the optimum value are rotational speed at level 2 (1225 rpm), traverse speed at level 2 (21 mm/min), D/d ratio at level 1 (3), pin profile at level 1 (based on the taper angle 0° (cylinder)), plunge depth at level 1 (0.1 mm), tilt angle at level 2 (2°) and location of base metal (lower metal, based on the tool rotation direction) at level 2 (advancing side 360°).

A.2 - Based on mean (ANOM)

- Only traverse speed is significant parameters at 95% confidence level. Rotational speed, D/d ratio and plunge depth are significant parameters at 90% C.L. Pin profile, tilt angle and location of base metal are insignificant parameters at any C.L.s.

- Interactions: X1.X5 and X3.X6 are statistically significant at 95% C.L. Interactions: X1.X2, X1.X7, X2.X5 and X4.X6 are statistically insignificant at any C.L.s.

- The traverse speed and D/d ratio and the interactions of X1.X5 and X3.X6 have the most contribution to the process and totally contribute about 71% for mean to overall contributions. The traverse speed has the highest contribution to the process about 16.943% as in Ref. [21] 34% but the traverse speed in some previous processes of joining aluminum alloy has the second highest contribution to the process as in Refs. [22] 28.3%, [8] 13.70%, [10] 30.17%, and [11] 33.24%. The D/d ratio has the second highest contribution to the process about 12.470%. Some of the previous processes of joining aluminum alloys show that the rotational speed has the highest contribution to the process instead of traverse speed and D/d ratio as 67% [22], 68.13% [8], 52.60% [10] and 41.30% [11].

- It can neglect the effect of the insignificant parameters (pin profile, tilt angle and location of base metal) and the insignificant interactions (X1.X2, X1.X7, X2.X5 and X4.X6) which totally have a contribution of 11.7% on the response when develops the model.

- The optimum levels which can be used to obtain the highest UTS within the process condition are rotational speed at level 2 (1225 rpm), traverse speed at level 2 (21 mm/min), D/d ratio at level 1 (3), pin profile at level 2 (based on the taper angle 17°), plunge depth at level 1 (0.1 mm), tilt angle at level 2 (2°), location of base metal (lower metal, based on the tool rotation direction) at level 2 (advancing side 360°).
D/d ratio, plunge depth and traverse speed are significant parameters at 99%, 95%, 90% confidence level, respectively. Rotational speed, pin profile, tilt angle and the location of base metal are insignificant parameters at any confidence levels.

- Interactions: X1.X5 and X3.X6 are statistically significant at 95% C.L. Interactions: X1.X2, X1.X7, X2.X5 and X4.X6 are statistically insignificant at any C.L.s.
- The traverse speed, D/d ratio, plunge depth and the statistical interactions between rotational speed and plunge depth and between D/d ratio and tilt angle have the most contribution to the process and totally contribute about 74.63% for S/N ratio to overall contributions. The D/d ratio has the highest contribution to the process about 22.402%.
- It can neglect the effect of the insignificant and the insignificant interactions which totally have a contribution of 13.67% on the response when develops the model.
- The optimum levels of the process parameter which can be used to achieve the optimum value are rotational level at level 2 (1225 rpm), traverse speed at level 2 (21 mm/min), D/d ratio at level 1 (3), pin profile at level 1 (based on the taper angle 0°), plunge depth at level 1 (0.1 mm), tilt angle at level 1 (1.5°), and the location of base metal (lower metal, based on the tool rotation direction) at level 2 (advancing side 360°).

B.2 – Based on mean (ANOM)

- D/d ratio, plunge depth and traverse speed are significant parameters at 99%, 95%, 90% confidence level, respectively. Rotational speed, pin profile, tilt angle and the location of base metal are insignificant parameters at any confidence levels.
- Interactions: X1.X5, X2.X5 and X3.X6 are statistically significant at 95%, 90%, 95% C.L. Interactions: X1.X2, X1.X7 and X4.X6 are statistically insignificant at any C.L.s.
- The traverse speed, D/d ratio, plunge depth and the statistical interactions between welding speeds and plunge depth and between D/d ratio and tilt angle have the most contribution to the process and totally contribute about 82.006% for S/N ratio to overall contributions. The D/d ratio has the highest contribution to the process about 21.425%.
- It can neglect the effect of the insignificant and the insignificant interactions which totally have a contribution of 5.90% on the response when develops the model.
- The optimum levels which can be used to obtain the maximum ductility within the process condition are rotational level at level 2 (1225 rpm), traverse speed at level 2 (21 mm/min), D/d ratio at level 1 (3), pin profile at level 1 (based on the taper angle 0°), plunge depth at level 1 (0.1 mm), tilt angle at level 1 (1.5°), and the location of base metal (lower metal, based on the tool rotation direction) at level 2 (advancing side 360°) [43, 44].

4.2. Verification of experimental results

Once the optimal level of control parameters is selected, the final step is to verify the improvement of quality characteristics using the optimal level. The estimated optimal level of parameters is calculated as:

\[ Y_{\text{predicted}} = Y_{\text{mean}} + \sum [Y_i - Y_{\text{mean}}] \]  

(2)

\( Y_i \) is the mean (S/N ratio or mean) response at optimal level of control parameters; \( Y_{\text{mean}} \) is the total mean (S/N ratio or mean) response.

The optimum results (or experiment) for UTS and ductility are not found in any experiment according to the selected array. A comparison between the predicted values and the experimental values of the UTS and ductility at the optimum levels is given in Table 7. The deviation between the experimental and predicted results for the optimum UTS and ductility are very close according to the results of L16-OA.

4.3. Metallographic analysis

The microstructure of the optimum joint which has the highest UTS within the process condition and the joint 8 (the weakest joint obtained according to the L16-OA) are discussed in this part. The joint efficiency of the optimum joint and the weakest joint is 85.3% (221.3 MPa) and 69.9% (181.8 MPa), respectively. The joint efficiency is compared to the strength of the softer metal used in this dissimilar joint. The UTS of the AA5454 and AA7075 is 260 MPa and 402 MPa, respectively. The optimum joint was obtained by using the parameters of 1225 rpm rotational speed, 21 mm/min traverse speed, 3 D/d ratio, tapered pin profile, 0.1 mm plunge depth, 2° tilt angle, and AA5454 on advancing side. The weakest joint was obtained by using the parameters of 1000 rpm rotational speed, 21 mm/min traverse speed, 4 D/d ratio, tapered pin profile, 0.25 mm plunge depth, 1.5° tilt angle, and AA5454 on the retreating side. The amount of the generated heat in FSW usually depends on two parameters: diameter of the shoulder and the combination of the welding speeds (RS + TS). It is clear that the frictional heat generated during the welding of the optimum joint is higher than the generated heat in the joint 8. The microstructure of the base metal of the AA5454 and the AA7075 is shown in Fig. 6. The strain hardening effect is observed in the microstructure of the AA5454 (5XXX strain hardening alloy). This alloy is rolled twice from 14 mm to 7 mm and from 7 mm to 3.5 mm. The grains of the AA7075 are very large and have an elongated pancake shape due to the hot rolling.

Fig. 7 shows the microstructure at the interface between AA5454 and AA7075 of the optimum joint and the joint 8, respectively. In the joint 8, there is little bonding without stirring between AA5454 and AA7075 in all the interface regions from the upper weld region to the bottom. At the interface on the optimum joint, The microstructure of all the regions from the upper (Fig. 7a), middle (Fig. 7b and c), and to the bottom (Fig. 7d) shows good stirring and more consolidate between AA5454 and AA7075 which improves the quality of the weld. In the AA7075 side. The grains in the NZ become finer and equiaxed in both the joints. The size of the grains decreases from the base metal through to the NZ.
Table 7 – The optimum results of UTS and ductility based on mean and S/N ratio.

<table>
<thead>
<tr>
<th>Optimal levels</th>
<th>Experiment</th>
<th>Prediction</th>
<th>Deviation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS (MPa)</td>
<td>X_{12}, X_{22}, X_{31}, X_{42}, X_{51}, X_{62}, X_{72}</td>
<td>222.5, 223.5, 217.1 = 221.03</td>
<td>1.75</td>
</tr>
<tr>
<td>Ductility %</td>
<td>X_{12}, X_{22}, X_{31}, X_{41}, X_{51}, X_{61}, X_{72}</td>
<td>9.25, 11.2, 12 = 10.833%</td>
<td>8.8</td>
</tr>
</tbody>
</table>

X_{nm}: n, parameter number, m: level number. X1, rotational speed (rpm); X2, traverse speed (mm/min); X3, D/d ratio; X4, pin profile (based on taper angle); X5, plunge depth (mm); X6, tilt angle; X7 location of base metal (based on tool rotation direction).

Fig. 6 – Optical micrograph of base metals (a) AA7075; (b) AA5454.

Fig. 7 – Optical micrographs of the optimum joint (AA5454 to AA7075) at the interface in different regions: (a) upper; (b, c) middle and (d) bottom.

4.4. Tensile properties

The results of the UTS of the 26 joints with a relation with the welding speeds are given in Figs. 8 and 9 as shown in Figs. 8 and 9 the UTS results of the joints made by using the tool (T1: D/d ratio = 3) and the tool (T2: D/d ratio = 4), respectively. All the results of the UTS show a nonlinear effect under different combinations of the welding speeds except the 1225 rpm rotational speed with both the tools (T1, T2). At 1225 rpm rotational speed, the UTS decreased with increasing the traverse speed from 17 mm/min to 67.5 mm/min with both the tools (T1, T2) and the best results were obtained between 17-21 mm/min traverse speed.

Fig. 8 – The UTS results of the joints made in the first stage of joining dissimilar aluminum alloys with tool (T1).
With the non-linear effect of the rotational speeds (1000–1550 rpm) at the traverse speeds from 17 mm/min to 67.5 mm/min, the 42 mm/min is the transition zone of the effect of the process parameters on the UTS at 1000 rpm and 1550 rpm with the tool (T1) and at 1500 rpm with the tool (T2) but the 21 mm/min–traverse speed is the transition zone of the effect of the process parameter at 1000 rpm and the tool (T2). The best conditions lead to achieving the highest UTWs in this area are 17–21 mm/min traverse speeds with 1000 rpm rotational speed and the tools (T1, T2), 42–67.5 mm/min traverse speeds with 1550 rpm rotational speed and tool (T2). To optimize the process parameters, it must select at least two levels of these parameters [37, 42]. The joints made by using the tool having the 4 D/d ratio have higher UTS than those made by using the tool having the 3 D/d ratio. The UTWs with the tool (T2) are approximately equal to the strength of the base metal of the Al-Si alloy at six parameter conditions (joints: 17, 19, 20, 23, 24, 25). Only one parameter condition with the tool (T1) gives the same tensile strength of the Al-Si alloy (the lower metal in this joint). The maximum UTS obtained is 125.94 MPa at the process parameters of 1225 rpm rotational speed, 17 mm/min traverse speed, and the tool (T2). The strength of the joints decreases with increasing the rotational speed and with increasing the tool shoulder diameter. The drop in the UTS compared to the strength of the lower metal used in this joint depends on the efficiency of the combination of the process parameters related to the frictional heat generated. The joints 19, 23, and 24 have a higher UTS than the UTWs of Al-Si alloy about 3–5 MPa but it is normal because the UTS of all joints was only tested one time (one test specimen) and then compared to the average UTS of Al-Si alloy (122, 118, 125.68 MPa). It is clear that the highest UTS obtained in this stage is approximately equal to the UTS of Al-Si alloy.

5. Conclusions

Modeling and optimization of FSW parameters of AA5454 to AA7075 joints are studied by using Taguchi methods. Taguchi L16-OA was used to optimize the process parameters. Seven parameters at two levels are selected. These parameters are rotational speed, traverse speed, D/d ratio, pin profile (based on the taper angle), tool tilt angle, plunge depth, and the location of base metal (based on the tool rotation direction). UTS and ductility were considered as the mechanical properties of the dissimilar joint. The results can be summarized as follows:

- For UTS: based on S/N ratio and mean, Rotational speed; traverse speed; D/d ratio and plunge depth are significant parameters at different confidence levels. Pin profile; location of base metal and tilt angle are insignificant parameters at any confidence levels. Based on standard deviation, traverse speed and pin profile are significant parameters at 99% and 90% C.L., respectively. Rotational speed; D/d ratio; plunge depth; tilt angle and location of base metal are not significant parameters at any C.L.s.
- The optimal levels determined from the L16-OA to obtain the highest UTS within process condition are 0.1 mm plunge depth, 1225 rpm rotational speed, tapered pin profile, 21 mm/min traverse speed, 2° tilt angle, 3 D/d ratio, and AA5454 on the advancing side.
- Based on the results of S/N ratio and mean of ductility: D/d ratio, plunge depth and traverse speed are significant parameters at 99%, 95%, and 90% confidence level, respectively. Rotational speed, pin profile, tilt angle and the location of base metal are insignificant parameters at any confidence levels.
- The optimal levels determined from the L16-OA to achieve the highest ductility within process condition are 0.1 mm plunge depth, 1225 rpm rotational speed, cylindrical pin profile, 21 mm/min traverse speed, 1.5° tilt angle, 3 D/d ratio, and AA5454 on the advancing side.
- Six mathematical models were developed for UTS and ductility as a function of the significant parameters and the significant interactions. For UTS, the accuracy of the models is 97.678%, 99.56%, and 58.670% for mean, S/N ratio, and standard deviation, respectively. For ductility, the accuracy of the models is 93.56%, 97.320%, and 50% for mean, S/N ratio, and standard deviation, respectively.
- The maximum joint efficiency obtained, compared to the strength of the softer metal used in the dissimilar joint, is 85.3%.

Conflict of interest

The authors declare that they have no conflict of interest.

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