Investigation of Adhesive Joint Strength for Dissimilar Metal Adherends by Using Taguchi Method

N Atikah¹, M Afendi¹, Shahriman A B¹, I Zunaidi¹, Z M Razlan¹, W K Wan¹, M N Mazlee² and M S A Majid¹

¹ School of Mechatronic Engineering, Universiti Malaysia Perlis, Kampus Pauh Putra, 02600 Arau, Perlis, Malaysia.
² Centre for Frontier Materials Research, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia

Abstract. The dissimilar metal joints of stainless and medium carbon steel have been emerged as a structural joint for various industrial applications which provides good combination of mechanical properties like strength, corrosion resistance with lower cost. This paper concerned with the growth of adhesive joint technique since adhesive joint has the applicability to joint wide variety of engineering materials. This study is to investigate the significance of factors in dissimilar AISI 304/1045 butt-joint specimen tensile strength by using Taguchi method and Analysis of Variance (ANOVA). The joining strength was evaluated with manufacturing factors of abrasive paper, heat treatment and adhesive thickness. It was obtained that abrasive paper has significant effect on adhesive joint strength while heat treatment effect is insignificant. Nevertheless, the joint strength decreased with increment of adhesive thickness.

1. Introduction
Dissimilar metal joint can be complicated and extents a wide-ranging of methodologies, materials and procedures [1]–[3]. It is often more difficult than joining the same material. Adhesive joint has a good spot in present industry. There are also a lot of comprehensive study on adhesive joint available yet not much study was done on the behaviours of adhesive bonding strength on heat treated metals specifically stainless steel and carbon steel. Statically design of experiment (DOE) is regularly seen as crucial part of experiment. Taguchi method is a simple, systematic, and efficient approach for optimizing the process parameters [4], [5].

2. Design of experiment (Taguchi method)
There are two groups of specimen studied which are as received (AR) and heat treated sequence 2 (SQ2). The experiment matrix in Taguchi method were formed after deciding on the control factors and orthogonal array. Table 1 is the studied control factors and its level. L9 orthogonal array was chosen in this study. The experiment matrix are shown in table 2. Three specimens were replicates for every experiment condition.
Table 1. Control factors and levels

| Control factors          | Level 1 | Level 2 | Level 3 |
|--------------------------|---------|---------|---------|
| Abrasive paper (grit)    |         |         |         |
| Heat treatment           | Annealing | Normalizing | Quenching |
| Adhesive thickness (mm)  |         |         |         |

Table 2. Experiment matrix

| Experiment conditions | Control factors (AR) | Control factors (SQ2) |
|-----------------------|----------------------|-----------------------|
|                       | Abrasive paper (grit)| Adhesive thickness (mm)| Abrasive paper (grit)| Heat treatment | Adhesive thickness (mm)|
| 1                     | 180                  | 0.5                   | 180                  | Annealing      | 0.5                   |
| 2                     | 180                  | 1.0                   | 180                  | Normalizing    | 1.0                   |
| 3                     | 180                  | 1.5                   | 180                  | Quenching      | 1.5                   |
| 4                     | 500                  | 0.5                   | 500                  | Annealing      | 1.0                   |
| 5                     | 500                  | 1.0                   | 500                  | Normalizing    | 1.5                   |
| 6                     | 500                  | 1.5                   | 500                  | Quenching      | 0.5                   |
| 7                     | 1000                 | 0.5                   | 1000                 | Annealing      | 1.5                   |
| 8                     | 1000                 | 1.0                   | 1000                 | Normalizing    | 0.5                   |
| 9                     | 1000                 | 1.5                   | 1000                 | Quenching      | 1.0                   |

3. Specimen and testing

3.1. Material
The adhesive joint specimens were prepared with accordance to ASTM D2094-00. The specimen are made of circular rod medium carbon steel (AISI 1045) and stainless steel (AISI 304) cut into 12.7 mm diameter and 38.1 mm length as adherends and a slow-setting epoxy adhesive, Araldite Standard 90 Minutes as adhesive. The adhesive consisted of two components which are resin and hardener. The mechanical properties of adherends and adhesive are shown in table 3.

Table 3. Mechanical properties of adherends and adhesive

| Material                     | Young’s modulus | Poisson ratio |
|------------------------------|-----------------|---------------|
| AISI 1045 (adherend 1)       | 206 GPa         | 0.290         |
| AISI 304 (adherend 2)        | 210 GPa         | 0.290         |
| Araldite Standard 90 Minutes (adhesive) | 1850 MPa | 0.396         |

3.2. Specimen fabrication
The surface treatment were applied by grinding the bonding area with Silicon Carbide (SiC) abrasive paper by using Metco grinding and polishing machine. Heat treatment were done on both adherends. AISI 1045 were heat treated at 925 °C for 90 minutes and subsequently cooled by three different cooling rates namely as furnace condition cooling (annealing), air condition cooling (normalizing) and room condition water quenching (quenching). AISI 304 were heat treated at 1050 °C for 90 minutes.
and subsequently cooled in room condition water quenching (annealing). The adherend’s surface were acetone wiped prior to bonding. The adhesive bonding process was prepared by mixing resin and hardener with weight ratio of 1:0.8 respectively. Adhesive were stirred for 3 minutes ahead of applying on adherend’s surface. The adherends were then fitted into the alignment jig and the adhesive thickness was controlled using the micrometer head as shown in figure 1. Lastly the specimen was cured fully in 12h at room temperature with handling strength in about 6h in the alignment jig.

![Figure 1. Specimen placed in an alignment jig](image)

### 3.3. Tensile test and surface roughness examination

The tensile test was conducted using Universal Testing Machine (UTM). Figure 2 shows the fixture set-up for tensile test of dissimilar AISI 304/1045 butt-joint specimen. The specimen was hold by a pair of holding jig. The test were conducted at a crosshead speed of 1.0 mm min⁻¹. Surface roughness of bonding area were measured by using a surface profilometer, F-Mitutoyo. The profiler moves along a single direction with a scanning length of 8.0 mm.

![Figure 2. Tensile test experiment set-up](image)

### 4. Results and discussion

The average tensile strength obtained were computed and presented in table 4. Based on the joint strength, statistical analysis by ANOVA was performed.

#### 4.1. Statistical analysis by ANOVA

Table 5 presents the analysis results for the two groups. For AR, the contribution of adhesive thickness is 59.38%, higher than abrasive paper, 28.76%. In addition to this, the change of level within the range investigated in abrasive paper and adhesive thickness does have significant effect on the joint strength since the $F$ ratio for both factors are more than 4. There are external factors that affect the joint strength by 11.86%. Meanwhile for SQ2, the main factor influencing the joint strength in this group is adhesive thickness, 67.51% followed by the abrasive paper with 12.80% and heat treatment with 11.00%. This result shows that the adhesive thickness is more significant than abrasive paper. Statistically, heat treatment have very little influence to joint strength in SQ2. The change of level
within the range of adhesive thickness investigated seems to have significant effect on the joint strength where the $F$ ratio is bigger than 4.

Table 4. Joint strength of dissimilar AISI 304/1045 butt-joint specimen

| Experiment conditions | Joint strength (N/mm$^2$) |
|-----------------------|---------------------------|
|                       | AR            | SQ2            |
| 1                     | 19.41         | 6.42           |
| 2                     | 8.69          | 2.95           |
| 3                     | 7.74          | 2.53           |
| 4                     | 11.58         | 4.87           |
| 5                     | 8.04          | 5.87           |
| 6                     | 5.20          | 7.21           |
| 7                     | 9.28          | 2.19           |
| 8                     | 6.07          | 8.03           |
| 9                     | 3.72          | 8.38           |

Table 5. ANOVA results for joint strength of AR and SQ2

| Group   | Factors                   | DOF | SSA | MS  | Contribution (%) | F   |
|---------|---------------------------|-----|-----|-----|------------------|-----|
| AR      | Abrasive paper (A)        | 2   | 48.42 | 24.21 | 28.76          | 4.85 |
|         | Adhesive thickness (B)    | 2   | 99.96 | 49.98 | 59.38          | 10.01 |
|         | Noise                     | 4   | 19.97 | 4.99  | 11.86           |     |
|         | Total                     | 8   | 168.36|       |                 |     |
| SQ2     | Abrasive paper (A)        | 2   | 6.24  | 3.12  | 12.80           | 1.47 |
|         | Heat treatment (B)        | 2   | 5.36  | 2.68  | 11.00           | 1.27 |
|         | Adhesive thickness (C)    | 2   | 32.89 | 16.44 | 67.51           | 7.77 |
|         | Noise                     | 2   | 4.23  | 2.12  | 8.69            |     |
|         | Total                     | 8   | 48.72 |       |                 |     |

4.2. Effect of abrasive paper, heat treatment and adhesive thickness.
Surface roughness of adherends decrease as abrasive paper grit increase for both AR and SQ2 group. Joint strength of AISI 304/1045 against surface roughness for AR and SQ2 group at 1 mm adhesive thickness were plotted in figure 3. It was observed that for AR group, the increased roughness of both AISI 304 and AISI 1045 improves the joint strength of adhesive AISI 1045/304 butt joint specimen. Some studies have verified that roughness effect for stainless steel and carbon steel differ to one another. For stainless steel, as roughness increases, adhesive bonding strength increases. But for carbon steel, as the roughness increases, bonding strength decreases. Thus, the observation for AR group indicates that roughness of AISI 304 plays the role in strengthen the joint strength.
The opposite results occurred in SQ2 group where increased roughness of AISI 1045 lower the joint strength. For AISI 304, the joint strength initially increases and then decreases with roughness. In addition for SQ2, the surface roughness of both adherends increased slightly after heat treatment. Noted that in this group, the microstructure and mechanical properties of each steels have changed because of the heat treatments processes. The mechanical properties for AISI 304 at three different roughness is same but the properties for AISI 1045 is different. The optimum surface roughness exists for a maximum joint strength and the roughness range depends on the adherend which explains why the behaviour of SQ2 specimen is not in good agreement with AR group [6]. The effect of adhesive thickness is similar for AR and SQ2 where both groups exhibit the same pattern. The joint strength decreases with an increase in adhesive thickness. These adhesive thickness and tensile bonding strength trends are similar to those obtained in a study by Naito et al. [7]. This might be due to the less flaws such as voids contained by the thin adhesive layers [8]–[10].

4.3. Main effects plot
The value for average joint strength for each factor at each level was obtained and the result were plotted in figure 6 for AR and figure 7 for SQ2. It can be seen that the optimum combination of factors and their levels A₁B₁ yield the highest joint strength for AR. While for SQ2, the optimum factors and their levels combination is A₂B₂C₁.
4.4. Confirmation test
The last step was to validate the estimated result against experimental value. Based on the main effect plot, the confirmation test was required because the obtained optimum combination of factors and their levels for SQ2 did not correspond to any of experiment condition in the experiment matrix except for AR group. The estimated value for optimum combination of factors and their levels, $Y_{opt}$, is calculated by using equation (1) and (2).

\[ Y_{opt} = m + (m_A - m) + (m_B - m) + (m_C - m) \]  
\[ m = \frac{T}{n} \]  

where, $m$ is the average joint strength, $m_A$ is the average joint strength for factor A, $m_B$ is the average joint strength for factor B and $m_C$ is the average joint strength for factor C, $T$ is sum of all responses, $n$ is the number of response.

The estimated joint strength is 9.763 N/mm$^2$ while the experimental value is 9.415 N/mm$^2$. The experimental value of adhesive butt joint of AISI 304/1045 is close to the estimated value and verifies that the experimental result for SQ2 group is strongly correlated to estimated result.

5. Conclusion
Abrasive paper and heat treatment increased the adherend surface roughness. The optimum surface roughness exists for a maximum joint strength and the roughness range depends on the adherend mechanical properties. Heat treatment changed the microstructure but lowered the joint strength of AISI 304/1045. ANOVA proved that heat treatment effect is insignificant. Joint strength decreased with increment of adhesive bond thickness. In this study, 0.5 mm adhesive thickness resulting the highest joint strength for both as received and heat treated group. Lastly, it is evident that Taguchi method provides simple and systematic methodology for optimizing the process parameters.

6. References
[1] Ciupack Y, Pasternak H, Mette C, Stammen E and Dilger K 2017 Adhesive bonding in steel construction-challenge and innovation Proc. Eng. on Mod. Build. Mater., Struct. and Tech. (Germany) vol 172 p 186–193
[2] Mishra R R, Tiwari V K, and Rajesha S 2015 A study of tensile strength of mig and tig welded dissimilar joint of mild steel and stainless steel Int. J. Adv. Mater. Sci. Eng. 3 23–32
[3] Farren J D, Dupont J N and Noecker F F 2007 Fabrication of a carbon steel-to-stainless steel transition joint using direct laser deposition — a feasibility study Suppl. to Weld. J. 55–61
[4] Athreya S and Venkatesh Y D 2012 Application of taguchi method for optimization of process parameters in improving the surface roughness of lathe facing operation Int. Ref. J. Eng. Sci 1 13–19
[5] Kamaruddin S, Khan Z A, and Foong S H 2010 Application of taguchi method in the optimization of injection moulding parameters for manufacturing products from plastic blend Int. J. Plast. Technol. 4 152–166
[6] Ghumatkar A, Budhe S, Sekhar R, Banea M D, and De Barros S 2016 Influence of adherend surface roughness on the adhesive bond strength Lat. Am. J. Solids Struct. 13 2356–70
[7] Naito K, Onta M and Kogo Y 2012 The effect of adhesive thickness on tensile and shear strength of polyimide adhesive Int. J. Adhes. Adhes. 36 77–85
[8] Ikekami K, Fujii T, Kawagoe H, Kyogoku H, Motoie K, Nohno K, Sugibayashi T, and Yoshida F 1996 Benchmark tests on adhesive strengths in butt, single and double lap joints and double-cantilever beams Int. J. Adhes. Adhes. 16 219–226
[9] Arenas J M, Narbo’n J J and Ali’a C 2010 Optimum adhesive thickness in structural adhesives joints using statistical techniques based on Weibull distribution Int. J. Adhes. Adhes. 30 160–165

[10] Banea M D, Silva L F M and Campilho R D S G 2015 The effect of adhesive thickness on the mechanical behavior of a structural polyurethane adhesive the effect of adhesive thickness on the mechanical behavior of a structural polyurethane adhesive J. Adhes 91 331–346