Microstructural investigation of the assessed high strength Al6082 self-piercing riveted joints

Ebad Bagherpour, Yan Huang and Zhongyun Fan

May 8, 2019

Microstructural investigation of the assessed high strength Al6082 self-piercing riveted joints

E. Bagherpour, Y. Huang, and Z. Fan
Brunel Centre for Advanced Solidification Technology (BCAST),
Brunel University London, Uxbridge, UB8 3PH, United Kingdom,
Ebad.Bagherpour@brunel.ac.uk

Abstract
Self-piercing riveting (SPR) as a solid-state joining technology has extended its application in the automobile industry in recent years, mostly in the joining of car body aluminium sheets. Several investigations have been carried out to study the effect of rivet, die and process parameters including material stacks on the joint quality either by physical experiment or computer simulation. The characteristic features of microstructures around the joint, optimize process parameters and improve joint quality, are not considered in these investigations. In the present work, a method to determine the SPR conditions that produce a joint of the best quality, based on an analytic hierarchy process (AHP) is proposed. Then, using the method, best condition to join two layers of 2.5mm thick AA6082 aluminium sheets in T6 condition by SPR were determined. With the application of six criteria including head height, bottom thickness, minimum bottom thickness, deformed rivet diameter, shear strength, and peel strength, the AHP assessment was able to define the best conditions for the SPR joining of the car body aluminium alloy sheets including AA6082. Finally, the microstructures of the best joint is examined by optical microscopy. It was confirmed that the area around the outer wall of the tail of the rivet in the lower sheet exhibited the highest deformation and possibly tolerated the highest tensile stress.

Keywords: *Mechanical Joints; Self Piercing Riveting (SPR), Microstructure,* analytic hierarchy process (AHP)

1. Introduction
Mechanical joints have a long history in metal joining started from the Bronze Age. Despite of this long history, its applications have been limited by the availability of weldable metals and feasible rivet materials for less expensive and easy automation welding techniques [1] until the end of the 20th century. Since 1975 [2], a developed method of riveting named as self-piercing riveting (SPR) started to find its way in industrial application due to its ability to join dissimilar materials, aluminium sheets, and pre-coated panels. The SPR process is used to attach two or more similar or dissimilar sheet materials by driving a rivet to the top (or top and middle) sheet(s) and partially piercing to the bottom sheet creates an interlock between the sheets by flaring the rivet skirt, directed by a suitable die, without piercing the bottom sheet [3, 2]. The riveting performance depends on several parameters, including the stack thickness, load of the process, die shape, die geometry, and geometry, shape, and hardness of the rivet.. A schematic of a joint section is illustrated in Figure 1. While deformed rivet diameter (D_{dr}) and rivet flaring (X) represent the interlocking, bottom thickness (t_b) has a strong effect on the strength of the joint. The procedure that is used by the automotive industry to evaluate the

quality of a SPRed joint involves measurement of the rivet head height (h) above (or below) the surface of the top sheet and the rivet flaring (X) [4].

To select the best condition for SPR processing to achieve all of the goals including a good interlock, sufficient t_b, around-zero h, and high peel and shear strengths, several experiments are needed. Therefore, comparing joints, ranking them, and choosing the best joint is one of the important stages in SPR processing. Generally these stages (comparing, ranking, and choosing) are significant in any of the material and process selection issues [5]. In the selection procedure, the multi-criteria decision making (MCDM) [6] methods have been used commonly for the properties that can be represented by numerical values. In 1990, Saaty [7] introduced a new methods of MCDM named as Analytic Hierarchy Process (AHP) that has been frequently used by decision makers facing a complex problem with multiple conflicting and subjective criteria due to its high potential and its simplicity.

In the present study a systematic assessment model is proposed to determine the optimal condition in order to obtain the best quality joint in the SPR processing with the aim of the AHP method. Finally, The microstructures of the best joint is examined by optical microscopy inorder to explore the flow behaviour of the material during SPR processing.

2. Assessment of SPR joints

AHP is a methodology for "relative measurement" [8]. The use of pair-wise comparisons between the quantities instead of direct allocation of their weights is the essence of the relative measurement and the AHP as well [9]. The AHP is based on three steps: problem modelling, comparative judgment of the alternatives and the criteria, and synthesis of the priorities [8]. The aim of this work is to select a joint having the best combination of interlocking and strength. To achieve the goal, five criteria include rivet's head height (h) , bottom thickness (t_b), deformed rivet diameter (D_{dr}), shear strength (F_s) and peel strength (F_p) are taking into account. Therefore, decision hierarchy structure for selecting a joint with the declared criteria among m ($J_1, J_2, \dots, J_m$) number of the joints is the one shown in Figure 2.

The pair-wise comparisons are recorded in a positive reciprocal matrix:

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1m} \\ a_{21} & 1 & \cdots & a_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & 1 \end{bmatrix} \quad (1)$$

where a_{ij} is the comparison between elements i and j.

According to Saaty's theory, each entries of Matrix A (Eq. (1)) is supposed to be the ratio between two quantities (weights)

$$a_{ij} = \frac{w_i}{w_j} \forall i,j \ . \quad (2)$$

For all the criteria except head height, the higher amount means the better quality. Therefore, unlike the others, head height could not be evaluated using Eq. (2) without considering the discussed issue. To overcome this problem, a reference head height of h_0, is assumed to be the goal for the criteria. Hence, the target for a joint is to have the relative height of h_0/h_i closer to 1. In this case, using Eq. (2), the entries of the pair-wise comparison matrix for the head height is $a_{ij} = \frac{h_j}{h_i} \forall i,j$.

Considering Eq. (1), condition of multiplicative reciprocity is satisfied as $a_{ij} = \frac{1}{a_{ji}} \forall i, j$.

Once a pairwise comparison matrix is completed, there are many methods to derive the priority vector **w** ($\boldsymbol{w} = \{w_1, w_2, \dots, w_n\}^T$). In the current study we used geometric mean method.

According to this method each component of **w** is obtained by $\boldsymbol{w} = \frac{\sqrt[m]{\prod_{j=1}^{m} a_{ij}}}{\sum_{i=1}^{m} \sqrt[m]{\prod_{j=1}^{m} a_{ij}}}$.

To complete the analysis, the described procedure is repeated for all subsystems in the hierarchy. Therefore, the pair-wise comparison matrix (A) for the whole hierarchy can be derived by assembling all the priority vectors. For this purpose, each of the priority vectors formed one of the columns in the comparison matrix (A):

$$A = \begin{bmatrix} \frac{\prod_1^n h_i}{h_1 \sum_1^m \frac{\prod_1^m h_i}{h_i}} & \frac{t_{b1}}{\sum_{i=1}^m t_{bi}} & \frac{D_{dr1}}{\sum_{i=1}^m D_{dri}} & \frac{F_{s1}}{\sum_{i=1}^m F_{si}} & \frac{F_{p1}}{\sum_{i=1}^m F_{pi}} \\ \frac{\prod_1^m h_i}{h_2 \sum_1^m \frac{\prod_1^m h_i}{h_i}} & \frac{t_{b1}}{\sum_{i=1}^m t_{bi}} & \frac{D_{dr2}}{\sum_{i=1}^m D_{dri}} & \frac{F_{s2}}{\sum_{i=1}^m F_{si}} & \frac{\sigma_{p2}}{\sum_{i=1}^m F_{pi}} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\prod_1^m h_i}{h_n \sum_1^m \frac{\prod_1^m h_i}{h_i}} & \frac{t_{bm}}{\sum_{i=1}^m t_{bi}} & \frac{D_{drm}}{\sum_{i=1}^m D_{dri}} & \frac{F_{sm}}{\sum_{i=1}^m F_{si}} & \frac{F_{pm}}{\sum_{i=1}^m F_{pi}} \end{bmatrix}. \qquad (3)$$

To now, the pair-wise comparison matrix was formed without any prioritization between the criteria. For this reason, a decision maker should prioritize each of the criteria by giving them a weight ($\boldsymbol{W}$) using Saaty's scale. Applying the same procedure as that of used for the criteria, the weight vector of the whole hierarchy is defined as

$$W = \left\{\frac{W_h}{\sum W}, \frac{W_{t_b}}{\sum W}, \frac{W_{D_{dr}}}{\sum W}, \frac{W_{F_s}}{\sum W}, \frac{W_{F_p}}{\sum W}\right\}^T. \qquad (4)$$

By multiplying A to W (AW), rank of alternatives is defined by the subsequent vector.

3. Experimental procedure

AA6082 aluminium sheets in T6 condition with the thickness of $2.5mm$ was used for SPR processing. Coupons of $40mm \times 40mm$ and $120mm \times 40mm$ were prepared by cutting the sheets using a guillotine for microstructural investigations and strength tests respectively. For the mechanical tests, an INSTRON 3367 universal testing machine with a capacity of 50 KN was used.

A Henrob servo-electric SPR machine was used for riveting with ability of using $\phi 5\ mm$ rivets. Stainless steel rivets mechanically plated alloy of zinc and tin (H00 serious of Henrob products) with $5mm$ diameter, and $6.5\ mm$, $7\ mm$, $7.5\ mm$, and $8\ mm$ lengths are used in this study. The shape of the rivets is flared hole- semi tubular. The hardness of the rivets varied from $420\ Hv$ to $460\ Hv$. Flat bottomed dies with diameters of $9.0\ mm$ and $10.0\ mm$ and various depths of $1.2\ mm$, $1.4\ mm$, 1.6 mm and 1.8 mm were used for SPR processing.

4. Results and discussions

Different joining conditions were tested to achieve an acceptable joint. Among these trials (more than of 40 conditions), only a limited number of them could achieve the requirements of a good quality joint. Therefore, the joints that could passed the initial quality check were inserted to the AHP model. Table 1 summarized the SPR conditions for the accepted joints. Table 2 summarized the interlocking parameters and the strength of the joints in Table 1. Inserting data in Table 4 into the Matrix (A) (Equation 3), the comparison matrix is defined as

$$A = \begin{bmatrix} 0.179 & 0.146 & 0.142 & 0.128 & 0.145 \\ 0.089 & 0.137 & 0.153 & 0.131 & 0.147 \\ 0.149 & 0.157 & 0.148 & 0.139 & 0.149 \\ 0.081 & 0.178 & 0.144 & 0.126 & 0.130 \\ 0.224 & 0.113 & 0.142 & 0.163 & 0.146 \\ 0.149 & 0.132 & 0.137 & 0.162 & 0.143 \\ 0.128 & 0.136 & 0.133 & 0.151 & 0.138 \end{bmatrix}. \qquad (5)$$

Now, it is essential to rank the criteria based on Saaty's scale which means the pair-wise comparison of the criteria. It is the decision maker's responsibility to verbally judge between the criteria based on their knowledge, scientific or industrial requirements/standards, and the customer's demand. The selected Saaty's scale are summarized in Table 3. The most important parameter in performance assessment of a joint is its strength, therefore, the highest relative importance numbers are associates to the strengths (shear and peel) over the others. However, the relative importance of shear and peel strengths were assumed to be same.

Using scales in Table 3 and Eq. 4 the weight vector of the whole hierarchy calculated as

$$W = \{0.18, 0.11, 0.068, 0.32, 0.32\}^T. \tag{6}$$

By multiplying Equation 5 into Equation 6 final priorities of the alternatives is obtained. The final priorities and rank of the joints are presented in Table 4.

J_5 is ranked as first. Considering the properties of this joint in Table 2, it is evident that the highest shear strength and the lowest head height are corresponds to this joint.

Figure 3 shows the microstructure of the joint in different areas (zones). As seen the lowest grain size is observed in zone 6 corresponds to the area near the outer wall of the rivets tail. This confirms the highest flow of the material in this area. On the other hands, area bellow the head of the rivet (zones 4 and 5) deforms less than the other zone. Therefore, Zones 6 and 3 that have the highest deformation, are more sensitive to crack formation and propagation.

Acknowledgements

Innovate UK is gratefully acknowledged for financially supporting this project.

References

[1] R. Cacko, "Review of different material separation criteria in numerical modeling of the self-piercing riveting process - SPR," Archives of Civil and Mechanical Engineering, vol. 8, no. 2, pp. 21-30, 2008.

[2] D. Li, A. Chrysanthou, I. Patel and G. Williams, "Self-piercing riveting-a review," The International Journal of Advanced Manufacturing Technology, vol. 92, no. 5, pp. 1777-1824, 2017.

[3] R. Haque, "Quality of self-piercing riveting (SPR) joints from cross-sectional perspective: A review," Archives of Civil and Mechanical Engineering, vol. 18, no. 1, pp. 83-93, 2018.

[4] L. Han and A. Chrysanthou, "Evaluation of quality and behaviour of self-piercing riveted aluminium to high strength low alloy sheets with different surface coatings," Materials & Design, vol. 29, no. 2, pp. 458-468, 2008.

[5] A. Jahan, K. L. Edwards and M. Bahraminasab, "4 - Multi-criteria decision-making for materials selection," in Multi-criteria Decision Analysis for Supporting the Selection of Engineering Materials in Product Design (Second Edition), A. Jahan, K. L. Edwards and M. Bahraminasab, Eds., Butterworth-Heinemann, 2016, pp. 63-80.

[6] H. Zafarani, A. Hassani and E. Bagherpour, "Achieving a desirable combination of strength and workability in Al/SiC composites by AHP selection method," Journal of Alloys and Compounds, vol. 589, no. , 2014.

[7] T. L. Saaty, "How to make a decision: The analytic hierarchy process," European Journal of Operational Research, vol. 48, no. 1, pp. 9-26, 1990.

[8] M. Brunelli, Introduction to the analytic hierarchy process, Springer, 2014.

[9] A. Ishizaka and A. Labib, "Review of the main developments in the analytic hierarchy process," Expert Systems with Applications, vol. 38, no. 11, pp. 14336-14345, 2011.

Table 1. SPR parameters for the acceptable joints

Joint	Die diameter, mm	Die depth, mm	Rivet diameter, mm	Rivet length, mm	Rivet Hardness, Hv	Velocity, mm/s	Force, Kgf
J_1	10	1.2	5	7	42	360	82.8
J_2	10	1.4	5	8	44	360	82.4
J_3	10	1.4	5	6.5	44	360	85.4
J_4	10	1.4	5	6.5	44	340	77
J_5	10	1.4	5	6.5	46	350	82.6
J_6	10	1.4	5	6.5	46	345	80.7
J_7	10	1.4	5	6.5	46	340	78.9

Table 2. SPRed joints specifications including interlocking parameters and strengths.

Joint	Head height (h), mm	Bottom thickness (t_b), mm	Deformed rivet diameter (D_{dr}), mm	Shear strength (F_s), Kgf	Peel strength (F_p), Kgf
J_1	0.05 ± 0.01	1.42 ± 0.1	1.3 ± 0.1	8.78 ± 0.15	3.01 ± 0.03
J_2	0.1 ± 0.02	1.33 ± 0.16	1.4 ± 0.1	9.04 ± 0.13	3.06 ± 0.04
J_3	0.06 ± 0.01	1.53 ± 0.12	1.35 ± 0.11	9.54 ± 0.2	3.1 ± 0.06
J_4	0.11 ± 0.02	1.73 ± 0.18	1.32 ± 0.1	8.68 ± 0.16	2.71 ± 0.05
J_5	0.04 ± 0.01	1.1 ± 0.04	1.3 ± 0.1	11.21 ± 0.1	3.01 ± 0.04
J_6	0.06 ± 0.01	1.28 ± 0.06	1.25 ± 0.1	11.11 ± 0.09	3.01 ± 0.03
J_7	0.07 ± 0.01	1.32 ± 0.07	1.22 ± 0.1	10.38 ± 0.12	2.87 ± 0.05

Table 3. Relative importance of the criteria

	Head height	Bottom thickness	Deformed rivet diameter	Shear strength	Peel strength
Head height	1	2	3	0.5	0.5
Bottom thickness	0.5	1	2	0.33	0.33
Deformed rivet diameter	0.33	0.5	1	0.25	0.25
Shear strength	2	3	4	1	1
Peel strength	2	3	4	1	1

Table 6. Rank of joints (alternatives) and their priorities

Rank	Final priorities	Joint
1	0.162	J_5
2	0.149	J_6
3	0.147	J_3
4	0.146	J_1
5	0.139	J_7
6	0.131	J_2
7	0.126	J_4

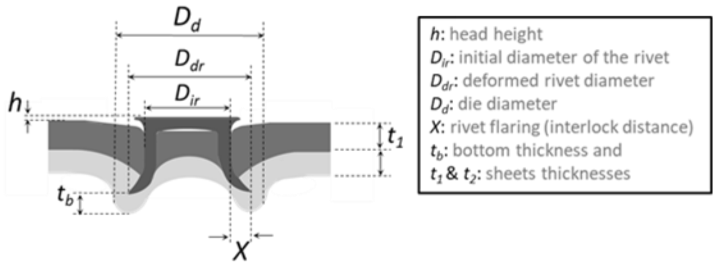

Figure 1: different parameters of a SPR joint.

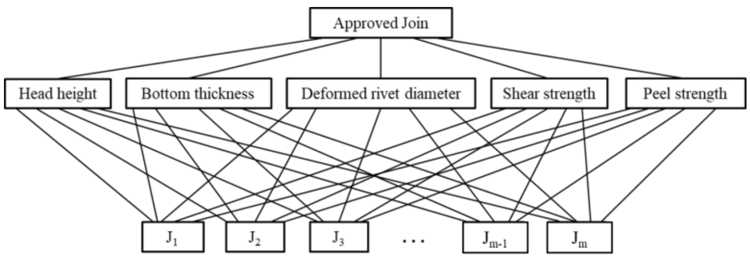

Figure 2: Decision hierarchy structure.

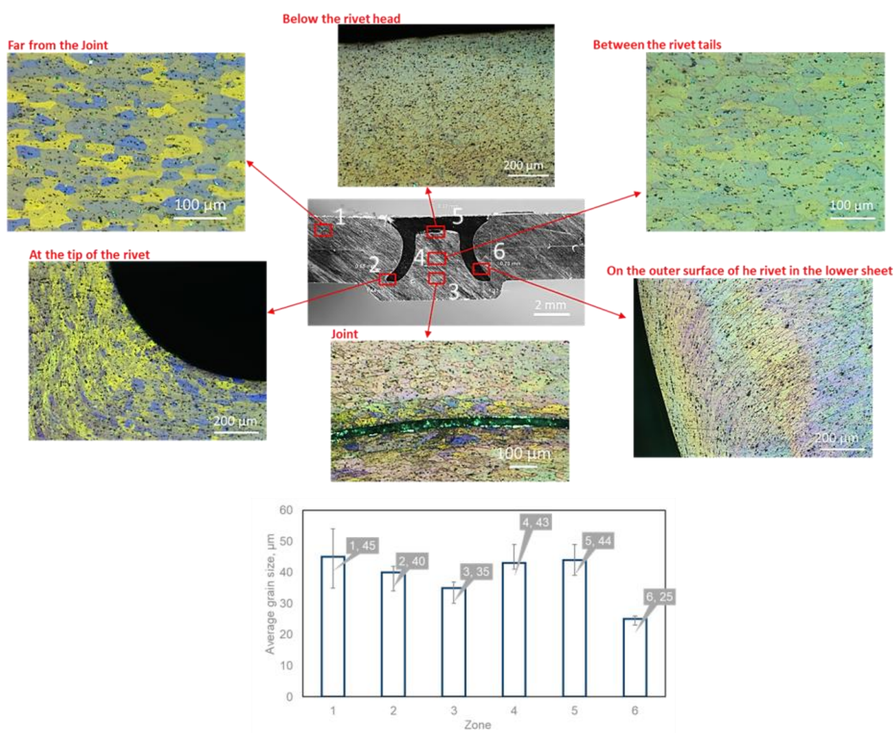

Figure 3: Microstructure of the joint in different zones