MECHANICAL PERFORMANCE OPTIMIZATION OF SIMILAR THIN AA 7075-T6 SHEETS PRODUCED BY REFILL FRICTION STIR SPOT WELDING

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Abstract: Refill friction stir spot welding was applied to weld similar thin AA 7075-T6 aluminum alloy sheets in a spot-like joint configuration without a keyhole. The welds were produced using a small tool consisting of sleeve and probe with diameters of 6 mm and 4 mm, respectively. Design of experiment was employed to optimize the welding parameters in terms of the cross tensile strength by using Box Behnken Design. Based on analysis of variance, it can be concluded that plunge depth strongly affects the mechanical performance of the weld. Optimal welding parameters in terms of rotational speed, plunge depth and speed are identified to reach a cross tensile strength of up to 660 N.

1. Introduction

In the past decades, welding technologies have grown significantly and contributed to the success of the engineering sectors such as in the joining of aircraft structures. Aluminum alloys have been used intensively in the transportation industry, in order to achieve a high fuel consumption efficiency by reducing weight [1-4]. Aluminum alloys are known to be difficult to weld using fusion welding such as arc or laser beam welding. Nowadays, joining of AA 5xxx and 6xxx series Al-alloys using resistance spot welding (RSW) is no longer an issue, and therefore RSW is being successful used in the automotive industry for example by Ford Motor Co. [5].

However, welding high strength aluminum alloys, such as AA 2xxx and AA 7xxx series in similar and dissimilar combinations using fusion welding is still challenging due to the formation of solidification cracking, i.e. hot cracking, and porosity in the fusion zone, which consequently impair their weldability [6-8]. During the solidification process, the gas evolution produced by the excessive hydrogen will lead to porosity formation if it is trapped in the weld. Hydrogen contamination induced porosity in AA 7XXX series due to higher solubility of hydrogen in superheated liquid aluminum [7]. In order to avoid the formation of such defects, solid-state welding processes such as refill friction stir spot welding (refill FSSW) have been introduced for welding hard-to-weld metals. The refill FSSW process, Figure 1, has become a promising welding technology for the aircraft industry in replacing current mechanical fasteners such as rivet, bolt, and screw. In a previous study [3], refill FSSW has been employed to weld 2-mm-thick AA 7075-T6 using a 5 mm diameter probe and 9 mm diameter sleeve where a maximum cross tensile strength (CTS) of 2500 N could be obtained. Despite that, the authors showed that there was still incomplete refill and defects inside the weld. In comparison to the previous work, this study employed a significant smaller diameter tool to weld thin AA 7075-T6 sheets in cross tensile joint configuration. Parameter optimization using design of experiment (DOE) was carried out to optimize the CTS.

2. Methodology

AA-7075 sheets in T6 temper condition with a thickness of 0.6 mm, a width of 50 mm and length of 150 mm were used in this study. The aluminum sheets were welded in cross tensile joint configuration in accordance to ISO 14272.2000 using a small tool consisting of a sleeve and a probe with diameters of 6 mm and 4 mm, respectively. The welding process was carried out at 10 kN welding force using the RPS 100 refill FSSW machine manufactured by Harms & Wende GmbH, Germany. The welds were tested using Zwick Roell 1478 tensile machine at room temperature after three days natural aging upon completion of the refill FSSW. A welding parameter window in terms of rotational speed, plunge depth and plunge speed, was determined based on visual analysis, resulting in suitable welds without surface defects such as incomplete refill and excessive flash, see Table 1. DOE based on Box Behnken Design (BBD) was utilized to optimize the welding parameters. Fifteen sets of welding parameters were determined by BBD. An analysis of variance (ANOVA) was performed to investigate the importance of each welding parameter and their influence on the mechanical performance.

3. Results and Discussion

The welding parameters obtained from the DOE based on BBD with their corresponding CTS results are presented in Table 2 and Figure 2. Based on the results, most of the samples have a CTS of about 500 N. The highest CTS of 593 N was produced by the welding parameters of 3000 rpm rotational speed, 0.7 mm plunge depth and 0.5 mm/s plunge speed. However, three welds, produced using a low plunge depth of 0.5 mm, showed low CTS of about 100 N. This is because the sleeve plunged only into the upper sheet since it is lower than the sheet thickness of 0.6 mm. This might result in minimum material mixing between the lower and upper sheets during welding leading to weak bonding.

ANOVA was utilized to quantify the contribution of each welding parameter and their effects on the CTS with a confident interval of 95 %, as presented in Table 3. P value is used as a tool to determine the significance of each welding parameter and the interaction strength between the welding parameters. In the present study, values lower than 0.05 are considered as significant, and the lower the value, the more significant is the corresponding welding parameter on the CTS. The contribution of each welding parameter to the CTS can be calculated by dividing the sum of squares (SS) of each welding parameter by the total SS. The welding parameters are considered significant if the percentage of contribution is higher than the associated error.

According to the results in Table 3, the plunge depth is the welding parameter affecting the mechanical performance of the welds significantly with 45.43 % contribution. Previous study [9] stated that different plunge depths induce a significant change in mechanical performance due to the hook formation and the height of the effective thickness, in addition to material mixing as mentioned earlier. Additional work still needs to be conducted to further characterize the effect of the plunge depth on the material mixing and the hook formation, and their influence on the mechanical performance. Meanwhile, both rotational speed and plunge speed do not have significant influences on the CTS.

Based on the results obtained from the BBD, a regression model for CTS prediction was developed (Table 3) and depicted in Figure 3. Figure 3(a) illustrated the correlation between plunge depth and plunge speed at constant rotational speed of 2250 rpm, in which a high CTS is predicted at medium to high plunge depth for the entire plunge speed range. At the constant plunge speed of 0.75 mm/s, the CTS is high at low and high rotational speed and medium to high plunge depth, as illustrated in Figure 3(b). At the constant plunge depth of 0.7 mm, the CTS is constantly high for the entire rotational speed range at low to medium plunge speed, as shown in Figure 3(c). ANOVA suggests that the optimized welding parameters to obtain the highest CTS of 643 N are 3000 rpm rotational speed, 0.9 mm plunge depth and 0.6 mm/s plunge speed, as presented in Table 4.

To validate the optimized welding parameters according to ANOVA, some welds were performed using the suggested parameters. The results showed that the suggested welding parameters produced welds with high CTS of 660 ± 36 N. The results showed that ANOVA was successfully predicted the optimized welding parameter leading to high CTS for welding similar AA7075. Additional confirmation tests were also performed to validate the regression model for CTS prediction by selecting additional welding parameters inside the parameter windows (Table 1) to produce some welds, as presented in Table 5. The results showed that the regression model for CTS prediction is in good agreement with the experimental results, as shown in Figure 4.

4. Conclusion

The refill FSSW parameters optimization have been performed to produce welds with high cross tensile strength. The design of experiment was successfully performed using Box Behnken Design and analysis of variance, in which the developed regression model to predict the cross tensile strength has a good agreement with the experimental results.

The optimum combination of parameters for welding similar thin AA 7075-T6 is identified as rotational speed of 3000 rpm, plunge depth of 0.9 mm, and plunge speed of 0.6 mm/s. This combination results in the highest cross tensile strength of up to 660 N.

Plunge depth has a significant influence of about 45 % on the cross tensile strength; a plunge depth lower than the thickness of the upper sheet results in a minimum mixing between upper and lower sheets.

5. Acknowledgement

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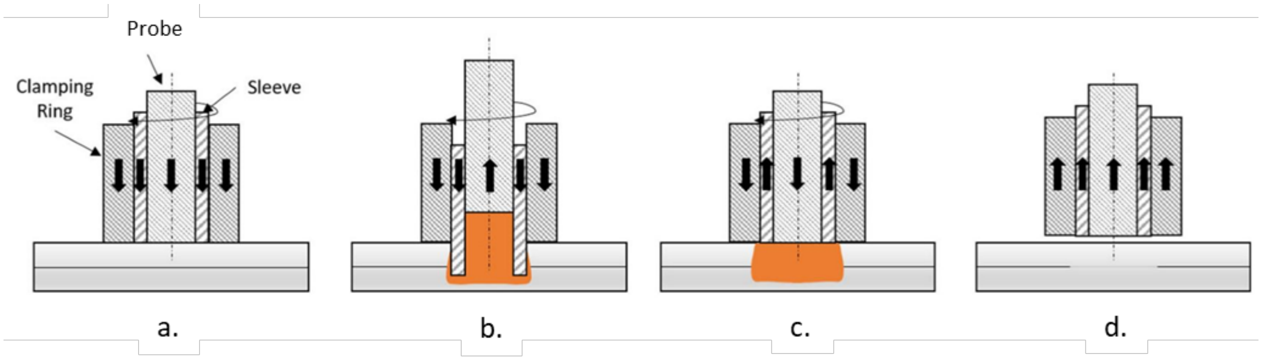


Figure 1 Schematic diagrams of refill FSSW process [9]. Positioning of the tool on the sheets (a), plunging of the rotating sleeve and retracting of the rotating probe (b), movement of the rotating sleeve and probe to initial position (c) and tool removal from the weld (d).

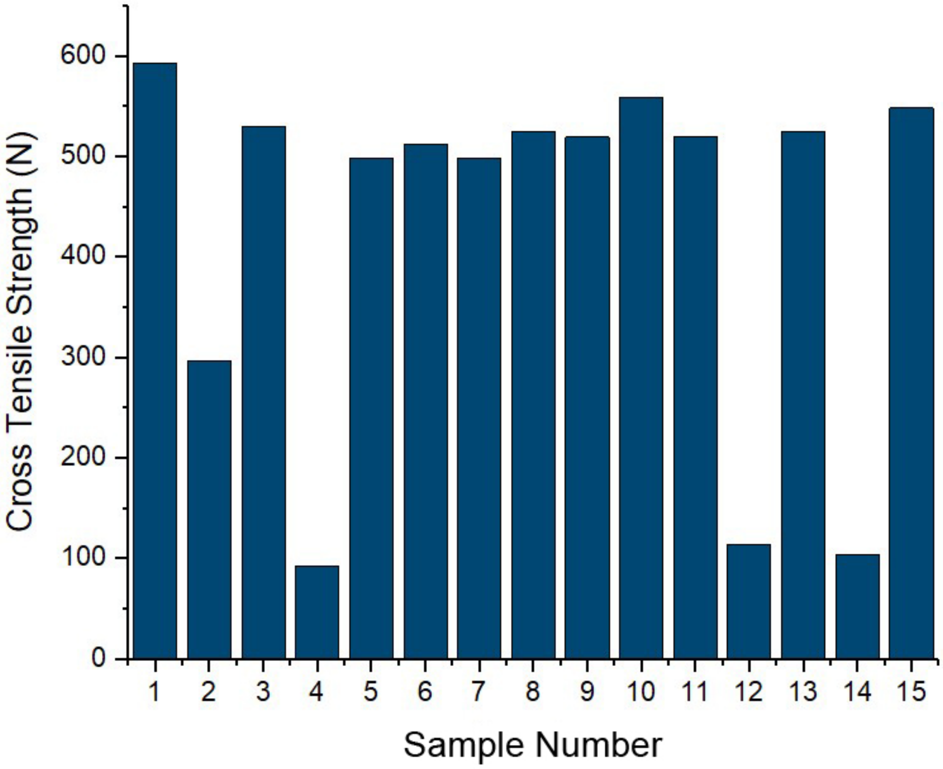
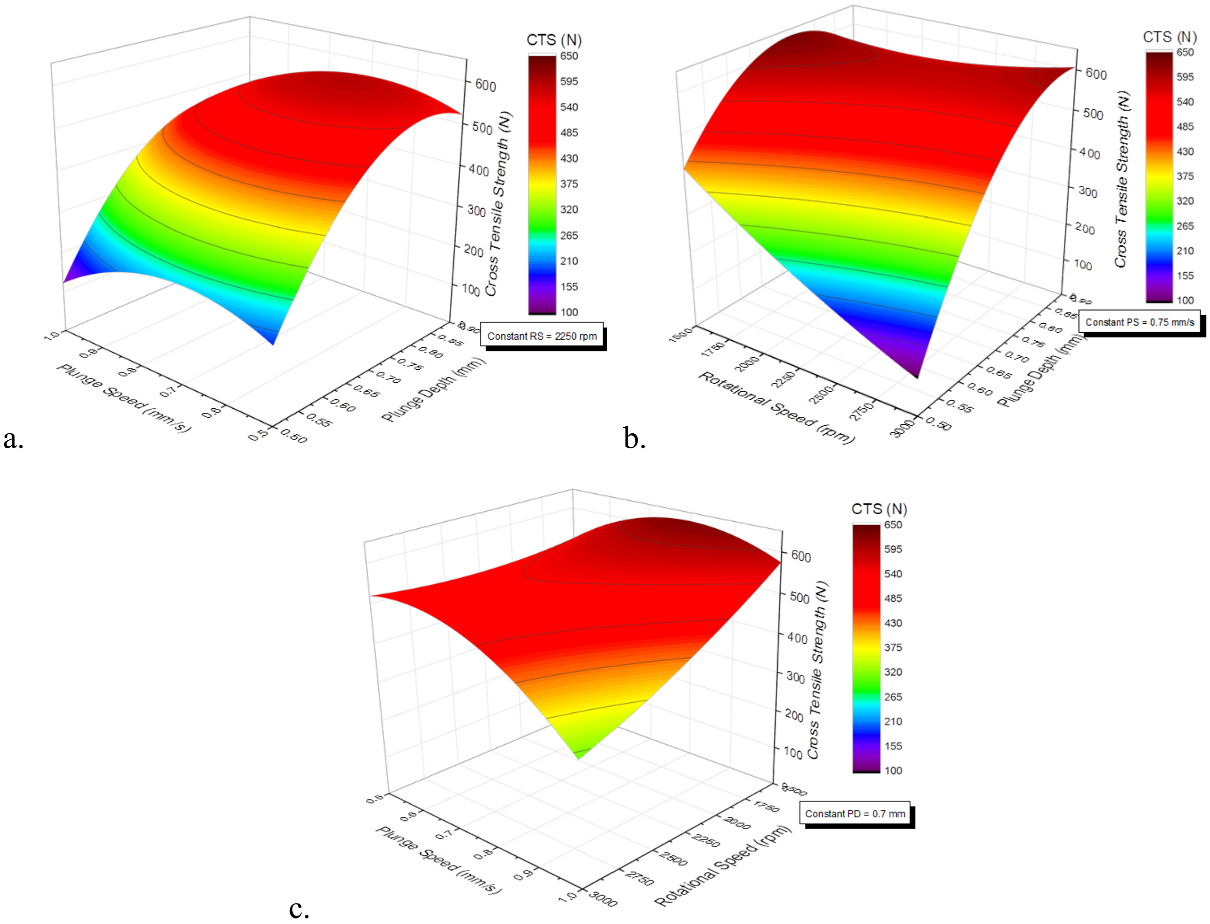


Figure 2 Histogram of the cross tensile strength for all combinations according to BBD.



a.

b.

c.

Figure 3 Surface plots of the cross tensile strength for various welding parameters.

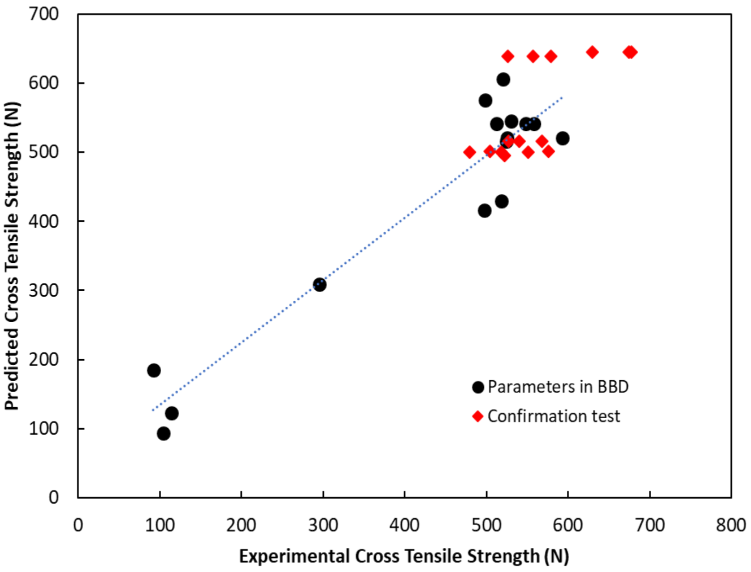


Figure 4 Validation of the regression model for CTS prediction.

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Table 1 Parameters ranges for welding similar AA 7075-T6.

Welding Parameter	Levels	
	-1	1
Rotational Speed, RS (rpm)	1500	3000
Plunge Depth, PD (mm)	0.50	0.90
Plunge Speed, PS (mm/s)	0.50	1.00

Table 2 Welding parameters obtained from BBD and their mechanical performance.

Samples	Rotational Speed (rpm)	Plunge Depth (mm)	Plunge Speed (mm/s)	Cross Tensile Strength (N)
1	3000	0.70	0.50	593
2	3000	0.70	1.00	296
3	1500	0.90	0.75	530
4	2250	0.50	0.50	92
5	1500	0.50	0.75	498
6	2250	0.70	0.75	512
7	1500	0.70	1.00	498
8	1500	0.70	0.50	524
9	2250	0.90	1.00	519
10	2250	0.70	0.75	558
11	3000	0.90	0.75	520
12	2250	0.50	1.00	114
13	2250	0.90	0.50	525
14	3000	0.50	0.75	104
15	2250	0.70	0.75	548

Table 3 Analysis of variance of the welding parameters and their corresponding mechanical performance.

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Contribution (%)**
Model	9	411122	45680	5.22	0.042	-
Linear	3	254430	84810	9.70	0.016	-
RS (Rotational Speed)	1	36046	36046	4.12	0.098	7.92
PD (Plunge Depth)	1	206626	206626	23.63	0.005	45.43
PS (Plunge Speed)	1	11758	11758	1.34	0.299	2.59
Square	3	101267	33756	3.86	0.090	-
RS*RS	1	1393	1393	0.16	0.706	0.31
PD*PD	1	78440	78440	8.97	0.030	17.25
PS*PS	1	24227	24227	2.77	0.157	5.33
2-Way Interaction	3	55425	18475	2.11	0.217	-
RS*PD	1	36864	36864	4.22	0.095	8.10
RS*PS	1	18360	18360	2.10	0.207	4.04
PD*PS	1	200	200	0.02	0.886	0.04
Error	5	43725	8745			-
Lack-of-Fit	3	42554	14185	24.23	0.040	9.36
Pure Error	2	1171	585			0.26
Total	14	454846				-
Predicted CTS = -1723- 0.422*RS+4571*PD+2703*PS+0.000035*RS*RS-3644*PD*PD-1296*PS*PS+ 0.640*RS*PD-0.361*RS*PS-142*PD*PS						

Table 4 Optimized welding parameters suggested by the ANOVA.

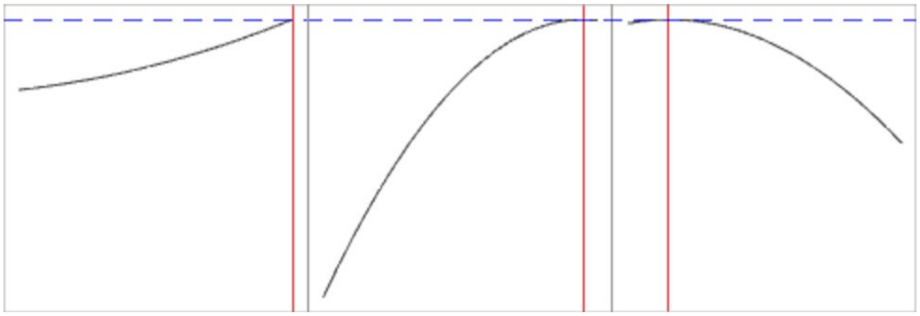
<table>
<tr><td>Optimal
D: 1.000
Predict</td><td>High
Cur
Low</td><td>RS
3000
[3000]
1500</td><td>PD
0.9
[0.8798]
0.5</td><td>PS
1.0
[0.5758]
0.5</td></tr>
<tr><td colspan="2">Cross tensile
maximum
y = 643.6387
d =1.0000</td><td colspan="3"></td></tr>
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Table 5 Additional results to validate the regression model for CTS prediction.

Sample	Rotational Speed (rpm)	Plunge Depth (mm)	Plunge Speed (mm/s)	Cross Tensile Strength (N)
1	3000	0.90	0.60	661 ± 36
2	2500	0.70	0.50	559 ± 49
3	2000	0.70	0.50	516 ± 36
4	3000	0.90	0.50	554 ± 27