The effects of welding parameters on the tensile shear strength of refill friction stir spot welding of 7075-T6 aluminium alloy joints

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Abstract. The paper presents the results of an analysis of the effect of welding parameters on the load capacity of joints obtained by the refill friction stir spot welding (RFSSW) method. This technology has a prospective application in aerospace and automotive industries, especially for aluminium alloys. The research was conducted for the overlapping joints made of two 7075-T6 aluminium alloy sheets with thicknesses 1.6 mm and 0.8 mm. Strength tests were conducted for two variants of loading the joint. The experiments were conducted according to statistical Hartley's plan PS/DS-P:Ha_3. The welding times *t* was varied in the range of 1.5 ÷ 3.5 s, the tool plunge depth *g* in the range of 1.5 ÷ 1.9 mm, and the tool rotational speed *n* in the range of 2000 ÷ 2800 rpm. For these parameters the analysis of experiment reproducibility, impact significance and adequacy of equations were made. The results of analysis according to the design of the experiment (DOE) indicate that all analyzed parameters have significant influence on the load capacity of joints. The biggest load capacity of joints in the case of the first variant was gained at the maximum spindle speed of 2800 rpm, the minimum tool plunge depth of 1.5 mm and welding time of 1.5 s. For the second variant, the maximum load capacity of joints was gained at the spindle speed of 2400 rpm, tool plunge depth of 1.5 mm and welding time of 2.5 s.

1 Introduction

Refill friction stir spot welding and using RFSSW to fill craters is becoming one of the most commonly used methods of spot welding in the automotive [1, 2] and aviation [1, 3] industries. The technology, especially in the case of aluminium alloys, has a great amount of potential application. 7Xxx aluminium alloys [4, 5] are currently among the strongest and most commonly available materials used in the aviation and transport industries. In aircraft structures, the RFSSW technique [6, 7] can potentially be an alternative to resistance spot welding. An example of using this technology could be welding the fuselage covering of an aircraft. The attractiveness of this joining method results from technological-economical benefits like high production output and welding process stability that ensures high repeatability simplifying the automation of the process. Another benefit would be the ability of joining materials with different properties and better safety conditions in the workplace, when compared to traditional welding methods [4, 8, 9, 10]. This technique can be used to joint different types of materials like composites [11, 12], thermoplastics [13, 14] and non-weld-able alloys [4, 5].

Experimental design and optimization are tools that are systematically used to study various types of problems such as academic studies, development problems, and production problems [15]. Considering the high cost and the amount of time needed to conduct a study, the experimental design needs to be properly planned, the experiment needs to be properly conducted and the results need to be properly analyzed [16]. The literature on the topic has many descriptions of various methods and experimental design plans. Their methods are properly supported, as are their mathematical fundamentals and results analysis methodologies. Thus, it is possible to adapt an experimental design to any research problem that results in a rational study [17]. Patel et al. [18] use a DOE experimental design when determining the effect of welding parameters and tool geometry on the shear strength of joints made using FSW.

The RFSSW method requires the selection of appropriate welding parameters because they decide on

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the quality of the joint. Incorrect process parameter selection causes the joints to have countless defects in the macro and microstructure, which will lower the strength of the joint [4, 19, and 20]. Thus, determining the parameters, which will affect the strength of a joint, is the most important. As a result, the Hartley static PS/DS-P:Ha$_3$ plan was selected to study the effect of process parameters of the RFSSW method on the shear strength of 7075-T6 aluminium alloy joints. The determined plan is characterized by its initial factors being selected in a strictly predetermined fashion and ordered according to certain rules that eliminate random factor selection. The plan is designed to minimize the number of experiments, and its greatest feature is the simplicity of the mathematical analysis [17].

2 Method

The effects of welding parameters on the tensile shear strength of refill friction stir spot welding were conducted according to statistical Hartley's plan PS/DS-P:Ha$_3$. The subject of the study was the overlapping joint of 7075-T6 aluminium alloy sheets with two different sheet thicknesses 1.6 mm and 0.8 mm (Fig. 1). The chemical composition of this alloy is Si - 0.4, Fe - 0.5, Cu - 1.2 ÷ 2, Mn - 0.3, Mg - 2.1 - 2.9, Cr - 0.18 ÷ 0.35, Zn - 5.1 ÷ 6.1, Ti - 0.2, other impurities: single0.05, total 0.15, Al - rest. The experimental investigations of the RFSSW process were conducted with an application of the HARMS WENDE machine. All experiments were realized with triple repetition. The significance level α = 0.05 was accepted for calculations.

The tool rotational speed n (rpm), tool plunge depth g (mm) and welding time t (s) were established as input factors. The output factor in the experiment was shear strength. Strength tests were conducted for two variants of loading the joint. In the first variant, with the usage of a special holder, pure shear strength was obtained (Fig. 2). For comparison, a tensile strength test was conducted in the second case. The single lap joint was subjected to tensile test on a ZWICK Z100 machine, where a grip translation speed was 5 mm/min.

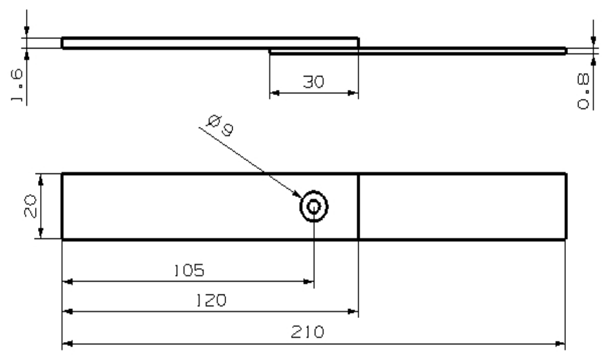

Fig. 1. Shape and dimension of the sample for RFSSW process.

The plan of the experiment implies the adoption of three levels of controlling factors: the minimum (-), the central (0) and the maximum (+). The welding times t was varied in the range of 1.5 ÷ 3.5 s, the tool plunge depth g in the range of 1.5 ÷ 1.9 mm, and the tool rotational speed n in the range of 2000 ÷ 2800 rpm. The matrix of the Hartley's plan with three input factors is presented in Table 1.

Table 1. Matrix of plan PS/DS-P: Ha$_3$.

Nr	x_1	x_2	x_3	x_1^2	x_2^2	x_3^2	x_1x_2	x_1x_3	x_2x_3
1	-	-	+	+	+	+	+	-	-
2	+	-	-	+	+	+	-	-	+
3	-	+	-	+	+	+	-	+	-
4	+	+	+	+	+	+	+	+	+
5	-	0	0	+	0	0	0	0	0
6	+	0	0	+	0	0	0	0	0
7	0	-	0	0	+	0	0	0	0
8	0	+	0	0	+	0	0	0	0
9	0	0	-	0	0	+	0	0	0
10	0	0	+	0	0	+	0	0	0
11	0	0	0	0	0	0	0	0	0

* x_1- coded value of tool rotational speed n, x_2 - coded value of tool plunge depth g, x_3 - coded value of welding times t.

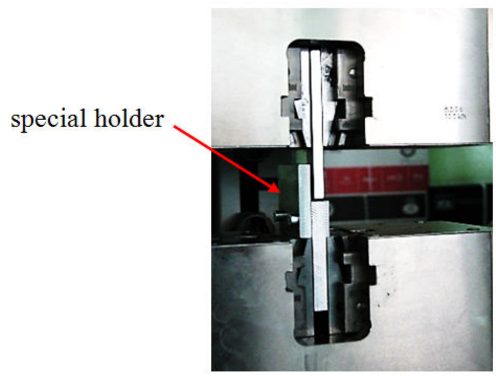

Fig. 2. Strength test example.

3 Results and discussion

The average load carrying capacity of joints resulting from the RFSSW method of various welding parameters is presented in Table 3.

Table 2. Average values of load capacity of joints obtained after welding process RFSSW method at differential parameters according to Hartley's plan.

No.	Input factors			Output factors	
	n rpm	g mm	t s	R_{tp} N	R_t N
1	2000	1.5	3.5	7000	6475
2	2800	1.5	1.5	7805	6480
3	2000	1.9	1.5	5510	4955
4	2800	1.9	3.5	5290	5265
5	2000	1.7	2.5	6735	5990
6	2800	1.7	2.5	6980	6260
7	2400	1.5	2.5	7350	6550
8	2400	1.9	2.5	6015	5535
9	2400	1.7	1.5	6720	6110
10	2400	1.7	3.5	6955	5910
11	2400	1.7	2.5	6400	5550

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The joints that were tested for pure shear through the use of a special device (variant I) show a 8-20% higher load carrying capacity compared to samples that underwent a simple shear strength test (variant II) (Fig. 3). The slight difference between the two variants is presented in experiment No.4 where the maximum values of the experimental factors are tested, i.e. n = 2800 rpm, g = 1.9 mm and t = 3.5s.

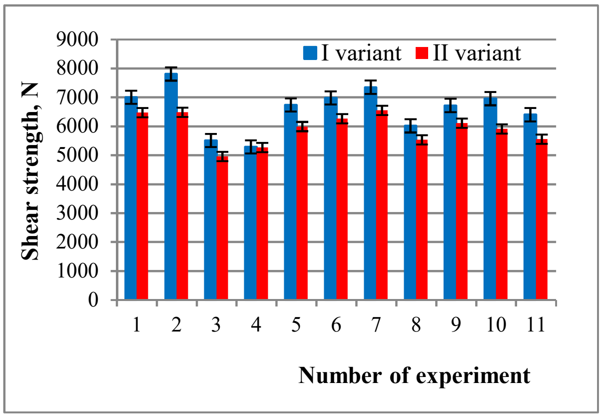

Fig. 3. Average values of shear strength of joints.

As a result of the regression, a functional relation between the process parameters (n, g, t) and the pure shear strength (R_{tp}), tensile shear strength (R_t), were determined. These relations are described by the following equations (Eqs. 1-2):

$$R_{tp} = 6763{,}29 - 890\,g - 1001{,}25nt \qquad (1)$$

$$R_t = 5593{,}96 - 625\,g - 683{,}75nt \qquad (2)$$

For the first variant, the biggest load capacity of joints, 7805 N, was gained at the maximum tool rotational speed of 2800 rpm. The minimum tool plunge depth of 1.5 mm and welding time of 1.5 s. A minimum value of load capacity of joints 5290 N, was obtained at experiment No. 4, for n = 2800 rpm, g = 1.9 mm and t = 3.5 s. For the second variant the maximum load capacity of joints 6550 N, was gained at the tool rotational speed of 2400 rpm, tool plunge depth of 1.5 mm and welding time of 2.5 s. At a tool rotational speed n = 2000 rpm, g = 1.9 mm and t = 1.5 s the smallest value load capacity of joints 4955 N, was observed. The tool plunge depth is very important parameter that affects the strength of joints. For the tool plunge depth of 1.5 mm the load capacity of joints is the best in turn for the g = 1.9 mm the worst.

When analyzing the results of the static shear strength tests (Figs. 4-14), 3 types of weld failure can be observed in RFSSW joints. The ones with the most shallow tool plunge depth n = 1.5 (Fig. 4a), (Fig. 5a) and the welding time of t = 2.5 s and rotational speed of n = 2400 rpm (Fig. 10b), (Fig. 11b) demonstrate weld shearing without damaging the welded material (type I) These also had the greatest load carrying capacity.

In the second case (type II) the welds were torn out of the thinner sheet metal, (Fig. 6a, 9a, 10a) and (Figs. 4b-9b, Figs. 12b-14b). This demonstrates the essential value of one the parameters, tool plunge depth g = 1.7 mm, which affect this type of joint. These joints have a lower load carrying capacity compared to other joints made with a lesser tool plunge depth.

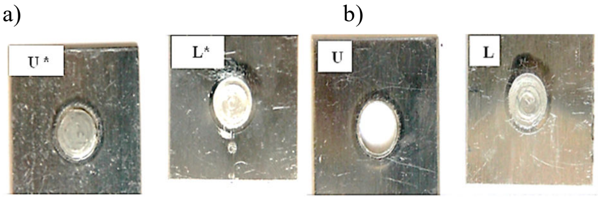

Fig. 4. Experiment No. 1. Illustration type of failure modes observed under the shearing test: a) I variant, b) II variant.
* (U) Bottom view of the upper sheet and (L) top view of the lower sheet.

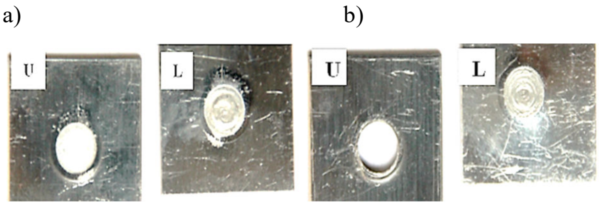

Fig. 5. Experiment No. 2. Illustration type of failure modes observed under the shearing test: a) I variant, b) II variant.

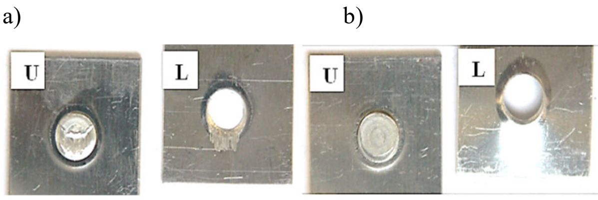

Fig. 6. Experiment No. 3. Illustration type of failure modes observed under the shearing test: a) I variant, b) II variant.

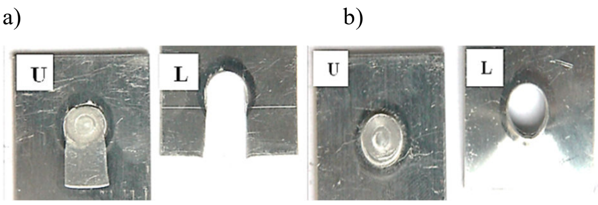

Fig. 7. Experiment No. 4. Illustration type of failure modes observed under the shearing test: a) I variant, b) II variant.

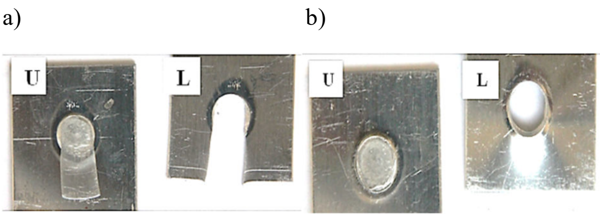

Fig. 8. Experiment No. 5. Illustration type of failure modes observed under the shearing test: a) I variant, b) II variant.

The type III failure occurred when there was a partial tear of the parent material and welded out of the bottom

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piece of sheet metal. This only occurred in the cases where the static shear strength test was conducted with the additional device (Fig. 7a, 8a, 11a-14a). The tool plunge depth of g = 1.7 mm and the rotational speed of n = 2400 rpm also had an effect on this type of failure.

a) b)

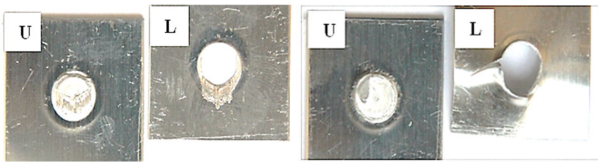

Fig. 9. Experiment No. 6. Illustration type of failure modes observed under the shearing test: a) I variant, b) II variant.

a) b)

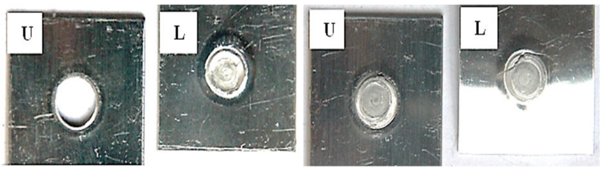

Fig. 10. Experiment No. 7. Illustration type of failure modes observed under the shearing test: a) I variant, b) II variant.

a) b)

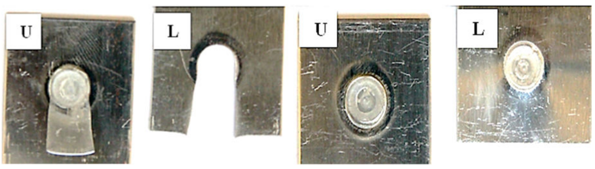

Fig. 11. Experiment No. 8. Illustration type of failure modes observed under the shearing test: a) I variant, b) II variant.

a) b)

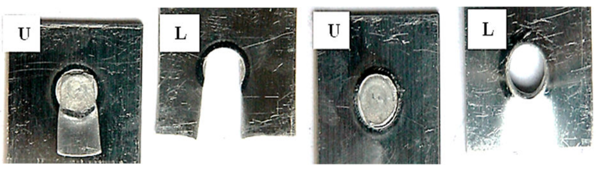

Fig. 12. Experiment No. 9. Illustration type of failure modes observed under the shearing test: a) I variant, b) II variant.

a) b)

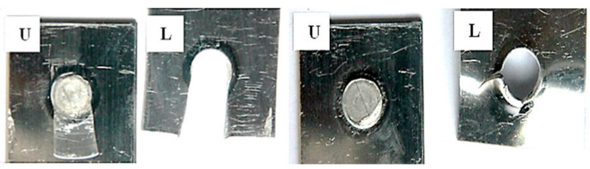

Fig. 13. Experiment No. 10. Illustration type of failure modes observed under the shearing test: a) I variant, b) II variant.

The high correlation coefficient of R = -0.91 shows that there is a strong relation between the tool plunge depth and the load carrying capacity of the joint. An increase in tool plunge depth reduces the load carrying capacity of the joint.

a) b)

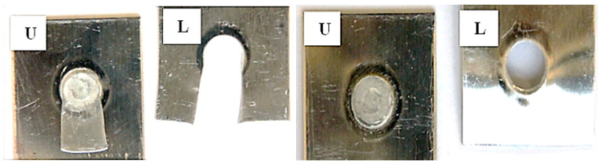

Fig. 14. Experiment No. 11. Illustration type of failure modes observed under the shearing test: a) I variant, b) II variant.

4 Conclusions

As the results of the investigation, the adequate equations were obtained describing the effect of welding parameters on tensile shear strength of the RFSSW process. These equations indicate that all analyzed parameters have a significant influence on the quality of welding joints. The load carrying capacity of the first variant is between 8 and 20% greater than the values obtained in variant II. The results of the static shear strength test demonstrate 3 types of mechanical failures for spot welds made with the RFSSW method. The tool plunge depth had a significant effect on the type of mechanical joint failure. An increase in tool plunge depth resulted in a decrease in the load carrying capacity. The greatest load carrying capacity was achieved for tests with an n = 1.5 mm tool plunge depth, while an n = 1.9 mm tool plunge depth resulted in the lowest load carrying capacity. This is confirmed by the high value of the correlation coefficient R = - 0.91. The confirmation of the test values and the calculated values weld load carrying capacity demonstrates that Hartley's plan is appropriate for this type of study.

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