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Research Article

THE EFFECT OF RFSSW PARAMETERS ON THE LOAD BEARING CAPACITY OF ALUMINUM 7075-T6 SHEET METAL JOINTS

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ABSTRACT

Friction Stir Spot Welding is one of the most contemporary methods of joining metals and alloys in their solid state. The ability to join elements made of aluminum alloys allows for utilizing this method in the manufacturing of aircraft structures while lowering the work load, costs, and weight, without sacrificing or even having better strength parameters than classic methods of joining elements. It ensures constant joint parameters, however it requires the use of optimal welding parameters such as: the rotational speed of the tool, tool delve depth, and welding time. The work presents the results of experiments conducted on 7074 aluminum sheet metal that was 1.8 and 0.8 mm thick, which conducted in accordance with the PS/DK32 research plan. The welding tests were done on a dedicated spot welding machine, while the strength tests consisted of static tensile strength tests. In the final part of the article contains an analysis and interpretation of the results.

Keywords: Friction stir spot welding, aluminium 7075-T6, process parameters.

INTRODUCTION

Aircraft structures must meet the most demanding safety requirements because of the exceptional responsibility they carry. This issue is extremely complex because these parts must, at the same time, have lowest possible mass, acceptable manufacturing costs, endurance, and the appropriate strength [6].

Its critical requisite standing before the aviation industry is the development of an inexpensive method for joining age hardened aluminum alloys, which will ensure good joint strength while requiring a lower work load, in comparison to traditional methods.

Difficulties in making high quality welded joints in the automotive industry through the use of traditional methods have been partially overcome with a new joining method known as friction stir welding. This method is based on local (point) friction heating in the area of joint by a rotary tool. This type of welding can be done by leaving a crater left from the tool pin (FSSW – Friction Stir Spot Welding) or by closing the crater (RFSSW – Refill Friction Stir Spot Welding [7, 16, 19]) (Fig. 1). The RFSSW method of welding sheet metal consists of three basic phases [7, 12]. In the first phase, the mixing pin and the sleeve are positioned on the plane of the top sheet of the joint. Next, the pin and sleeve are accelerated to their nominal rotational speed (n). The simultaneous rotation of the pin and sleeve generate heat from friction, which heats and plasticizes the metal in the joint area.

The second phase consists of the penetration of the joint by the sleeve, which plunges into the material causing (g) its plasticization. Simultaneously, the pin is withdrawn, thus ensuring that there is space for the translated material. Next, an opposed motion of the pin and sleeve squeeze the plasticized metal in the direction of the joint. At the end of the process, the sleeve and pin are reset

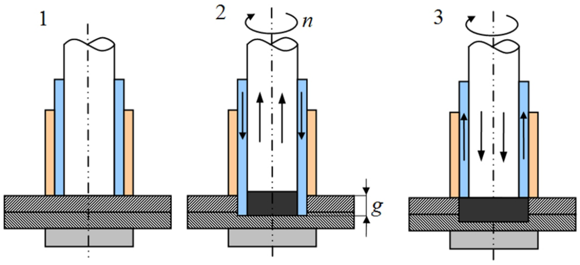

Fig. 1. Steps of Refill Friction Stir Spot Welding [15]

in the initial position, after which the tool withdraws from the joint.

Spot welding causes a decline in riveting and gluing light alloys because of its multiple advantages [1, 8, 18-21]:

- It does not require drilling parts and using rivets as additional fasteners,
- The load carrying capacity of welds can reach a greater value than riveted joints,
- Welded joints have a great resistance to corrosion due to the absence of elements with a different electrochemical potential than the joined material,
- It is possible to conduct simple repairs of joints,
- No part of the joint extends beyond the surface of the joined elements,
- Possibility of not being air tight because of the joint is eliminated.

The knowledge of the phenomena that occur during the process of spot welding is not quite satisfactory, which makes it difficult to select the optimal parameters for conducting the process for selected aviation grade alloys. Many authors [2-11, 15-17] have tested the effects of the initial parameters of spot welding on the load carrying capacity of joints and achieved various results concerning the significance of the effect of each parameter and the optimal values. Zhahua and others [21] conducted research regarding spot welding of 1mm thick 5052-H112 aluminum sheet metal, stating that welding time did not have a significant effect on the load carry capacity of the joint. On the other hand, research regarding the spot welding of AA3003H11 aluminum sheet metal conducted by Mumin Tutar [14] shows that all of the initial parameters of the process including rotational speed n, tool dive depth g, and welding time t have a significant effect on the process. Thus, it is impossible to unambiguously decide what the optimal values of the initial parameters of the process are because they depend on the type of material, thickness of the joined sheets, and type and condition of the tool [3, 9, 11, 13]. The goal of the research was to develop a mathematical model of the effect of initial parameters of the RFSSW method on the load carrying capacity of lap joints on 7075-T6 aluminum sheet metal, which is widely used in aircraft structures.

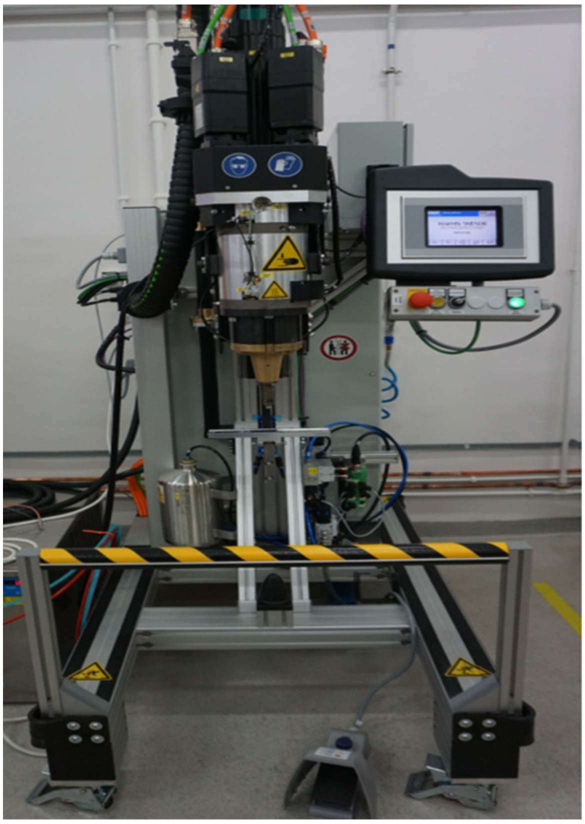

Fig. 2. Haras & Wende RPS 100 VA11 refill friction stir spot welding station

RESEARCH METHODOLOGY

The sheet metal spot welding research was conducted on a Haras & Wende RPS 100 VA11 friction stir spot welding machine. The subject of the research was a lap joint between 7075-T6 sheet metal of 1.8 and 0.8mm thickness. The AW-7075 aluminum alloy (Fortal) has high mechanical strength – comparable to structural steel, and great fatigue strength. It is a very good material for chip machining, deep pocketing as well, has average corrosion resistance, and is a good candidate for grinding, polishing and electric discharge machining. It is used for blow molds, molds for foams, punching tools, and in the aviation industry as heavily loaded structural parts.

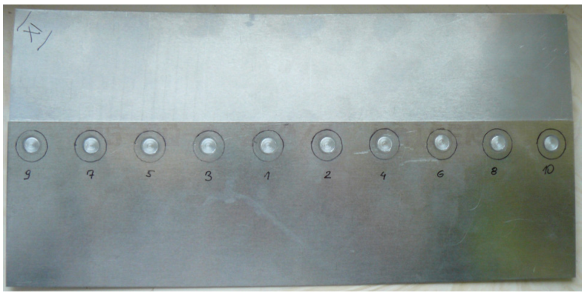

Fig. 3. Spot sequence during spot welding tests

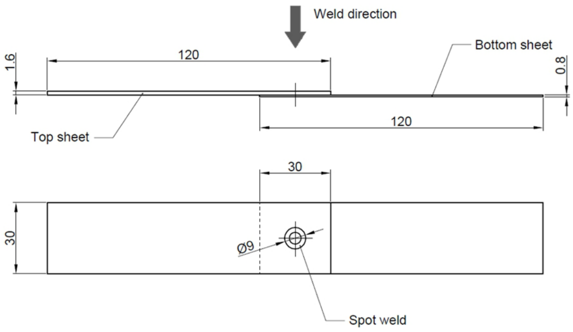

Fig. 4. Static shear strength test sample dimensions

The shear strength tests of the load carrying capacity of the joints were conducted on a ZWICK Z-100 strength test machine. The translation speed of the jaws during the test was 5mm/min. The spot welding tests on the 7075-T6 aluminum sheet metal were conducted in the order presented in Figure 3. The resulting sheets were used to make samples for a static shear test with lap length and width of 30mm (Fig. 4).

The research initially showed that the spot welding process was most affected by tool rotational speed n and tool dive depth g. The welding time, suggested by the machine manufacturer, (t = 1-1.5s) with a $\alpha = 0.05$ significance level variance did not significantly affect the spot welding process, nor did it affect the load carrying capacity of the joint. The results have a large spread with a low correlation coefficient of 0.059.

In order to achieve viable information from the conducted tests with minimum effort, the tests were conducted based on a static 3 level PS/DK 3^2 plan. In this plan, the initial factors are represented by 3 levels (Fig. 5) [5]:

- higher – labeled +1
- average (zero) – labeled 0
- lower – labeled -1

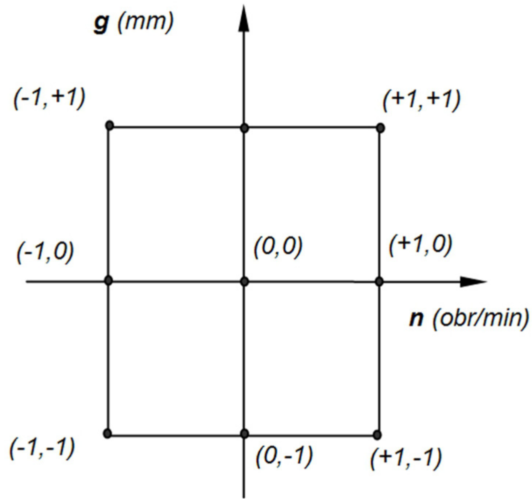

Fig. 5. Graphic interpretation of the PS/DK 3^2 plan [5]

Based on the conducted research, the initial factors were:

- rotational speed n, variable in the range of 2200-3000rpm,
- tool dive depth g, variable in the range of 1.35-1.75mm.

The tests were conducted at constant welding times of 1.5s. Table 1 presents the values of the parameters and method of coding the factors.

Table 1. Values of technological parameters set in the experiment

Inpuct factors	n [rpm]	g [mm]
The minimum (-)	2200	1.35
The central (0)	2600	1.55
The maximum (+)	3000	1.75
The code of the variables	$x_1 = \dfrac{n-2600}{400}$	$x_1 = \dfrac{g-1.5}{0.2}$
Output factor	F[kN]	

Table 2. Matrix test plan PS/DK 3^2 and test results

No.	x_0	x_1	x_2	x_1^2	x_2^2	$x_1 x_2$	$\bar{y}$	$S^2(y)_i$
1	+	+	+	+	+	+	3,763	0,003233
2	+	+	0	+	0	0	4,097	0,001233
3	+	+	-	+	+	-	3,807	0,000933
4	+	0	+	0	+	0	2,767	0,017033
5	+	0	0	0	0	0	3,247	0,008133
6	+	0	-	0	+	0	2,957	0,000533
7	+	-	+	+	+	-	2,217	0,000933
8	+	-	0	+	0	0	2,813	0,006433
9	+	-	-	+	+	+	2,440	0,001600

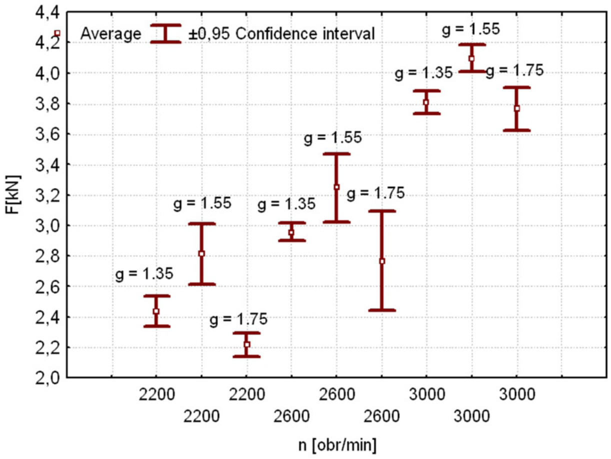

Fig. 6. Static shear strength test results

RESULTS AND ANALYSIS

Logical framework of the experiment and results of the static shear strength test measurements were placed in Table 2. It also contains the calculation results of the variance values of the measurements $S^2(y)_i$.

The largest force values recorded during the static shear strength test had a tool dive depth of 1.55mm at every level of rotational speed. It should be noted that an increase in rotational speed resulted in an increase in load carrying capacity. At a rotational speed of 2200 rpm, an average joint strength of 2.81kN was achieved. Increasing the rotational speed to 2600 rpm caused observable increase of joint load carrying capacity of 15.3% (3.25kN). The largest force (4.09kN) was registered for the speed of 3000 rpm (Fig. 6).

The goal of the research was to develop an adequate mathematical model in the form of a second degree polynomial with a significance level of α = 0.05:

$$y = b_o + \sum b_k x_k + \sum b_{kk} x_k^2 + \sum b_{kj} x_k x_j \tag{1}$$

where: x_k, x_j – initial factors, b_o, b_k, b_{kk}, b_{kj} – equation regression coefficients, y – result factor (measured value)

The function was determined based on the dependence:

$$b_0 = \frac{1}{9}(-\bar{y}_1 + 2\bar{y}_2 - \bar{y}_3 + 2\bar{y}_4 + 5\bar{y}_5 + 2\bar{y}_6 - \bar{y}_7 + 2\bar{y}_8 - \bar{y}_9) = 3.252 \tag{2}$$

$$b_1 = \frac{1}{6}(\bar{y}_1 + \bar{y}_2 + \bar{y}_3 - \bar{y}_7 - \bar{y}_8 - \bar{y}_9) = 0.699 \tag{3}$$

$$b_2 = \frac{1}{6}(\bar{y}_1 - \bar{y}_3 + \bar{y}_4 - \bar{y}_6 + \bar{y}_7 - \bar{y}_8) = -0.076 \tag{4}$$

$$b_{11} = \frac{1}{6}(\bar{y}_1 + \bar{y}_2 + \bar{y}_3 - 2\bar{y}_4 - 2\bar{y}_5 - 2\bar{y}_6 + \bar{y}_7 + \bar{y}_8 + \bar{y}_9) = 0.199 \tag{5}$$

$$b_{22} = \frac{1}{6}(\bar{y}_1 - 2\bar{y}_2 + \bar{y}_3 + \bar{y}_4 - 2\bar{y}_5 + \bar{y}_6 + \bar{y}_7 - 2\bar{y}_8 + \bar{y}_9) = -0.393 \tag{6}$$

$$b_1 = \frac{1}{4}(\bar{y}_1 - \bar{y}_3 - \bar{y}_7 + \bar{y}_9) = 0.045 \tag{7}$$

The repeatability rating (stability) of the conditions of conducting the experiment was made with the use of Cochran criteria. In order to verify the hypothesis of the variance repeatability, a G coefficient was determined:

$$G = \frac{S^2(y)_{i\max}}{\sum_{i=1}^{N} S^2(y)} = 0.4251 \tag{8}$$

Which was compared to the critical value based on the accepted significance level of α = 0.05 and the number of degrees of freedom determined based on the relationship:

$$f_1 = N = 9 \tag{9}$$

$$f_2 = r - 1 = 2 \tag{10}$$

where: r – the number of parallel measurements

The value of Cochran's statistics were less than the critical value $G_{kr} = G_{(\alpha,f1,f2)} = 0.4775$ (0.4251 < 0.4775). As a result, the repeatability of the experimental conditions can be considered satisfactory. The factor significance rating of the equation regression was conducted by comparing its values with the critical value determined from the formula:

$$b_{kr} = t_{(\alpha,f)}\sqrt{\frac{S^2(y)}{Nr}} = 0.0128 \tag{11}$$

where $t_{(a,f)} = t_{kr} = 2.1009$ is the test value of the t coefficient from the t-Student chart.

Considering the absolute value of all the equation regression coefficients had a value greater than the critical value $|b_k| > b_{kr}$. It was accepted that they affect the function regression value significantly. After substituting the determined values of the b_o, b_k, b_{kk}, b_{kj} coefficients in to equation (1), the following regression equation was achieved:

$$y = 3.252 + 0.699x_1 - 0.076x_2 + 0.199x_1^2 - 0.394x_2^2 + 0.045x_1x_2 \tag{12}$$

After decoding the regression equation modelling the effects of friction stir spot welding on the load carrying capacity F, resulting in the following form (Fig. 7):

$$F = -13.668 + 28.683g - 9.847g^2 + 0.00561n + 1.246 \cdot 10^{-6} n^2 + 0.000562ng \tag{13}$$

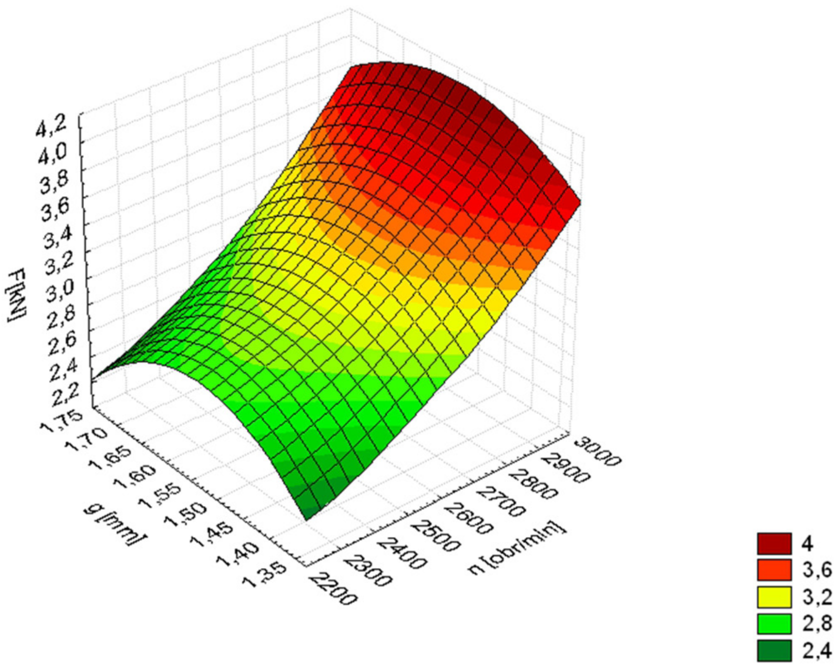

Fig. 7. Spot welding parameter effect on the load carrying capacity of joints

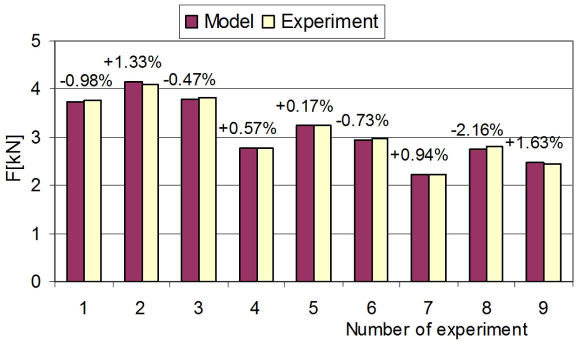

Fig. 8. Theoretical and experimental joint load carrying capacity

To determine how adequate the regression equation is, a Fisher-Snedecor test was used. During first stage of the analysis, the adequateness variance was determined:

$$S_{ad}^2 = \frac{r\sum_{i=1}^{N}\left(\overline{y_i} - \overline{\overline{y}}_i\right)^2}{N-k-1} = 0.01117 \tag{14}$$

where: $\overline{y}_i$ – average value of measurement results in the i[th] experiment, $\overline{y}_i$ – the value calculated from the regression equation for initial and result factors of the i[th] experiment, k – the number of regression equation expressions (without a free expression) after rejecting insignificant expressions, r – number of repetitions, N – number of experiments

Next, the value of the F test coefficient were determined:

$$F = \frac{S_{ad}^2(y)}{S^2(y)} = 2.5095 \tag{15}$$

It was compared with the critical value from the Fisher-Snedecor distribution $F_{kr} = F_{(a, f1, f2)} = F_{(0.05, 3, 18)} = 3.1599$. Due to the value of the test coefficient being smaller than the critical value $F < F_{kr}$ ($2.5095 < 3.1599$), the resulting regression equation (13) was accepted as adequate with a significance level of $\alpha = 0{,}05$. The maximum error of the regression function (Fig. 8) does not exceed 2.16%, however the mean square error of the research results and mathematical model was 1%.

An analysis of the results shows that the greatest load carrying capacity can be achieved at 3000 rpm and at a tool dive depth of 60% of the lap joint. Excessively shallow tool delves do not allow the achievement of withstanding adhesive joining of the sheet metal. However, excessive depths cause a visible weakening of the thinner sheet. This results in a total shear of the thinner fragment during the static shear test causing a weakening of the joint.

CONCLUSION

Friction stir spot welding represents one of the most modern methods of joining aluminum alloys. The results of the experiment show that the method can be successfully used in the aviation industry because it can ensure high joint strength while lowering the workload during installation. However, it requires determining the correct setting parameters like rotational speed and tool dive depth. The results of this study show that the greatest load carrying capacity can be achieved at a rotational speed of 3000 rpm and a tool dive depth of 60% of the lap joint. It should be noted that the that high rotational speed of the tool causes the significant plasticization of the material which sticks to its work surfaces and gets in the space between the sleeve and pin, disrupting its work. Conducting the process at such parameters requires frequent cleaning of the tool, which increases the work load.

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