UDK 621.791.1:669.715:621.3.017.71
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 52(3)283(2018)

FRICTION STIR WELDING OF 2024-T3 ALUMINIUM ALLOY SHEET WITH SHEET PRE-HEATING

VRTILNO TORNO VARJENJE PREDGRETE PLOČEVINE IZ ALUMINIJEVE ZLITINE 2024-T3

Andrzej Kubit[1], Rafał Kluz[1], Krzysztof Ochałek[1], Dawid Wydrzyński[1], Tomasz Trzepieciński[2]

[1]Rzeszow University of Technology, Department of Manufacturing and Production Engineering, al. Powst. Warszawy 8, 35-959 Rzeszów, Poland
[2]Rzeszow University of Technology, Department of Materials Forming and Processing, al. Powst. Warszawy 8, 35-959 Rzeszów, Poland
tomtrz@prz.edu.pl

Prejem rokopisa – received: 2017-06-26; sprejem za objavo – accepted for publication: 2017-11-23

doi:10.17222/mit.2017.084

Friction stir welding is one of the most modern methods of joining metals and their alloys in the solid state. Ensuring the stability of working parameters requires a determination of the optimal welding parameters such as the rotational speed of the tool and the feed rate. This article presents the results of tests on welding of 1-mm-thick 2024-T3 aluminium sheet metal conducted in accordance with a PS/DK3[2] test plan. The welding tests were conducted on a universal milling machine, and the static strength tests were conducted on a static tensile-testing machine. In order to decrease the deformation of the joined sheets, some welding trials were also conducted with initial heating of the sheet metal. Therefore, a special fixture with a heated bed was developed. The tests show that the pre-heating of thin sheets that are friction stir welded leads to a reduction in the deformation size of the joined sheets. It was found that the smallest deformation of the joined sheets was observed in the case of joining sheets heated up to a temperature of 200 °C. Pre-heating of the joined sheets decreased the size of the deformations by 57.62 %.

Keywords: aluminium alloy, friction stir welding, joint capacity, strength

Vrtilno-torno varjenje je ena od najbolj modernih metod spajanja kovin in njihovih zlitin v trdnem stanju. Zagotavljanje stabilnih delovnih parametrov določajo optimalni parametri varjenja, kot sta hitrost vrtenja orodja in hitrost pomika varjencev. V pričujočem članku avtorji podajajo rezultate preizkusov varjenja 1 mm debele pločevine iz Al zlitine 2024-T3 v skladu s preizkuševalnim planom PS/DK32. Preizkuse varjenja so izvajali na univerzalni stružnici. Mehansko trdnost zvarnih spojev pa so določili s pomočjo standardnega trgalnega stroja. Zato, da bi zmanjšali deformacijo spajane pločevine so nekaj preizkusov varjenja izvedli na predgreti pločevini. V ta namen so morali razviti posebno držalo z ogrevano posteljico (uporovno ogrevano pečico). Preizkusi so pokazali, da predgrevanje tanke pločevine zmanjša deformacijo vrtilno-torno varjenega spoja. Ugotovili so tudi, da najmanjšo deformacijo doseţejo, če je pločevina pred varjenjem predgreta na 200 °C. Predgrevanje pločevine zmanjša deformacijo za 57,62 %.

Ključne besede: zlitina na osnovi aluminija, vrtilno torno varjenje, nosilnost, trdnost varjenega spoja

1 INTRODUCTION

Friction stir welding (FSW) is an environmentally friendly solid-state technique for joining metals and their alloys (at temperatures lower than the melting temperatures of the based materials). It is especially useful in the joining of materials that are traditionally considered to be difficult to weld, such as steel and high-strength aluminium, copper and titanium alloys, and even some alloys of nickel, zirconium, and copper.[1–4] The FSW joining process avoids the formation of solidification cracking and porosity.

The main idea of FSW relies on introducing a rotating cylindrical tool into the contact with the joined elements and moving it along the seam of the joint. As a result, the friction, which generates heat, plasticizes the material to create a mechanical-plastic joint. In these conditions, the materials penetrate each other in the solid state by rotating around the axis of the tool, ensuring stirring in the area of the joint without reaching the melting point. After making the joint, the tool is removed from the work zone.[5–7]

The ability to join elements made of aluminium alloys allows this method to be used in the manufacture of aircraft structures, while lowering the workload, costs, and weight, maintaining strength parameters that are comparable to or better than those obtained by traditional joining methods with the use of joining elements. The FSW process offers the advantages of ensuring:[3]

- elimination of the need to bevel sheet metals,
- higher resistance to brittle cracking of the joint than the parent material,
- high static and dynamic strength properties, higher than those achieved by conventional methods,
- the possibility of conducting the process on conventional milling machines,
- simple tooling technology
- no overheating of the heat-affected zones, which are consequently not weakened,

- lack of heat cracking as a result of welding.

In order to ensure that the joining conditions are stable, it is necessary to determine the optimal welding parameters such as the geometry and tool rotational speed,[8,9] feed rate, tool inclination angle, downward force, and tool pin depth (**Figure 1**). During the FSW process, the joined materials are mechanically stirred, and this stirring is accompanied by the generation of a large amount of heat. The heat generated by the friction between the tool and the sheets leads to material flow. The large temperature gradients, like in traditional welding, generate thermal stresses. This is one of the flaws that occur during the process of linear sheet metal welding. Undoubtedly, the diameter of the flange and the downward force play an important role in the heating of the material. The amount of heat generated is greater due to an increase of these parameters. Using an insufficient downward force results in the material being insufficiently stirred, which results in voids within the weld.

When the temperature is too low, the joint is a result of adhesion, which can be characterized as having low strength. When the pressing force is too large, the weld is concave and its transverse section is smaller.[10] The temperature during the welding process has a direct effect on the quality of the joint. When high-melting-point alloys are processed, they are initially heated in order to decrease their yield stress. The tests presented by J. Tang and Y. Shen[11] show that an increase in the rotational speed of the tool leads to an increase in the process temperature as well. On the other hand, an increase in the feed rate lowers it. At low tool rotational speeds, the flange generates the majority of the heat, while an increase in rotational speed causes the role of the pin in the heating of the material to become greater.

In the aviation industry, it is especially important to develop technology that decreases the deformation of thin sheet metal during welding, while maintaining a good joint strength. In this paper the FSW technique is used to join aluminium alloy sheets. A special fixture with a heated bed is developed in order to decrease the deformation of the joined sheets. Further, a series of tests on the effect of process parameters on the load capacity of the joint were conducted. The tests were conducted using a static three-level plan. On the basis of this, a mathematical model was developed. For the process parameters that ensured the greatest load capacity of the joint, additional tests were conducted with initial heating of the sheet metal. The effect of feed rate and tool rotational speed on the load capacity of joints is analysed. Due to the technological limitations regarding the ability to control the tool's downward force, the feed rate and tool rotational speed were selected as the variable parameters of the FSW. The goal of the tests was to develop a suitable mathematical model in the form of a second-degree polynomial with a significance level of $\alpha = 0.05$:

$$y = b_0 + \sum b_k x_k + \sum b_{kk} x_k^2 + \sum b_{kj} x_k x_j \qquad (1)$$

where x_k and x_j are the initial factors, b_o, b_k, b_{kk}, and b_{kj} are regression function coefficients, and y is the result factor (measured value).

In order to achieve a correct model, the main focus was placed on the values of feed rate (40–80 mm/min) and tool rotational speed (900–1500 min^{-1}). The results of the measurements and some of the calculations are presented in **Table 1**.

Table 1: PS/DK3^2 test logic matrix and experimental results

No.	x_0	x_1	x_2	x_1^2	x_2^2	$x_1\ x_2$	$\bar{y}$	$\bar{\bar{y}}$	$S^2(y)_i$
1	+	+	+	+	+	+	4.31	4.38	0.01045
2	+	+	0	+	0	0	4.62	4.59	0.0189
3	+	+	-	+	+	-	4.54	4.53	0.001033
4	+	0	+	0	+	0	4.77	4.76	0.06305
5	+	0	0	0	0	0	4.81	4.79	0.00445
6	+	0	-	0	+	0	4.61	4.57	0.0443
7	+	-	+	+	+	-	4.70	4.79	0.0039
8	+	-	0	+	0	0	4.54	4.65	0.0021
9	+	-	-	+	+	+	4.37	4.25	0.0079

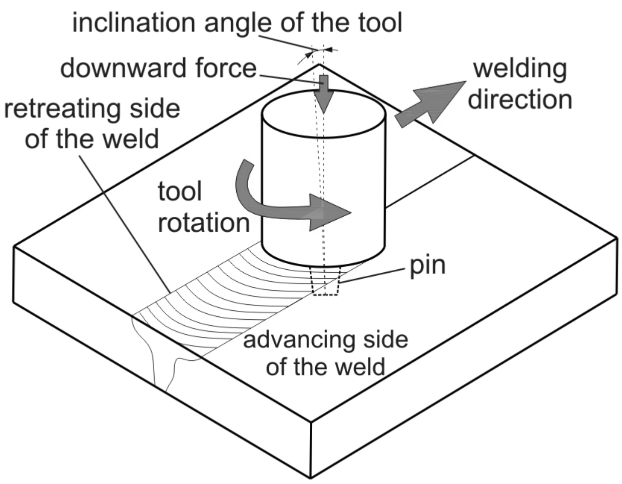

Figure 1: Diagram of friction welding process

2 METHODOLOGY

Initial tests showed that the factors with the greatest effect on the FSW process were the feed rate v_f, tool rotational speed n, and downward force. The remaining parameters did not have a significant effect on the quality of the joint. Due to the technological limitations regarding the ability to control the tool pressing force, the tests were conducted at different values of feed rate and tool rotational speed. In order to attain reliable information from the trials conducted at a minimum workload, the tests were conducted in accordance with a static three-level PS/DK3^2 test plan.[12]

3 EXPERIMENTAL PART

3.1 Material

The tests on the FSW welding process were conducted on a universal vertical milling machine. The subject of the tests was butt joints in 1-mm-thick 2024-T3 aluminium sheet, which belongs to the unweldable group of materials, characterized by poor oxidation resistance. The chemical composition of this material is listed in **Table 2**. The nominal mechanical properties of the joined material are an ultimate tensile strength of R_m = 360–425 MPa, yield stress of $R_{p0,2}$ = 250–290 MPa, hardness of 104–123 HB, elongation of A_5 = 12–14%. The thermal conductivity of the 2024-T3 aluminium alloy is 137–170 W/m K. The 2024–T3 alloy is used to manufacture aircraft equipment, transmission shafts, bolts, parts of hydraulic valves and pistons, and worm drives.

3.2 Experimental procedure

A rotational tool with a helix pin (**Figure 2a**) was made of high-speed steel and heat treated to increase its hardness to 55 HRC. The dimensions of the tool are presented in **Figure 2b**. In order to improve the welding process, a special fixture was designed, which ensured constant pressure and a repeated position of the joined sheet metal relative to the tool. When considering additional heating of the welded sheets, a fixture with a heated work bed (**Figure 3**) was designed and produced.

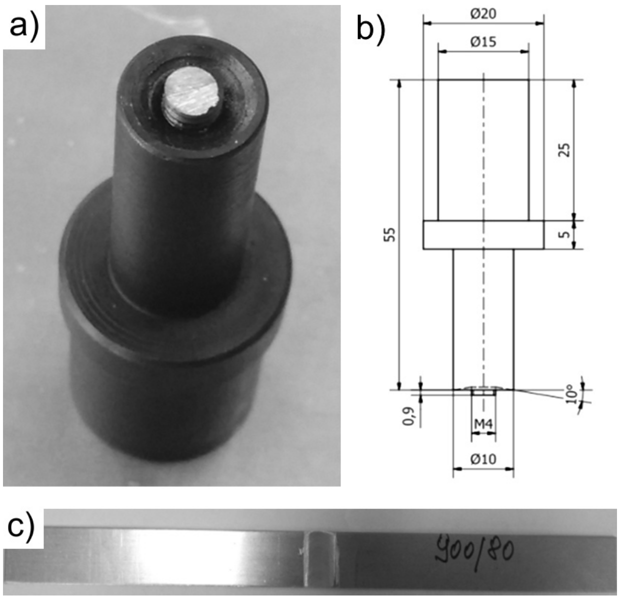

Figure 2: a) View and b) dimensions of the tool used for welding sheet metal, and c) a sample used in the tensile strength test

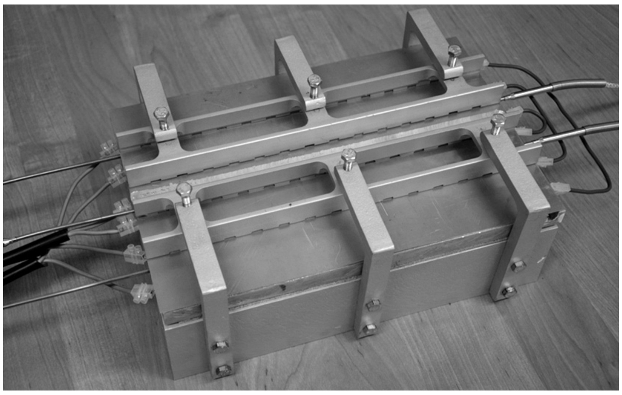

Figure 3: FSW fixture with heated bed

The fixture allows pre-heating of the whole volume of the sheet and makes it possible to control the sheet temperature during the welding process. The clamps of the fixture were designed to allow observation of the temperature distribution and to absorb a minimal amount of heat (small contact area). The frame was made from a channel section attached to an aluminium plate, where 12 heating coils and five sensors with CP-03 converters were placed. Due to its temperature range and measurement precision, the PT100 sensor was selected. The heating system was controlled by a Siemens LoGoV8 PLC controller. The system was divided into three circuits. In order to ensure faster temperature control, two coils were placed in each channel of the aluminium alloy plate. In order to reduce the temperature gradient, the circuits were placed symmetrically relative to the centre of the plate. A temperature sensor was placed directly below the place where the welding was to occur and this sensor was surrounded on both sides by a circuit. The following two circuits were placed symmetrically and PT100 sensors were placed between them. The heating bed was thermally insulated from the steel fixture base.

3.3 Tensile testing

The maximum tensile strength of the welded joints is determined in a uniaxial tensile-strength test conducted on a Zwick/Roell Z100 universal testing machine. The samples (**Figure 2c**) used in the strength tests were cut from the butt jointed sheets perpendicularly to the weld seam. The width of the samples was 12.5 mm.

The tensile force *F* was measured with an initial tension of 5 N and a speed of 0.2 mm/s. During the uniaxial static tensile tests, the maximum load capacity of the welded joint was measured.

Table 2: Chemical composition of the 2024-T3 aluminium alloy, in mass fractions (*w*/%)

Cu	Si	Fe (max)	Mn	Mg	Zn (max)	Cr	Ti	Others		Al
								Each	Total	
3.80–4.90	0.50	0.50	0.30–0.90	1.20–1.80	0.25	0.10	0.15	0.05	0.015	Bal.

4 RESULTS

4.1 Effect of feed rate

The results of the tests on the FSW joints show that the destructive forces *F* attain a value of 4.31 kN for samples welded at a rotational speed of 1500 min^{-1} and feed rate of 80 mm/min and a maximum value of 4.81 kN for a rotational speed of 1200 min^{-1} and feed rate of 60 mm/min. These values represent 75.61–84.38 % of the force required to destroy a sample made of the base material (5.7 kN). An analysis of the change in load capacity of the joint as a function of feed rate (**Figure 4a**) shows the nonlinear character of the effect of the feed-rate change on the amount of load carried by the joint. The similarity of the curves determined for the tool rotational speeds of 1200 min^{-1} and 1500 min^{-1} is visible. Both curves exhibit an initial tendency to increase the load capacity with the increase of feed rate and then reach a maximum value followed by a slight decrease in the load capacity of the joint. This decrease is more evident in samples made with a rotational speed of 1500 min^{-1}. In the case of samples made at a rotational speed of 900 min^{-1}, a nearly linear increase in strength with an increase in feed rate is observed.

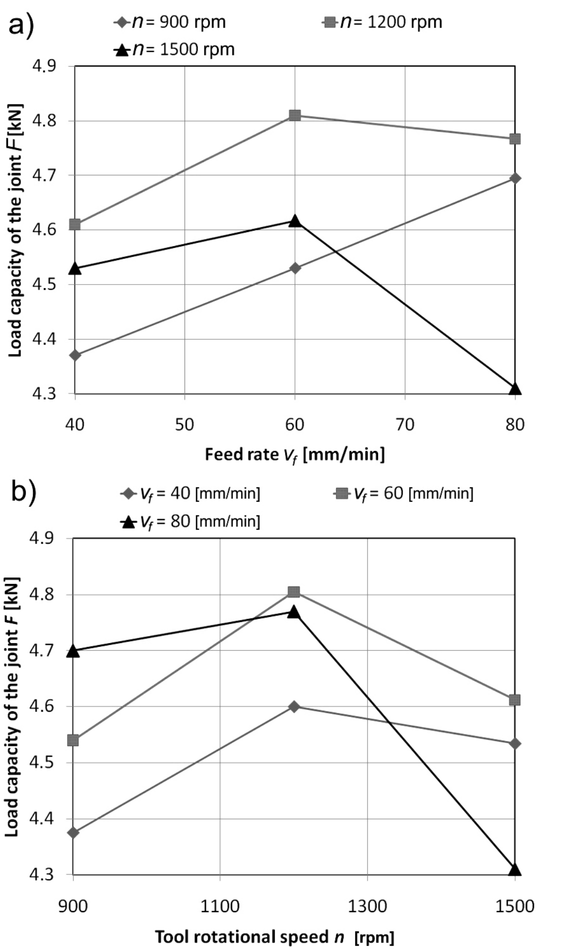

Figure 4: Maximum load carried by a welded joint as a: a) function of feed rate and b) as a function of tool rotational speed

4.2 Effect of tool rotational speed

In the case of the graph presenting the relationship between the maximum load carried by the joint as a function of rotational speed (**Figure 4b**), the curves of the respective feed rates show the same tendency. Regardless of the adopted feed rate, the greatest joint strength was observed for those joints made with a rotational speed of 1200 min^{-1}. All of the characteristics are nonlinear and visualize the trend of decreasing strength with increases in the tool rotational speed. In the case of the curve representing the feed rate of 40 mm/min, it can be observed that the maximum load of 4.61 kN is achieved at 1200 min^{-1}, after which an increase in rotational speed lowers the strength of the joint. The largest decrease of joint strength was recorded for samples made with a feed rate of 80 mm/min.

It should be noted that this type of analysis is insufficient to determine the complete effect of changing the working parameters on the quality of the welded joint created. A correct analysis requires the development of a mathematical model in the form of a function (Equation (1)).

4.3 Statistical analysis

The assessment of repeatability (stability) of the conditions in which the experiments were conducted was carried out with the use of Cochran's C test.[13] This test is used to decide whether a single estimate of a variance (or a standard deviation) is significantly larger than a group of variances (or standard deviations) with which the single estimate is supposed to be comparable. In order to verify the hypothesis of repeatability of the variance, a coefficient *G* was determined in Equation (2):

$$G = \frac{s^2(y)_{i\max}}{\sum_{i=1}^{N} s^2(y)} = 0.3794 \tag{2}$$

which was compared to the critical value based on the assumed significance level of $\alpha = 0.05$ and the number of degrees of freedom determined based on the relationships in Equations (3) and (4):

$$f_1 = N = 9 \tag{3}$$

$$f_2 = r - 1 = 2 \tag{4}$$

where *r* is the number of repetitions and *N* is the number of experiments.

The value of Cochran's statistic was less than the critical value $G_{\text{kr}} = G_{(\alpha,\text{f1},\text{f2})} = 0.4775$ (0.3794 < 0.4775). As a result, the repeatability of the experimental conditions can be considered satisfactory. The assessment of the significance of the coefficients in the regression equation was conducted by comparing its values with the critical value determined from the formula:

$$b_{\text{kr}} = t_{(\alpha,\text{f})}\sqrt{\frac{s^2(y)}{Nr}} = 0.0105 \tag{5}$$

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

Because the absolute values of all the equation regression coefficients were greater than the critical value $|b_k| > b_{kr}$, it was assumed that they affect the regression function value significantly. After substituting the determined values of the coefficients b_o, b_k, b_{kk}, and b_{kj} into Equation (1), the following regression equation was achieved:

$$y = 4.794 - 0.031x_1 - 0.0956x_2 - 0.0178x_1^2 - 0.13x_2^2 - 0.0174x_1x_2 \quad (6)$$

After decoding Equation (6), the regression equation modelling the effect of the FSW parameters on the load-carrying capacity F (**Figure 5**) takes the following form:

$$F = -1.483 + 0.0786\, v_f - 0.000325\, v_f^2 + 0.00639\, n - 0.000029\, v_f\, n - 1.981 \cdot 10^{-6}\, n\, v_f \quad (7)$$

To determine how adequate the regression equation is, a Fisher–Snedecor test was used. During the first stage of the analysis, the adequacy of the variance was determined in Equation (8):

$$s_{ad}^2 = \frac{r\sum_{i=1}^{N}\left(\bar{y}_i - \bar{\bar{y}}_i\right)^2}{N-k-1} = 0.0368 \quad (8)$$

Where $\bar{y}_i$ is the average value of the measurement results in the *i-th* experiment, $\bar{\bar{y}}_i$ is the value calculated from the regression equation for the input and output factors of the *i-th* experiment, k is the number of regression equation expressions (without a free expression) after rejecting insignificant expressions, r is the number of repetitions, and N is the number of experiments.

Then, the value of the F-test coefficient was determined in Equation (9):

$$F = \frac{s_{ad}^2(y)}{s^2(y)} = 2.126 \quad (9)$$

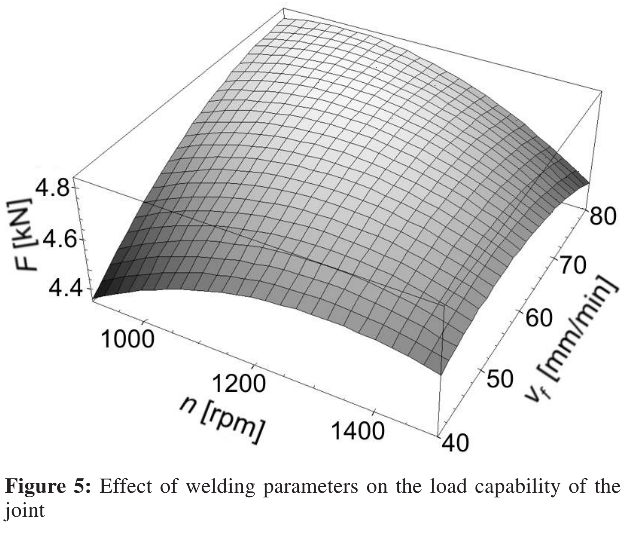

Figure 5: Effect of welding parameters on the load capability of the joint

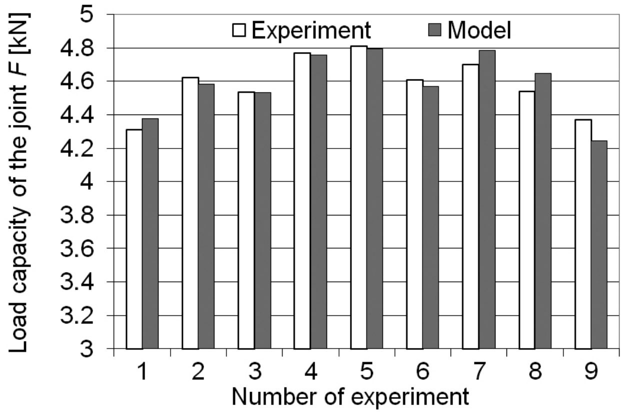

Figure 6: Theoretical and experimental load capacity of the joint

This value has been compared with the critical value from the Fisher-Snedecor distribution $F_{kr} = F_{(\alpha,f1,f2)} = F_{(0.05,3,18)} = 3.1599$. Because the value of the test coefficient was smaller than the critical value $F < F_{kr}$ (2.126 < 3.1599), the resulting regression Equation (13) was accepted as adequate at a significance level of $\alpha = 0.05$. The maximum error of the regression function (**Figure 6**) does not exceed 2.36 %; however, the mean square error of the research results and the mathematical model was 0.41 %.

4.4 Effect of sheet pre-heating

In order to determine the amount of joint deformation after welding, a grid (**Figure 7**) was placed on the welded sheet metal. Next, the joints were measured with a height calliper.

The values of these deformations for non-heated and pre-heated joints are presented in **Figures 8a** and **8b**, respectively. During the welding of the samples made with the parameters ensuring maximum joint strength ($n = 1200\ \text{min}^{-1}$, $v_f = 60$ mm/min), a maximum temperature of 350 °C was registered. On this basis, the bed-heating temperatures of (150, 180, and 200) °C were selected for further analyses. Next, the welding tests were conducted

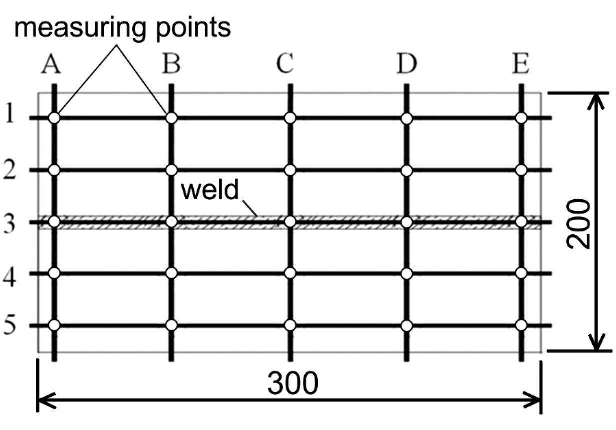

Figure 7: Grid placed on welded sheet metal

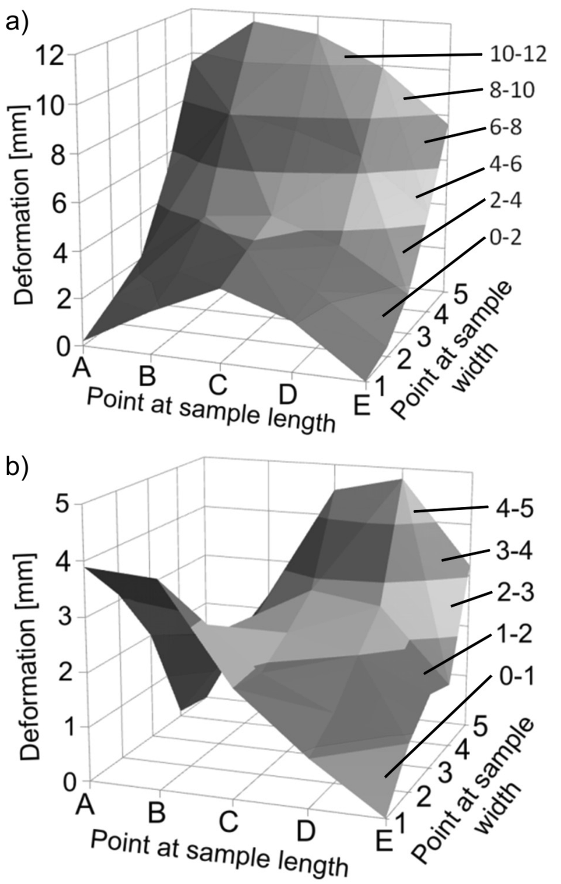

Figure 8: Sheet-metal deformation resulting from FSW: a) without and b) with pre-heating

and the amount of sheet deformation was measured. The best results were achieved for the pre-heating temperature of 200 °C, which resulted in the smallest deformation (**Figure 8b**). A further increase in temperature did cause a decrease in the amount of sheet-metal deformation of 4.8 mm.

The results show that the pre-heating of the thin FSW sheet metal leads to a decrease in the amount of deformation, which can be observed by comparing the results shown in **Figures 8a** and **8b**. The difference between the amounts of deformation is significant. The maximum deformation of sheet metal without pre-heating was 11.6 mm (**Figure 8a**), while introducing pre-heating into the process decreased this value to 4.8 mm (**Figure 8b**).

5 CONCLUSIONS

The results of the FSW joining experiments on 2024-T3 alloy sheets show that the best results that gave the greatest load capacity of the joint were achieved by a joining process realized at a rotational speed of 1200 min^{-1} and a feed rate of 60 mm/min. The strength of the joint was equivalent to 84.38 % of the force required to destroy the sample of base material. With the use of an additional heat source that ensures pre-heating of the whole volume of the joined sheets and maintenance of the temperature during welding, a much more evenly spread temperature gradient was achieved. The tests show that pre-heating of FSW thin sheet leads to a reduction in the amount of deformation due to the heat generated during the FSW process. In the case of the tests conducted, pre-heating of the sheet metal to a temperature of 200 °C decreased the amount of deformation by 57.62 % compared to the non-preheated sheets.

6 REFERENCES

[1] M. M. Z. Ahmed, S. Ataya, M. M. El-Sayed Seleman, H. R. Ammar, E. Ahmed, Friction stir welding of similar and dissimilar AA7075 and AA5083, Journal of Materials Processing Technology, 242 (**2017**), 77–91, doi:10.1016/j.jmatprotec.2016.11.024

[2] S. Balos, L. Sidjanin, M. Dramicanin, D. L. Zlatanovic, A. Antic, FSW welding of Al-Mg alloy plates with increased edge roughness using square pi tools of various shoulder geometries, Mater. Tehnol., 50 (**2016**), 387–394, doi:10.17222/mit.2015.088

[3] D. Ghahremani Moghadam, K. Farhangdoost, Influence of welding parameters on fracture toughness and fatigue crack growth rate in friction stir welded nugget of 2024-T351 aluminum alloy joints, Transactions of Nonferrous Metals Society of China, 26 (**2016**), 2567–2585, doi:10.1016/S1003-6326(16)64383-2

[4] L. Giraud, H. Robe, C. Claudin, C. Desrayaud, P. Bocher, E. Feulvarch, Investigation into the dissimilar friction stir welding of AA7020-T651 and AA6060-T6, Journal of Materials Processing Technology, 235 (**2016**), 220–230, doi:10.1016/j.jmatprotec.2016.04.020

[5] D. G. Hattingh, C. Blignault, T. I. van Niekerk, M. N. James, Characterization of the influences of FSW tool geometry on welding forces and weld tensile strength using an instrumented tool, Journal of Materials Processing Technology, 203 (**2008**), 46–57, doi:10.1016/j.jmatprotec.2007.10.028

[6] Y. B. Tan, X. M. Wang, M. Ma, J. X. Zhang, W. C. Liu, R. D. Fu, S. Xiang, A study on microstructure and mechanical properties of AA 3003 aluminum alloy joints by underwater friction stir welding, Materials Characterization, 127 (**2017**), 41–52, doi:10.1016/j.matchar.2017.01.039

[7] H. Sidhar, N. Y. Martinez, R. S. Mishra, Friction stir welding of Al–Mg–Li 1424 alloy, Materials & Design, 106 (**2016**), 146–152, doi:10.1016/j.matdes.2016.05.111

[8] P. Sadeesh, M. V. Kannan, V. Rajkumar, P. Avinash, N. Arivazhagan, K. D. Ramkumar, S. Narayanan, Studies on friction stir welding of AA 2024 and AA 6061 dissimilar metals, Procedia Engineering, 75 (**2014**), 145–149, doi:10.1016/j.proeng.2013.11.031

[9] S. Sree Sabari, S. Malarvizhi, V. Balasubramanian, Characteristics of FSW and UWFSW joints of AA2519-T87 aluminium alloy: Effect of tool rotation speed, Journal of Manufacturing Processes, 22 (**2016**), 278–289, doi:10.1016/j.jmapro.2016.03.014.

[10] H. Su, C. S. Wu, A. Pittner, M. Rethmeier, Thermal energy generation and distribution in friction stir welding of aluminum alloys, Energy, 77 (**2014**), 720–731, doi:10.1016/j.energy.2014.09.045

[11] J. Tang, Y. Shen, Numerical simulation and experimental investigation of friction stir lap welding between aluminum alloys AA2024 and AA7075, Journal of Alloys and Compounds, 666 (**2016**), 493–500, doi:10.1016/j.jallcom.2016.01.138

[12] M. Korzyński, The experiment methodology, WNT, Warsaw 2006

[13] W. G. Cochran, The distribution of the largest of a set of estimated variances as a fraction of their total, Annals of Human Genetics, 11 (**1941**), 47–52, doi:10.1111/j.1469-1809.1941.tb02271.x