D. KLOBČAR, J. TUŠEK, A. SKUMAVC, A. SMOLEJ

ISSN 0543-5846
METABK 53(1) 21-24 (2014)
UDC – UDK 621.791.1:669.715=111

PARAMETRIC STUDY OF FRICTION STIR SPOT WELDING OF ALUMINIUM ALLOY 5754

Received – Primljeno: 2013-02-14
Accepted – Prihvaćeno: 2013-05-10
Original Scientific Paper – Izvorni znanstveni rad

The paper presents a parametric analysis of friction stir spot welding (FSSW) of aluminium alloy 5754 in a lap joint. Experimental plan was done according to the response surface methodology (RSM), where tool rotation speed varied between 988 and 3511 rpm, plunge rate between 24,4 and 150 mm/min and dwell time between 1 and 3,5 s. The plunge depth was held constant at 0,4 mm. The welds were tensile-shear tested and the microstructure was analysed. Mathematical models describing the relationship between welding parameters and spot strength, axial force and rotational moment were developed and the optimal FSSW parameters were found.

Key words: friction stir spot welding, EN-AW 5754, force measurement, dynamometer, tensile test

INTRODUCTION

The steel auto body assembly is today primary joined using electric resistance spot welding (RSW), since it is quick, robust and cheap (one welded spot costs approx. 0,05 $) [1, 2]. The trend in the automotive industry is to use the light weight metals like aluminium alloys (AA), magnesium alloys (MA) and advanced high-strength steels (AHSS) in order to lower vehicle mass, green gas emissions and fuel consumption and to additionally reduce the consumption of energy for vehicle production [3-9]. Effective joining of these metals and joining of dissimilar materials is now in demand. RSW of AA and MA is far more difficult and expensive due to high temperature and electric conductivity and the tendency to degrade the electrodes. The automotive industry is investigating different joining methods like: a) mechanical fastening (ImpAcT, Rivtac, self-pierce riveting (clinching)), b) adhesive bonding, c) laser and gas tungsten arc welding, and d) solid state welding techniques (ultrasonic spot welding, friction stir welding (FSW) and friction stir spot welding (FSSW)) [10, 11]. Mechanical joining methods are very effective but associated with high consumable costs. Fusion processes have poor weldability and higher levels of distortion. Ultrasonic spot welding is showing some promise. Among these methods FSSW is energy efficient solid state joining method, which could be used either by itself or in combination with adhesive bonding. It could be used to join dissimilar metals like AA to copper, magnesium, titanium or steel [8, 12-15].

FSSW is a novel variant of the "linear" FSW developed and patented by Mazda Motor Corp. FSSW creates a spot, lap-weld without bulk melting. During the FSSW the rotating tool is plunged into the upper sheet of a lap joint, while the anvil supports the down force. The strength of the joint depends of the welding parameters: tool rotation speed, plunge rate, plunge depth, and dwell time, which is typically between 1 - 4 s. At FSSW the material under the tool is softened and plastically deformed to high strains, and the oxide layer is disrupted at the joint interface in order to form a metallurgical bond. The disadvantages of this process are aesthetically undesirable keyhole produced by lifting the material beside the tool, tinning of the top sheet and difficulties to produce a full metallurgical bond, leading to low strength failures by cleavage fracture along the joint line. On the other hand Mazda reported over 90 % operation energy savings and over 40 % capital investment reductions compared to conventional RSW of AA, at the first application on its 2003 RX-8 model, when AA rear door was FSSW in mass production [8].

Researchers are currently investigating the weldability of different materials and dissimilar materials [8, 14, 15]. A lot of effort is made on the optimisation of the welding parameters and tool geometries as well as on the techniques for refilling the keyhole [10, 16]. The following tool geometries are under investigation: a) classical treated pin with different pin heights (the optimal pin height is such that the pin penetrates 25 % into the thickness of the bottom sheet), b) zero pin length tools, c) tools with different features on the tool shoulder, and d) different tools and techniques, which enable filling of the keyhole (autoadjusting pin tool apparatus, retractable or double acting refilling tool, self-refilling FSW, friction taper plug welding, friction hydro pillar processing) [8, 17].

This paper presents the feasibility study of FSSW parameters on the strength of produced spot weld on

D. Klobčar, J. Tušek, A. Skumavc,Faculty of Mechanical Engineering, University of Ljubljana, A. Smolej, Faculty of Natural Sciences, University of Ljubljana, Ljubljana, Slovenia

AA5754 using classical tool with treaded pin. In the study we explored the possibility to produce acceptable spot welds at short dwell times. We investigated the influence of FSSW parameters on the axial force, moment and energy input, development of microstructure and morphology of the stir zone.

EXPERIMENTAL WORK

Welding

A standard EN-AW 5754 AA in temper O was used for experiments. Its nominal chemical composition was: 2,738 wt. % Mg, 0,313 wt. % Mn, 0,208 wt. % Si, 0,036 wt. % Cr, 0,337 wt. % Fe, 0,045 wt. % Cu, 0,046 wt. % Zn, 0,18 wt. %Ti and the rest Al. The upper test coupon was 1,6 mm thick and the bottom one 2 mm. Their dimensions were 110×25 mm. They were welded in a lap joint with 25 mm cover. A Mori Seiki Frontier M1 CNC milling machine was used for FSSW and welding was done in position control. Welding tool was prepared from 1,2343 (X38CrMoV5-1) tool steel quenched and tempered to 45 HRc. The tool shoulder was 18 mm in diameter, concave with scrolled shoulder. The tapered and treaded pin was 5 mm in diameter, 2,2 mm long. The tool rotated clockwise. Experimental plan was done according to the RSM. Tool rotation speed (ω) varied between 988 and 3511 rpm, plunge rate (p_r) between 24,4 and 150 mm/min and dwell time (d_t) between 1 and 3,5 s. The plunge depth was held constant at 0,4 mm. During each welding test, axial force and torque were measured using dynamometer Kiag Swiss 9273, multichannel charge amplifier Kistler 5070 and LabView software in which measuring protocol was prepared. The weld energy input was calculated from integrating the torque curve, using the relationship:

$$U = \frac{2\pi}{60}\omega\int_{t_0}^{t_s} Tdt \qquad (1)$$

where T is the torque and t_0 and t_1 are the tool contact and withdrawal times.

Tensile lap shear testing

Welded samples were subjected to tensile shear test, where tensile shear force (TSF) against displacement was determined. The tensile shear strength (TSS) was calculated by dividing TFS with the surface ring underneath the tool shoulder with diameters 18 mm and 5 mm. Failure energy (FE)/ kNmm was determined with integration of TSS curve. The fractured weld samples were examined and photographed (top coupon from top and bottom and the bottom coupon from the top). The type of failure mode was determined.

Weld microstructure

The samples for microstructure analysis were examined using a light optic microscope.

RESULTS AND DISSCUSION

Figure 1 shows axial force (AF) and torque (T) measured during experimental FSSW for three different welding regimes and figure 2 the results of the RSM analysis. Figure 1a shows that the AF raises two times, i.e first when tool pin touches the welded workpiece and the second time when tool shoulder touches it. After initial raise, the force gradually drops as the material in contact becomes softer due to frictional heating and stirring.

The maximal AF measured were similar and in the range between 11 and 15 kN (Figure 2 a). The highest influence on AF has the p_r and ω, while the effect of d_t is smaller. Maximal AF are increased by higher p_r and decreased by a higher ω, since the higher heat input promotes tool penetration into the material. Similarly as Yuan et al. [18] we noticed that machine deformed in Z – direction and that the plunge depth was probably not reached in all cases, but only at higher tool rotation speed and longer times. Similarly to the AF the T also raises in two stages (Figure 1 b).

With the increase of d_t, the T drastically decreases since the heated material becomes softer and is pushed away to the side of the tool. While the maximal AF are in small range the maximal T is between 15 and 52 Nm (Figure 2 b). The T is increasing with increasing p_r, and decreasing with increasing ω and d_t. Later has the minor effect. The highest effect on T has ω. The weld energy input (Equation 1, Figure 2 c) is increasing with increas-

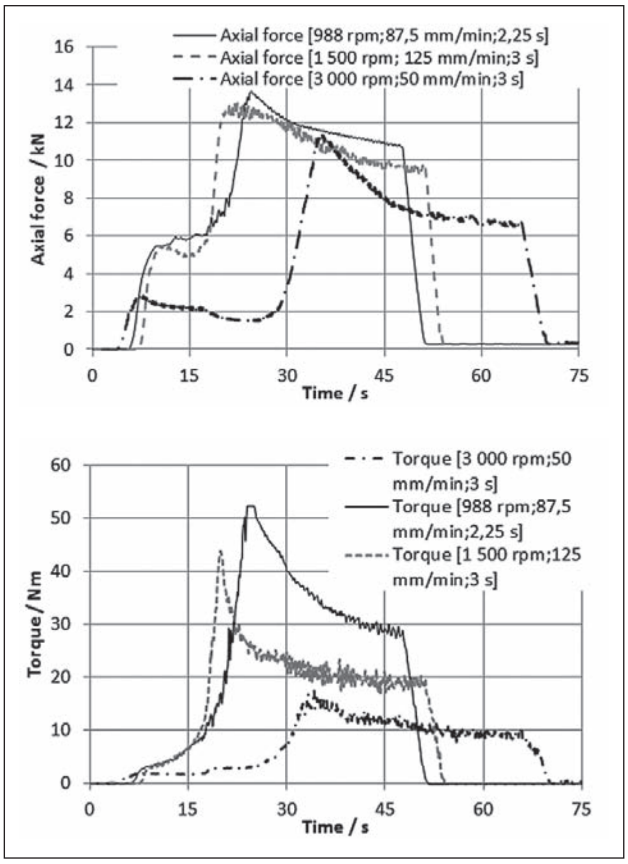


Figure 1 a) Axial force and b) torque measured with dynamometer during FSSW

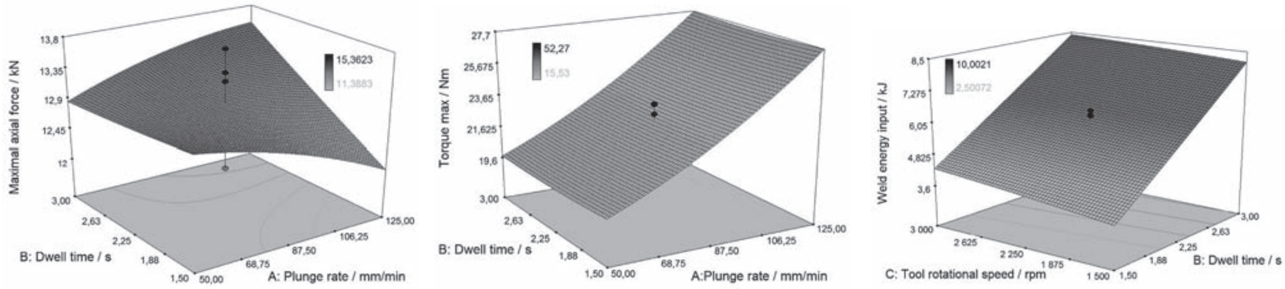


Figure 2 The influence of welding parameters on a) axial force, b) torque, and c) energy used

ing of all parameters. The highest influence on weld energy has the d_t.

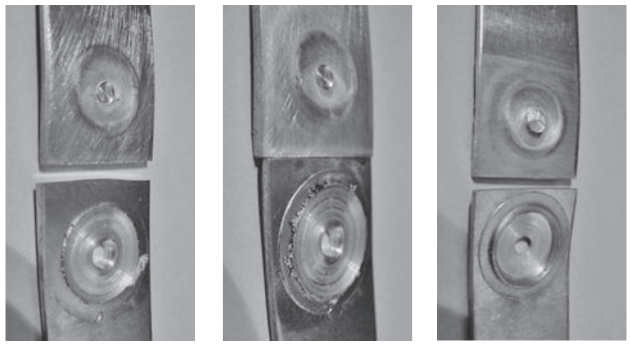
The tensile shear test is sensitive to a material thickness and the joint usually bend out of plane. The joint is thus subjected to shear and tensile force or "peel" force, which is greatest at the nugget edge. The failure behaviours of FSSW joints can be separated into three main modes: (i) mode I: shear failure following the joint line between the sheets in plane (reported for thicker sheets > 2 mm), (ii) mode II: lower strength mixed cleavage failure that starts by cleavage (debonding), following the oxide debris delineating surfaces between two sheets, (iii) mode III: nugget pull out where the interface does not fail and the top sheet tears around the edge of the shoulder contact area leaving the weld nugget attached to the bottom sheet. This failure mode is also encouraged by thinning of the top sheet at the edge of the tool shoulder, due to the shoulder plunge [10]. Failure by mode III is associated with moderately higher shear strength and far larger fracture energy compared to mode II [10].

Figure 3 shows examples fractured weld samples produced at 2 250 rpm and at different plunge rates and dwell times. The d_t has an influence on TSS and fracture mechanism. At 2,25 s d_t and 24,4 mm/min the weld nugget was pulled out from the top sheet and the TSS reached ~ 8 kN. In the other two cases (Figure 3 a, b) lower TSS was obtained without a nugget pull-out due to a smaller bond strength achieved.

Bakavos et al. [10] reported that regions between two lapped sheets consists of (i) kissing bond, (ii) partial intermittent bond, where intermittent voids and segments of continuous interfacial oxide are still present and (iii) a full metallurgical bond, where the oxide is dispersed and no voids remain.

Similar was observed also in our research. Figure 4 shows the macrosection of the joint that achieved the highest tensile shear strength. The joint line consists of kissing bond (KB) (near the edge of the shoulder contact area), partial metallurgical bond (PMB) and full metallurgical bond (FMB) (close to the tool pin). FMB was produced due to greater disruption of the interface near the weld keyhole. Here the FMB presents only about 20 % of the weld bond line.

The RSM analysis of TSF is shown on Figure 5 a. The p_r has the highest and negative influence on TSS, while has the ω and d_t the positive influence. The maxi-



a) b) c)

Figure 3 Examples of failure mode of samples FSSW at 2 250 rpm and a) 87,5 mm/min, 1 s; b) 87,5 mm/min, 2,25 s; and c) 24,4 mm/min, 2,25 s

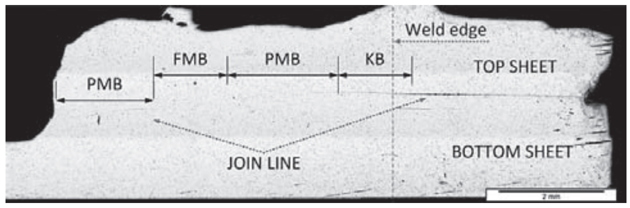


Figure 4 Macrosection and weld bond line with (FSSW at 3 000 rpm, 50 mm/min, 3 s)

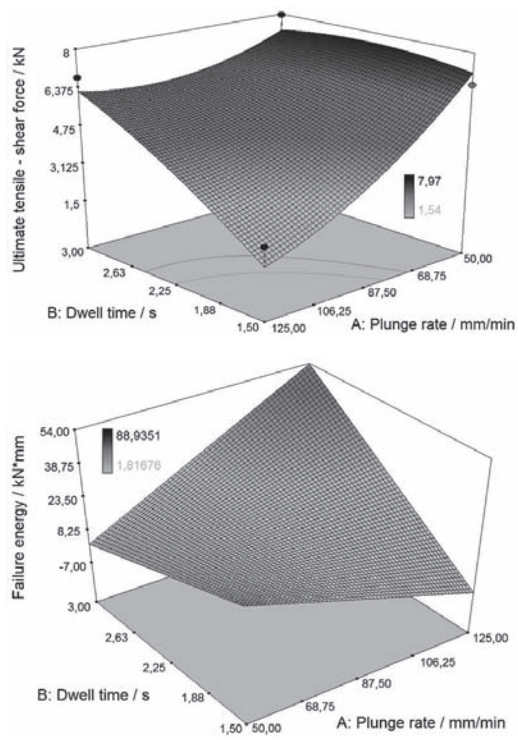


Figure 5 The influence of welding parameters on a) ultimate tensile shear force and b) failure energy

mal TSS in our research was reached at 3000 rpm, 50 mm/min plunge rate, 3 s dwell time. The strength reached 32,8MPa, which presents 22 % of shear strength of the base AA 5754. If we compare this result with results of other researchers we notice that their maximal joint strengths achieved the strength between 17 and 42 %, using different tool geometries, shapes, tool dimensions and welding parameters [10, 18-21].

The analysis of FE (Figure 5 c) shows that d_t has the highest and positive effect on FE. Positive effect has also p_r, while has the ω the weakest and negative effect. The highest FE of 89 kN mm was obtained at 3000 rpm, 125 mm/minp_r, 3 s d_t and second highest (70 kNmm) at 1500 rpm, 125 mm/min, 3 s. FE at highest TSS of 7,97kN achieved only 15,6 kNmm.

A further analysis showed that the highest joint strength (more than 6,3kN) were reached when maximal value of the measured T was between 15 Nm and 19 Nm, and maximal value of the AF was the lowest. In one exception we measured joint strength of 6,13kN at higher T value of 43,8 Nm (1500 rpm, 125 mm/min, 3 s), at which we also measure one of the highest FE values. This means that at highest values of joint strength we do not reach the highest values of FE. A further research is needed to figure the influence of plunge depth and machine deformation in position control welding.

CONCLUSIONS

The following conclusions can be summarized:

- The higher lap joint TSS and failure energy can be obtained at lower p_r (< 50 mm/min) and higher ω (> 2250 rpm) and d_t (> 2,5 s).
- At optimal parameters the measured T (max. and average) and average AF are the lowest and consequently the load on the machine.
- The presence of interfacial oxide diminishes the quality of FSSW welds, since the crack propagation follows the oxide layer subjected to the external loading.

Acknowledgments

The authors wish to thank Vinko Rotar, Zoran Hojnik, Nika Breskvar, Boris Bell and Tomaž Martinčič for the help at experimental work and data analysis at this research. The research was sponsored by Slovenian Research Agency under the grant L2-4183.

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Note: The responsible translator for English language is Urška Letonja, Moar. Prevajanje