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Research Article

ANALYSIS OF STRUCTURE AND SHEAR/PEEL STRENGTH OF REFILL FRICTION STIR SPOT WELDED 7075-T6 ALUMINIUM ALLOY JOINTS

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ABSTRACT
The article presents an analysis of the macrostructure and mechanical properties of spot welds of joints made by Refill Friction Spot Stir Welding (RFSSW) method. RFSSW is a relatively new technology that is gaining wider use, not only in the automotive and aviation industries because it is a less energy intensive method than resistance spot welding. The primary focus of the article is the effect of welding time on the quality of the welded joints of sheet metal using the aforementioned method. The research was conducted on a joint between two pieces of sheet metal of various thicknesses (1.6 mm and 0.8 mm) made of a common aviation grade aluminium alloy 7075-T6 Alclad. Metallographic sections of select variants were made in order to analyze the structure of the joint. Strength tests with a static load were conducted in different loading configurations. A traditional tensile strength test was conducted on the lap joint, which revealed a complex stress state within the joint and an analogous test was conducted with the use of a stiffening holder that ensured a pure shear state in the joint. Peel tests were also performed on the lap joints with using a special holder.

Keywords: spot welding, friction stir welding, aluminium alloy joining.

INTRODUCTION

Friction stir spot welding (FSSW) is a method used to join material that was developed primarily by the automotive industry [12, 14] and the aerospace industry [12, 17]. The FSSW is an alternative method for the commonly used Resistance Spot Welding (RSW). FSSW can be characterized by its relatively low energy demand [7, 25]. It is estimate that FSSW is 25% less costly than RSW [32]. In addition, FSSW is simpler because it requires less exact cleaning of the welded surfaces [23, 25, 31]. Friction stir welding also has the advantage of being able to join together different metals [15, 20, 24, 27, 30]. The authors of the works [1, 3, 4, 5, 8, 21] describe the technology as being able to be used to join thermoplastics and composites.

Friction spot welding is a derivative of a Friction Stir Welding (FSW), in which the tool moves linearly along the material [8]. FSSW enables the creation of lap joints [32].

The properties of joints made using the FSSW technique result from the properties of the process, which are [13]: rotational speed of the tool, tool dive depth speed, tool dive time and the time the tool remains at full depth, tool penetration depth, and the geometry of the tool (pin diameter and shape, pin length, and sleeve diameter and shape).

The primary disadvantage of FSSW is the appearance of a hole in the axis of the spot weld [26]. A development of FSSW is Refill Friction Stir Welding (RFSSW) [11], in which the tool is made of two parts and the hole that results from the withdrawal of the tool is filled. As a result, the spot weld is much stronger [26].

The RFSSW method can make two joint variants depending on the sequence of pin and sleeve movement based on which part of the tool delves

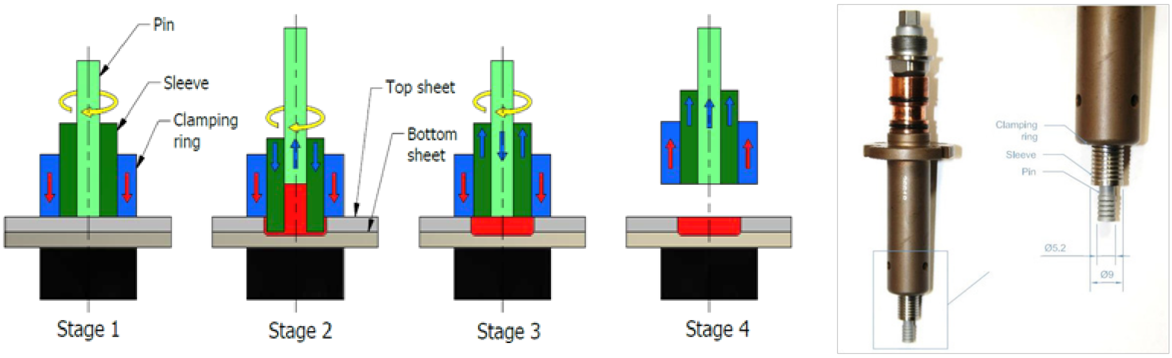

Fig. 1. Schematic illustration of the RFSSW processes (left) and tool geometry used in research (right)

into the joined materials. The article presents a solution for the variant, where the sleeve delves into the joined sheet metal, while the pin has the responsibility of squeezing the previously pushed out material. A schematic of the process and geometry of tool used in research were presented in Fig. 1.

During the first stage of the process, the clamping ring squeezes the welded sheets metal. Next, the rotating sleeve delves into the material, pushing material out into the space created by the retreating pin. Then, the sleeve remains at the maximum dive depth for a determined amount of time, after which it returns to the exit position and the pin squeezes the pushed-out material.

The method is effective; however, it requires precisely made tools and complex control parameters in order to achieve optimal spot weld properties [22].

The RFSSW method is especially sensitive to the process parameters. When incorrectly selected, they can cause internal flaws within the structure of the spot weld that are invisible to the naked eye, which is especially dangerous in aircraft structures [6, 19].

Considering the spot welding parameters, it should be noted that some authors stress tool rotational speed as the determining factor of the strength of the joint [2], stating that for select material there is an optimal range of tool rotational speed that results in high strength joints. The research of other authors focused on tool plunge rates, the pin rotational speed ration as the significant determining factors of spot weld quality [18]. The authors [32] focused on comparing different rotational speeds like 1500, 1750 and 2000 rpm, while the welding times were 3, 4 and 5 s.

It is accepted in the study that lower welding times are analyzed in terms of macrostructure and strength test in order to discover the lowest welding time need to create a proper joint.

MATERIALS AND METHODS

The study presents research on the topic of RFSSW joints of aluminium alloy 7075-T6 Alclad sheet. The chemical composition of the material is presented in Table 1. The material is widely used in the aviation industry [9, 10, 16, 28].

Fig. 2 presents the lap joint used for the shear and peel strength tests. Lap joints of sheet metal of various thicknesses were considered; the top sheet had thickness of 1.6 mm, while the lower sheet was 0.8 mm thick. The joint was made on a HARMS WENDE machine.

The joints were made for several different welding times such as: 1.5, 2.0 and 2.5 s. A constant tool rotational speed of 2600rpm was selected along with a plunge depth equal to the thickness of the top sheet (1.6 mm).

The strength tests were conducted for different variants of loading the joint. The fundamental strength test was a tensile/strength test of a single lap joint. Due to the complex stress state within the joint (because of low thickness of bottom sheet – 0.8 mm) pure shear strength tests were conducted with the use of special fixture enabling

Table 1. Chemical composition of 7075-T6 aluminium alloy (wt.%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other impurities		Al
								Single	total	
0.40	0.50	1.2~2.0	0.30	2.1~2.9	0.18~0.28	5.1~6.1	0.30	0.05	0.15	Rest

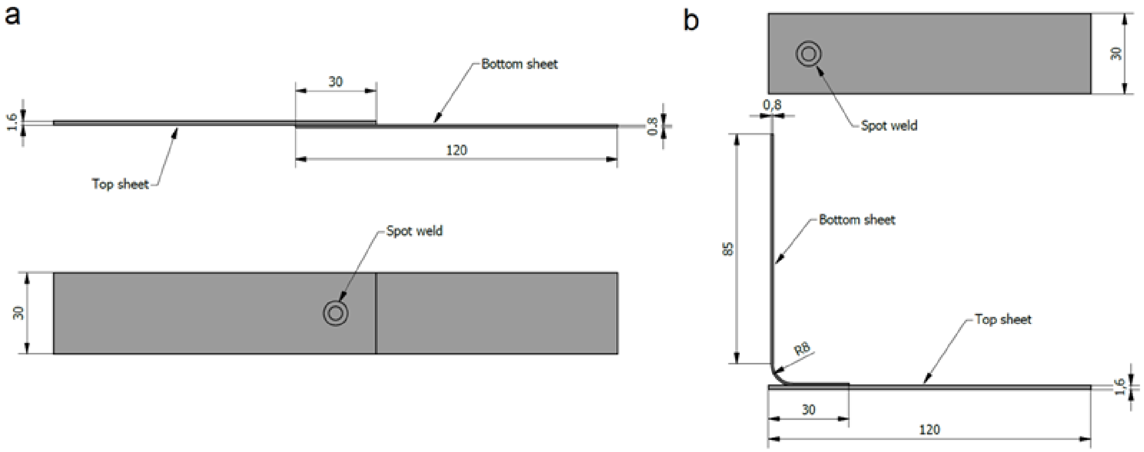

Fig. 2. Configuration and dimensions of test specimens: (a) tensile/shear test specimen and (b) peel test specimen

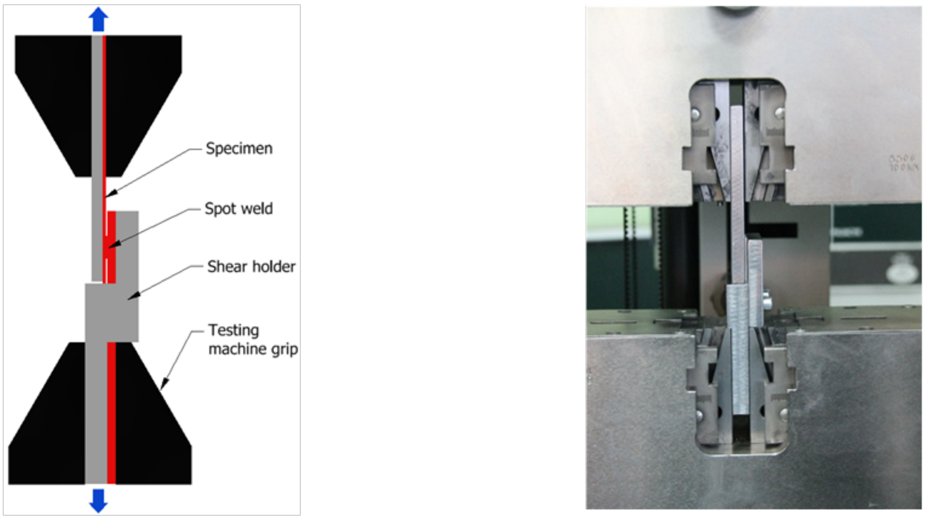

Fig. 3. Scheme of fixing of specimen for tensile/shear test (left) and view of real test bench (right)

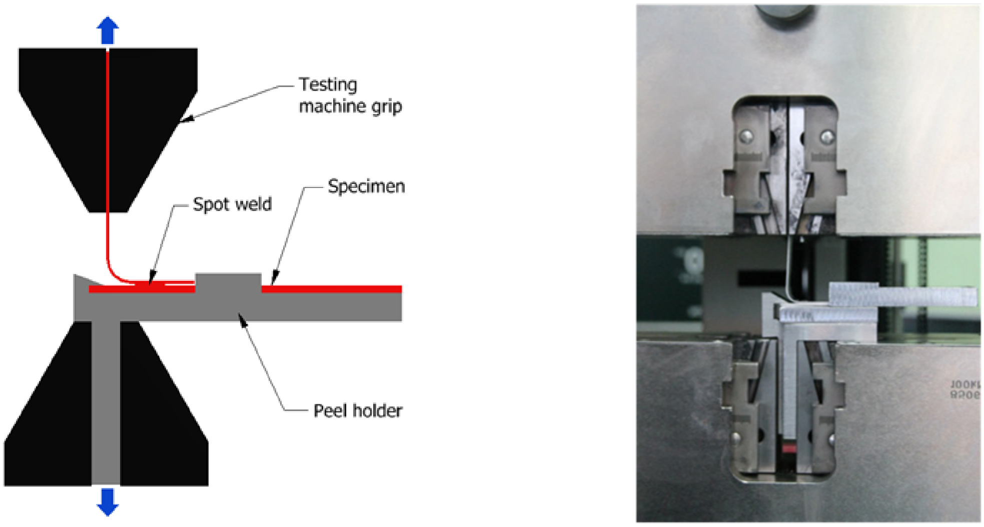

Fig. 4. Scheme of fixing of specimen for peel test (left) and view of real test bench (right)

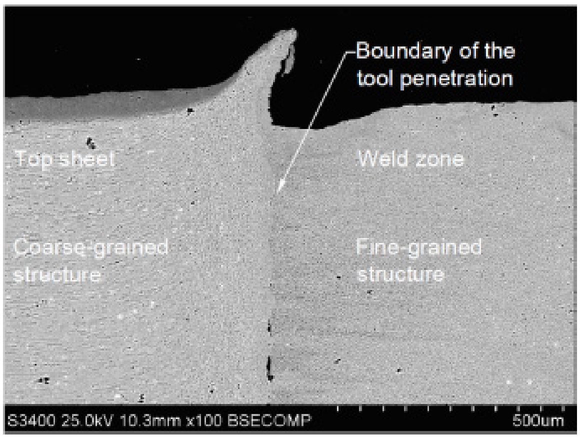

Fig. 5. SEM image of the boundary between sheet and tool penetration zone

the bending of the sheet metal during loading (Fig. 3). The tests were conducted on a ZWICK Z100 strength test machine with a grip translation speed of 5 mm/min.

A peel strength test of the spot welds was done by mounting the samples in the holder presented in Fig. 4 during the strength test. The peel strength test was conducted with a grip translation speed of 10 mm/min.

RESULTS AND DISCUSSION

Images of the spot weld microstructure of all variants show a significant fragmentation of the grains within the structure of the weld in regards to the parent material (Fig. 5). Grain fragmentation within the structure of spot weld is a positive phenomenon from the point of view of material strength.

However, the variants with a welding time of 1.5 s and 2 s (Fig. 6.) a boundary between sheet and tool penetration zone can be observed and it is a structural notch. A thermomechanical processing occurs in the penetration area of the tool, and more precisely the sleeve, in the material, this area is narrowed to the diameter of the tool (4.5 mm from axis of the weld) as a result. In this area, a significant grain fragmentation of the material can be observed. 4.5 mm from the axis of the joint, there is an evident boundary between aforementioned areas. Beyond this border, the structure of the material gradually shifts from having small grains to grains the size of the parent material, and this is still a zone of thermomechanical processing. The visible boundary between the areas of the spot weld signify that there is a weak point in the structure, which is an undesirable phenomenon that has a negative effect on the joint and its fatigue strength.

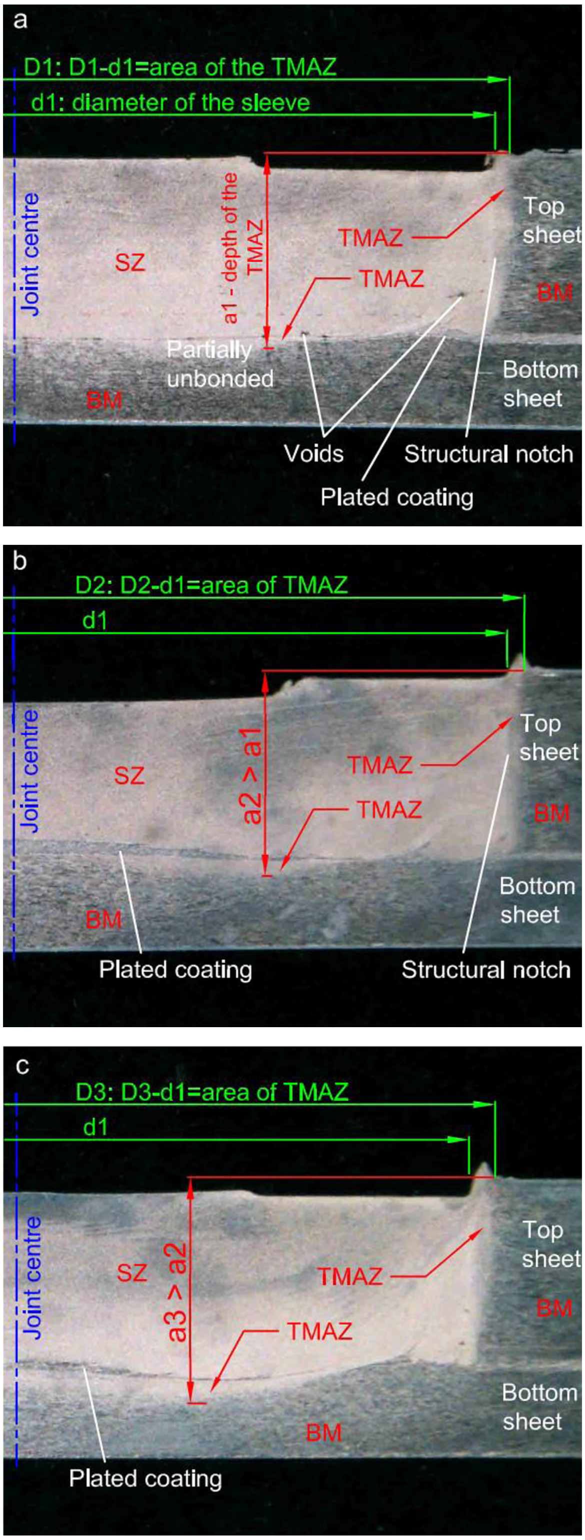

Fig. 6. Macrostructures of RFSSW stir zone for different times of welding: (a) 1.5 s; (b) 2.0 s; (c) 2.5 s. Marked areas: SZ – Stir Zone, BM – Base Material, TMAZ – Thermo-Mechanically Affected Zone

In the case of the 2.5 s welding time, the tool penetration area more smoothly transitions in the thermomechanical processing area beyond the tool zone (Fig. 6c); there are no visible clear boundaries between them. This situation clearly shows the quality of the joint in comparison to other solutions. An analysis of the microstructure shows that an excessively short welding time does not heat the joined elements enough, and it does not conclude with a proper phase change, which leads to defects in the spot weld structure causing weak points as a result.

Focusing on the observations of the bottom of the weld, it can be seen that there is a visible difference in the area affected by heat on the bottom sheet. For the shortest welding time, it is insignificant, which can be supported by the grain structure that did not under phase change because most of the material appears identical to the parent material. It can be noticed in this case that the plated coating creates a heat shield, which diverts heat away from the area of the weld. This is a result of the difference in heat conductivity between pure aluminium and 7075-T6 aluminium, which are 229 W/mK and 134 W/mK respectively. In the case of a 1.5 s welding time, a visible boundary between the small grain structure of the spot well and the structure of the bottom sheet can be observed; this signifies a weak point in the structure. Every increase in weld time leads to better penetration of the thermal change area below the tool plunge line and removes weak points from the bottom of the weld. During the 2.5 s welding time, there is a smooth transition from the small fragmented grain structure of the welded area to the area of grains typical of the parent material.

The analysis of weld sections shows that an excessively short welding time leads to appearance of weak points on the boundary made by the mechanical plunge of the tool. Time is paramount for the appropriate temperature stability required from proper phase changes.

Static tensile strength tests of a lap joint show that based on complex stress conditions in the tensioned joint, it was determined that it is not possible to compare samples of different variants because some of the cases underwent pure shearing. During this, the thinner sheet underwent plastic deformation and the area around the spot weld peeled. In order to compare the shear strength of each variant, a device that forced near pure shearing regardless of the specimen variant. The device was designed to minimalize the effect of friction.

The results of tests on samples loaded with shear holder that forced a shearing condition in the joint are presented in Fig. 7a. The tendency discussed in the analysis of the microstructure is confirmed here. Joints with the shortest welding times have the lowest strength. However, there is a large spread in the results. It should be noted that there is a lack of repeatability. In the case of variants welded for 2 s, the results are slightly better; there is a higher strength and the repeatability is greater. The 2.5 s welds have great repeatability and strength is the biggest of considered variants.

The device used to force a shearing condition in the joint is good for analyzing the effect of parameters on the shear strength. However, it does not represent the loading condition of the joint during normal operation. As a result, tests in the perpendicular direction to the welded zone were conducted, loading the joint for peeling.

The peel test results were presented in Fig. 7b. It can be noticed that there is a similar tendency like in the case of shear test; the highest peel strength and lowest result spread from the longest weld time. This confirms that it is required to weld for an appropriate amount of time

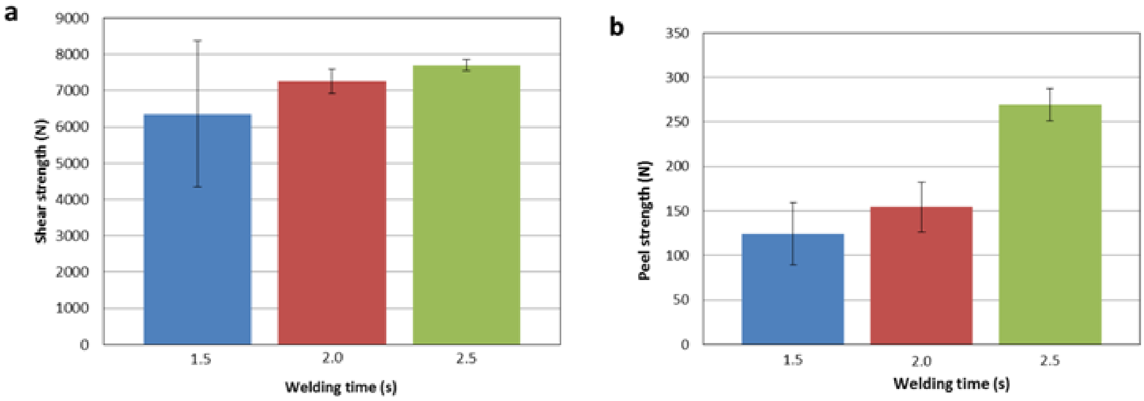

Fig. 7. Results of the static strength test: (a) shear test; (b) peel test

in order to achieve a proper phase change in the weld structure and avoid weak points.

CONCLUSIONS

In the aforementioned tests, the focus was placed on considering the effect of welding time on the shear and peel strength of joints. It showed unanimously that in the range of welding times between 1.5-2.5 s that the longer welding improves the quality of the joint. The flaws of joints made with short welding times like structural weak points and discontinuity of the weld structure like voids are unacceptable in high responsibility structures. It was shown that the static strength of a joint when subject to the aforementioned load directions can have a high value, but in the case of fatigue strength, the weld containing defects is unacceptable. The study only considers the parameter of penetration time of the tool into the welded sheet metal, showing that the lower time does not allow for achieving good temperature conditions required for proper phase change in the joint. In order to achieve correct temperature conditions, the rotational speed of the tool can also be manipulated, which is the topic of future research. Generally, it is paramount to determine the optimal parameters that ensure the desired quality of joints while considering the criteria like tool durability and the economics of the process. From the point of view of tool lifespan and process costs, welding time should be as short as possible. The tool dive depth can also be manipulated. In regards to tool lifespan, the depth should be as shallow as possible.

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