

DOI: 10.24425/118906

J. ANDRES*, A. WROŃSKA*[#], T. GALACZYŃSKI*, G. LUTY*, R. BUREK***EFFECT OF PROCESS PARAMETERS ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF RFSSW LAP JOINTS OF THIN AL7075-T6 SHEETS**

Refill friction stir spot welding (RFSSW) is a new technique of metal structures joining. Within the framework of activities of PZL Mielec in R&D area (program *Innolot*) researches are realized which aim is to develop the RFSSW technology as a method of joining thin aluminum elements used in aircrafts constructions. The paper presents results of investigations on the RFSSW lap joints welded using rotations in the range from 1500 to 2000 rpm and tool sleeve plunge depth from 1.6 to 1.8 mm. Thin aluminum sheets of thickness 0.8 and 1.6 mm coated with alclad or anodized were welded. Results of the investigations prove that the most common cause of specimens breaking was presence of geometrical defect – the so called hook and weak bonding between parent material and working area of internal sleeve of RFSSW tool. The best tensile strength was reached in case of joint welded at rotational speed 2000 rpm and tool plunge depth 1.6 mm and 1.7 mm (5.37 kN and 5.87 kN adequately). These joints were characterized by very fine and uniform microstructure in the area between sleeve stirred zone and parent material.

Keywords: refill friction stir welding, lap joining, aerostructures, aluminum alloy, alclad

1. Introduction

Aircraft industry is one of leading and developing branches of engineering industry. On order to keep the level of development and to ensure competitiveness in the European and global market among aircraft producers companies (both fixed wings and helicopters producers) are looking for new, alternative methods of joining thin walled aerostructures in order to ensure proper mechanical properties of a joint, reduction of weight, costs and time consumption of a process. Innovative technology of Friction Stir Welding (FSW) is one of so called Free Fasteners Aerostructures technologies. FSW allows constructing advanced metal structures characterizing by increased durability. This method also allows reducing time consumption of process as well as reducing weight and pricing of component. What is more, application of this technology allows simplifying construction and improving quality of final product as human errors occurred during use of conventional methods of joining these structures are eliminated. Researches and analysis conducted in aircraft companies show that about 80% of faults are caused by assembling errors during joining parts with fasteners. These faults have great impact on “poor quality” costs and may cause delays in production processes and deliveries.

FSW method can be an alternative to conventional joining methods, such as welding, electric resistance welding or fasteners requiring methods. It is worth to notice, that FSW process is solid state process (small size of heat-affected zone). This process

allows to obtain proper dimensional stability and repeatability. Both weldable and unweldable aluminum alloys may be joined with this method. Mechanical properties of weld are similar to parent material properties. Another advantage is weight reduction (elimination of fasteners), improvement of joint tightness and aerodynamic of construction. FSW joints quality may be controlled only on the basis of process parameters monitoring. What is more, there is possibility of complete automation or robotization of joining process.

Friction Stir Spot Welding (FSSW) method can be used for lap joints as alternative to conventional methods of spot joining (both fasteners methods and fastener-free methods). Main disadvantage of FSSW joints is exit hole occurring as the result of pin exiting joined sheets. In addition to stress concentration in this area due to thinning of the material, there is also a problem of corrosion processes, which initiate in an exit hole [1].

Therefore new method, Refill Friction Stir Spot Welding (RFSSW), was developed. Main difference between RFSSW and FSSW is elimination of exit hole. The most promising and perspective method, that can be used in aircraft industry is method patented by GKSS-GmbH. In this method, tool consisted of three elements: pin, sleeve and clamping ring (Fig. 1). This kind of tool's construction allows to carry out RFSSW process in two ways – joined package is penetrated by pin or sleeve. In presented research the second method was chosen (penetration by a sleeve). RFSSW is four stage processes: tool is positioned and heat is generated as a result of friction between rotating

* PZL MIELEC A SIKORSKY COMPANY, MIELEC, POLAND

[#] Corresponding author: agata.wronska@lmco.com

sleeve and pin and material; then sleeve penetrates material and pin is retreating. After second stage, sleeve is retreating and pin presses plasticized material into an exit hole. Finally whole tool retreats from surface of joined materials. The basic task of clamping ring is to prevent any movements of material, ensure lack of gaps between joined metal sheets. In addition, during welding no plasticized material flows outside a tool thanks to clamping ring presence [2-4].

2. Experimental procedure

The object of the experiment was to study the effects of selected parameters of RFSSW process and surface preparation of joined elements on microstructure and mechanical properties of lap joints. Tested specimens were made of aluminum alloy Al 7075-T6. Chemical composition of this alloy is shown in Table 1. Supplied sheets were double-side covered with alclad (7072). The average alclad thickness was equal to 3.2% of total sheet thickness per each side. Chemical composition of alclad (7072) is given in Table 2.

TABLE 1

Chemical composition of 7075 alloy

Element	Mass %	Element	Mass %
Zn	5.1÷6.1	Cr	0.18÷0.28
Mg	2.1÷2.9	Zr+Ti	max. 0.25
Cu	1.2÷2.0	Ti	max. 0.20
Fe	max. 0.50	Others, separately	max. 0.05
Si	max. 0.40	Others, total	max. 0.15
Mn	max. 0.30	Al	Balance

TABLE 2

Chemical composition of alclad (7072)

Element	Mass %
Si + Fe	max. 0.7
Cu	max. 0.10
Mn	max. 0.10
Mg	max. 0.10
Zn	0.8÷1.3
Others, separately	max. 0.05
Others, total	max. 0.15
Al	Balance

Harms & Wende RPS100 welding machine was used during the research. Tested joints were created by using tool, which allows to weld parts thinner than 4 mm. The diameter of the spot welds was ~9 mm. Specimens were welded from the side of upper (thicker) sheet metal. RPS100 and a RFSSW tool are shown in Figure 1.

The thicknesses of welded metal sheets were: 1.6 mm and 0.8 mm for upper and lower sheet respectively. Shape and dimensions of specimens were adopted according to AWS D17.2 standard. Typical lap joint welded by RFSSW method is shown in Figure 2.



Fig. 1. RPS100 welding machine (left) and RFSSW tool (right)



Fig. 2. Two aluminum sheets welded by RFSSW method

Effect of rotational speed and tool penetration depth were investigated. The results of preliminary researches carried out so far within Innolot FAST_FSW project in PZL Mielec allowed to limit parameters to the following ranges: rotational speed of 1500 rpm÷2500 rpm and depth of tool penetration equal to 1.6 mm÷1.8 mm. Time of material mixing was fixed at the value of 2 seconds. Range of chosen processing parameters is shown in Table 3.

TABLE 3

RFSSW process parameters

Specimen no.	Parameters			Welding time, s
	Sheet surface condition	Rotational speed, rpm	Tool penetration depth (plunge depth), mm	
1P	As received – alclad	1500	1.6	2
2P		1500	1.7	
3P		1500	1.8	
4P		2000	1.6	
5P		2000	1.7	
6P		2000	1.8	
7P		2500	1.6	
8P		2500	1.7	
9P		2500	1.8	
1A	Oxide layer – anodizing	2500	1.8	

In order to investigate influence of anticorrosive layer on RFSSW process, some specimens were anodized, which resulted in thin oxide layer formation on the surface of an aluminum sheet. Subsequently specimens were welded using the same parameters as in case of specimen 9P (Tab. 3).

Welded joints were visually inspected and then specimens for destructive testing were cut. Specimens dedicated for metallographic tests were grinded, polished and etched with Keller's reagent. Microstructure was observed on digital optical microscope and stereoscope.

Tensile strength of joints was conducted in accordance to PN-EN ISO 6892-1 standard. MTS Landmark machine with sensors of force and displacement was used. For each parameters set three specimens were tested. Breaking force was registered for all specimens. After breaking specimens were visually inspected and metallographic tests were carried out. These observations allowed for more accurate analysis of joint's rupture cause.

All tests were executed in order to define optimum range of RFSSW parameters that allow to obtain the best mechanical properties of RFSSW joints.

3. Results and discussion

Figures 3÷5 present macro- and microstructure of selected RFSSW joints. There are some characteristic zones in RFSSW welds, as shown in Figure 3: internal and external mixing zone, formed respectively by the pin and the shoulder (A and B), thermomechanical affected zone (C), heat affected zone (D) and base material (E). Very detailed characteristic of specified zones in RFSSW welds can be found in available literature, among others [4÷7]. Some structural defects described in further part of this paper were also marked in selected figures (Fig. 4a, 5a).

Due to RFSSW trigeminal tool's construction creating proper weld is a result of carefully chosen parameters and operator's experience as well. One of important stages of RFSSW process is cleaning of the tool. This stage is realized by a machine. Pin, shoulder and clamp are separated by narrow spaces, so they can move easily relative to each other. With every weld done, plasticized material accumulates between parts of a tool. As a result a flash around a spot weld may appear on the border of action area of sleeve and clamp (Fig. 3 and 4). Little flash is an integral part of RFSSW weld and does not affect the tensile strength. Significant roughness is frequently observed in weld face in area of pin action. This is result of plasticized material sticking to a face of a pin. Creation of flash and roughness is particularly favored by alclad (protective layer) presence on joined metal sheets' surfaces: soft and plastic material adheres easily to working surface of RFSSW tool. What is needed to be added, quality of weld's face is usually worsened by a degree of tool's depletion. During its exploitation spaces between tool parts are increasing, thus greater amount of material is sticking to a tool.

All specimens except for anodized one are characterized by lack of a notch. Notch- the groove around the spot weld- is

a typical geometrical failure appearing in RFSSW welds and is an effect of insufficient plasticization of material and insufficient filling of gap left by retreated sleeve in the last stage of welding process.

Quality of RFSSW joints is directly associated with microstructural features of welds. In this paper two basic parameters were investigated: rotational speed and depth of tool penetration). Microscopic observations have shown that with an increase of tool penetration depth, thickness of upper sheet decreased. An inverse relationship was observed in the lower sheet – the deeper the tool penetrates, the deeper zone of mixing is. The measurement results showed that with increasing the level of the tool plunge depth, the proportions of material plasticized by a pin and a shoulder changed.

Friction welding of sheets covered with alclad is challenging issue as presence of this protective layer limits possibilities of obtaining homogenous microstructure in weld area. Figures 3 a-c present microstructure of joints welded by a tool rotating with a speed of 2000 rpm. On the bottom of welds bonding ligament may be observed (layer of alclad closed within RFSSW joints, usually thicker in a central part of a weld). Bonding ligament's shape depends on RFSSW process parameters. For lower rotational speed bonding ligament is localized in a central part of a weld, whereas for high rotational speed bonding ligament extends almost the entire width of the weld. Similar dependence was observed in a case of tool plunge depth. With the increase in the tool plunge depth, alclad located on the surfaces of joined sheets is moved towards the bottom of the weld (Fig. 3). The increase in the tool plunge depth caused that bonding ligament

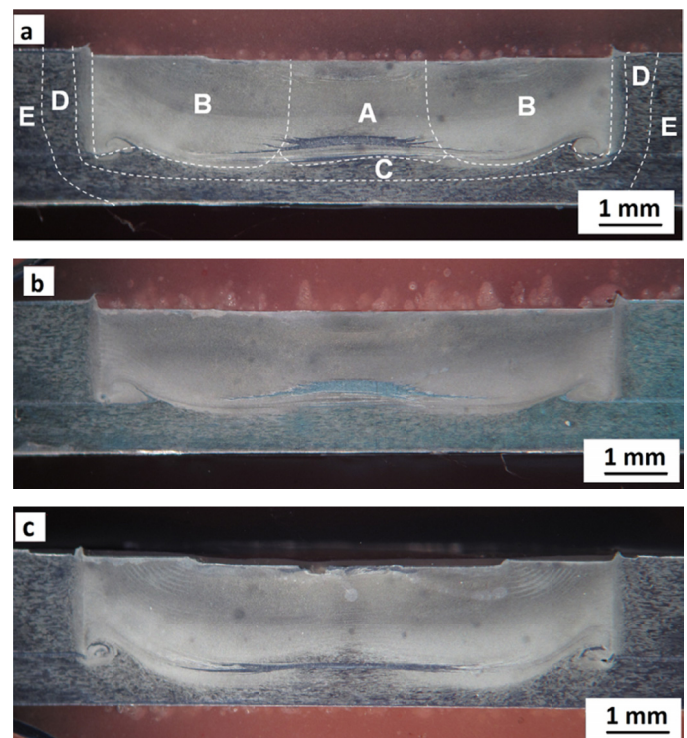


Fig. 3. Macrostructure of selected RFSSW joints welded at rotational speed of 2000 obr/min and different plunge depth of the tool: a – specimen 4P, b – specimen 5P, c – specimen 6P

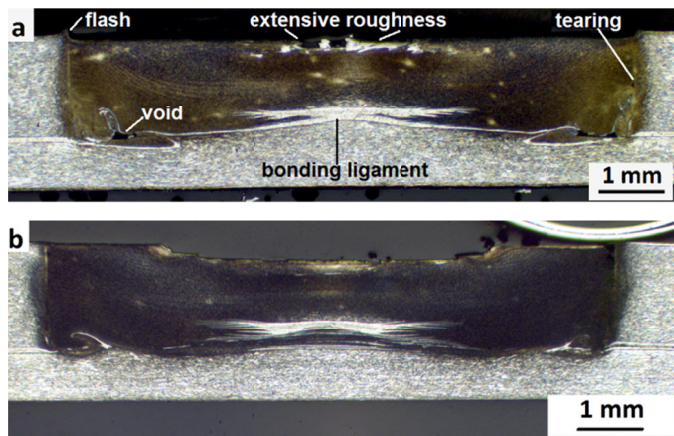


Fig. 4. Macrostructure of RFSSW joints of sheets with alclad – specimen 9P (a) and with anodic oxide layer – specimen 1A (b)

retains the flat shape. Bonding ligament's shape is important issue, because as other researchers claim [4,8] such kind of failure may be a place, where crack can be easily propagated.

A characteristic feature of lap joints is contact line (thin oxide layer between joined sheets) deformation in a thermo-mechanical affected zone. In some cases this deformation extends even further to a mixing zone. This is a structural failure, which can initiate joint cracking, because the tip of the hook is susceptible to stress accumulation. In more than half of investigated specimens, the end of a contact line is localized near the boundary between thermomechanical deformation zone and outer recrystallization zone (Fig. 5). The configuration of the contact line in the form of a small hook directed downwardly was mainly observed for specimens welded at a rotational speed of 2000 rpm and a tool plunge depth of 1.8 mm and in the case of welded joints with the speed of 2500 rpm and a 1.6 mm tool plunge depth (Fig. 5 b-c).

Contact line deformation mostly observed as hooking is very dangerous issue, especially in welds where some voids

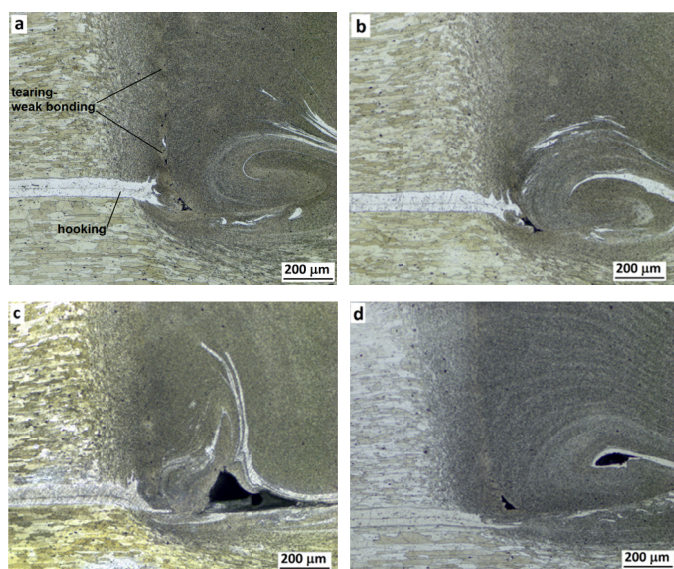


Fig. 5. Defects in RFSSW joints-microstructure of cross-sections of specimens: a-3P, b-6P, c-7P, d-1A

also appears in the bottom of a weld in a sleeve impact zone (Fig. 5c, d). Then there is a significant probability that the destruction of the joint will come by separating of weld from the bottom plate at lower value of breaking force than expected. Such situation occurred in case of RFSSW specimens welded with the speed of 2500 rpm. Maximum size of voids was even more than 300 μm.

Small voids (also called as tearing) were observed along boundary of sleeve action area (i.e. Fig. 5a). This form of discontinuity occurred in welds, when material that fill space emptied by a retreating sleeve was not plasticized enough. This type of failure was observed in joints welded with a rotational speed of 1500 rpm where poor plasticity of metal is effect of low temperature in a weld. Small voids or clearly visible boundary along the zone of sleeve action occur also when anodized sheets were welded. Probably in this case, despite of using the high rotational speed, plasticization of material was insufficient to create a durable joint between the weld and the parent material. Anodized layer may be limitation in obtaining a sufficiently high temperature and plastic deformation of the welded material despite its slight thickness (of the order of several micrometers). Oxide layer is rather brittle and porous, which may promote the formation of microstructural inhomogeneity and the formation of discontinuities. There is lack of further information about influence of oxide layer on microstructure and properties of RFSSW welds. This mean, that this subject should be investigated broader. In case of welds, where joint between weld and

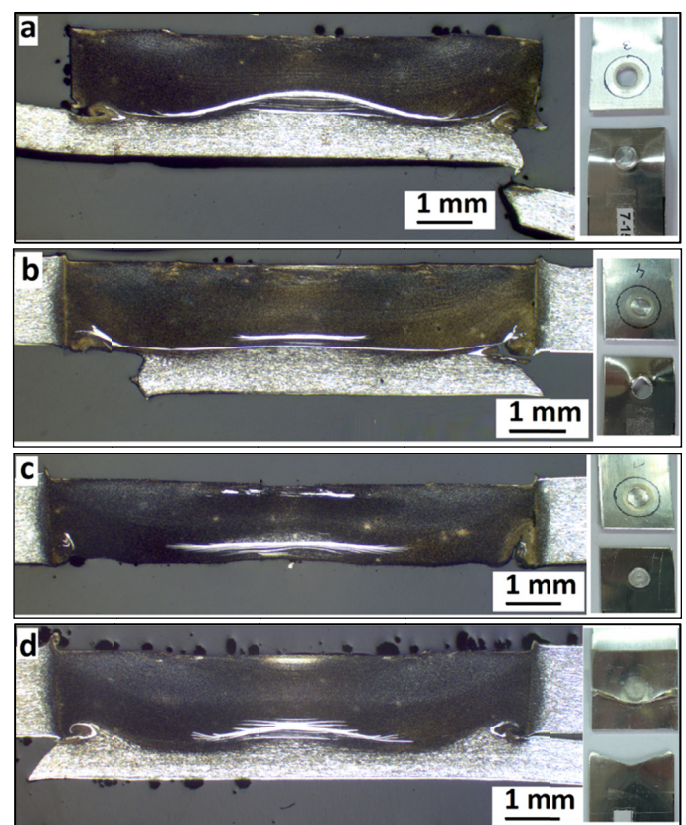


Fig. 6. Different types of failure mechanism in RFSSW joints: a) spot weld separation from upper sheet, b) spot weld separation from bottom sheet, c) shearing, d) bottom sheet breaking

parent material (along the area of sleeve action) is poor, weld is separated from the upper sheet during loading (Fig. 6a).

In case of joints welded with a rotational speed of 2000 rpm (specimens 4P, 5P, 6P) the boundary of sleeve impact zone was actually invisible. This means that mixing of a material was proper and weld was strongly joined with a parent material. These joints were destroyed by shearing and the beginning of breaking was localized at the end of the contact line (Fig. 6c) or by rupture of lower sheet also in a place, where contact lines end (Fig. 6d). These specimens were characterized by the best mechanical properties. The highest values of load were carried by specimen 5P, welded at rotational speed 2000 rpm and depth of tool penetration 1,7 mm.

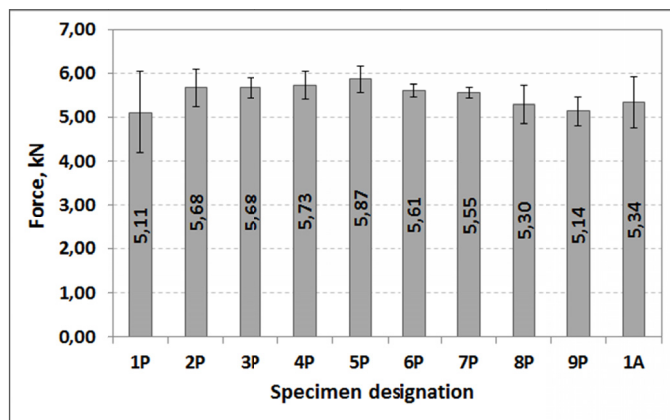


Fig. 7. Results of tensile strength tests of RFSSW joints

The rest of investigated joints broke at lower force values (Fig. 7), mainly because of relatively weak join between weld and parent material (specimens 1P, 2P, 3P, 1A) or presence of voids in the bottom of a weld (specimens 7P, 8P, 9P). No influence of bonding ligament was observed on joints' mechanical properties.

4. Conclusions

Summarizing results of investigations that were realized within this paper the following conclusions can be drawn:

- Parameters of RFSSW process proposed in this paper, for sheets with alclad guarantee obtaining of joints free from notch around the spot weld,
- No influence of presence or shape of bonding ligament on mechanical properties was found,
- Too low rotational speed (i.e. 1500 rpm) does not allow to achieve sufficient plasticity of metal. Poor joining between weld and parent material is result of this. This type of joints were broke by rupture of weld from the upper sheet,
- To high rotational speed (2500 rpm) promotes creation of large voids in the bottom of a weld. This, together with deformation of a contact line lead to breaking of a joint, typically by separating of weld from lower sheet,
- Best mechanical performance of RFSSW welds were provided when rotational speed was equal to 2000 rpm and a depth of tool penetration of 1.6 mm or 1.7 mm (for a welding time of 2 seconds). These welds were characterized by a very good mixing of a material in a sleeve impact zone,
- It is necessary to conduct more complex research on the effects of protective layers used in the production conditions (i.e. anodizing) on the quality of RFSSW welds.

Acknowledgements

Financial support of The National Centre for Research and Development, European Union, PZL Mielec A Sikorsky Company in the framework of European Regional Development Fund Project "Advanced techniques for the fabrication of airframe structures using innovative friction stir welding (FSW) technology", Nr INNOLOT/I/4/NCBR/2013 is gratefully acknowledged.

REFERENCES

- M.P. Mubiayi, E.T. Akinalbi, WCECS 2 (2014).
- L.C. Campanelli, U.F.H. Suhuddin, A.I.S. Antonialli, Journal of Materials Processing Technology **213**, 515-521 (2013).
- Y.Q. Zhao, H.J. Liu, Z. Lin, S.X. Chen, J.C. Hou, Science and Technology of Welding and Joining **19**, 7, 617-622 (2014).
- Z. Shen, Y. Chen, J.S.C. Hou, X. Yang, A.P. Gerlich, Science of Technology of Welding & Joining **20**, 48-57 (2015).
- P.S. Effertz, V. Infante, L. Quintino, U. Suhuddin, S. Hanke, J.F. dos Santos, International Journal of Fatigue **87**, 381-390 (2016).
- Z. Shen, X. Yang, S. Yang, Z. Zhang, Y. Yin, Materials and Design **54**, 766-778 (2014).
- M. Reimann, T. Gartnerb, U. Suhuddina, J. Göbela, J.F. dos Santos, Journal of Materials Processing Technology **237**, 12-18 (2016.)
- Z. Li, S. Gao, S. Ji, Y. Yue, Journal of Materials Engineering and Performance **25** (4), 1673 (2016).