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Rafał BUREK
Dawid WYDRZYŃSKI
Jarosław SĘP
Wojciech WIĘCKOWSKI

THE EFFECT OF TOOL WEAR ON THE QUALITY OF LAP JOINTS BETWEEN 7075 T6 ALUMINUM ALLOY SHEET METAL CREATED WITH THE FSW METHOD

WPŁYW ZUŻYCIA NARZĘDZIA NA JAKOŚĆ POŁĄCZEŃ ZAKŁADKOWYCH BLACH ZE STOPU ALUMINIUM 7075 T6 WYKONANYCH METODĄ FSW*

The article concerns the issues of tool wear effect on the quality of a friction stir welding joint quality. The experiment used aluminum alloy 7075 T6 sheet metal, which is used primarily in the aerospace industry. 1.0mm and 0.8mm thick lap joints were tested. Tool wear was determined based on multiple readings on a multisensory machine. The tool wear evaluation was done on the basis of a static tensile strength test and metallographic sections of the joints. The pin of the tool works in more demanding conditions and is more exposed to friction. This results from tooling operations performed at full depth dive in the jointed material. When also considering the small dimensions of the pin such as the diameter and the great forces occurring in this process, it is easy to see why this element is most susceptible to tool wear. The welding process causes the tool to undergo friction wear, which is the cause of reduced tool dive depth in the jointed material. As a result, it is paramount to constantly control the tool extension to achieve the desired quality parameters of the joint. After creating 200m of joints, a decrease in the strength of joints was observed as well as the repeatability of the results connected to a change in the stirring conditions in the material. The change in joint strength and tool wear is also confirmed in the metallographic analysis, which states that the continued degradation of the tool makes it subject to a decrease in size of the characteristic sizes of the thermoplastic zone that is the main determining factor of the joint strength.

Keywords: *friction stir welding, FSW, Al 7075 T6 Alloy.*

Opracowanie podejmuje problematykę wpływu zużycia narzędzia na jakość zgrzeiny otrzymanej metodą zgrzewania tarciowego z przemieszaniem FSW. Do badań użyto stopu aluminium Al 7075 T6, stosowanego głównie w przemyśle lotniczym. Badano połączenia zakładkowe blach o grubości 1,0mm i 0,8mm. Zużycie narzędzia oceniano na podstawie pomiarów na maszynie multisensorycznej. Ocenę wpływu zużycia przeprowadzono w oparciu o statyczną próbę rozciągania oraz analizę zgładów metalograficznych wykonanych połączeń.Trzpień narzędzia pracuje w trudniejszych warunkach i jest bardziej narażony na ścieranie. Wynika to z pracy przy pełnym zagłębieniu w łączonym materiale. Zważywszy również na stosunkowo małe wymiary trzpienia tj. jego średnicę i duże siły występujące w procesie to ten element jest najbardziej narażony na zużycie. W procesie zgrzewania narzędzie ulega zużyciu ściernemu, co jest powodem zmniejszania zagłębienia narzędzia w materiale łączonym. W związku z powyższym konieczna jest ciągła kontrola wysunięcia narzędzia dla uzyskania pożądanych parametrów jakościowych zgrzeiny. Po wykonaniu 200m zgrzeiny zauważono zmniejszenie wytrzymałości zgrzeiny, jak również powtarzalności wyników związany ze zmianą warunków mieszania materiału. Zmiana wytrzymałości zgrzeiny oraz zużycia narzędzia ma również potwierdzenie w badaniach metalograficznych, z których wynika, iż w związku z postępującą degradacją narzędzia zmniejszeniu ulegają wymiary charakterystyczne strefy termo–plastycznej odpowiedzialnej w głównej mierze za wytrzymałość zgrzeiny.

Słowa kluczowe: *zgrzewanie tarciowe z przemieszaniem, FSW, Al 7075 T6.*

1. Introduction

One of the methods of joining metal elements, which is becoming more and more popular in recent times is friction stir welding (FSW). Friction stir welding was developed by Mr. Wayne Thomas in the Welding Institute (UK) in 1991 to join light metal [25]. The technique is based on joining material in the solid state, which makes it possible to produce constant joints in materials that were considered difficult or impossible to weld. Compared to other welding methods of joining metals, FSW is energy efficient, universal, and ecological [6, 17, 20, 28]. The quality of welded joints is dependent on the process parameters. A weld results from localized heating of the material by the tool's rotation as well as tool dive to a desired depth and its translation along a specified tool path at a selected rate. The plasticized material, resulting from the friction between the material and tool, moves around the pin. The element becomes joined as result friction stirring of the semisolid state material [9]. Besides the process parameters, it is also critical to specify additional parameters like tool geometry, mounting system, welding direction etc. [5, 21, 27]

Due to the high strength of FSW joints, this method can easily compete with traditional joining methods. The applications of this method instead of traditional welding or riveting is appealing because it lowers the manufacturing costs and the mass of the product. Due

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** to these reasons, FSW has been classified as a key technology in the production of airplane fuselages and wings [15, 32]. The list of material used in aircraft skins is primarily populated by aluminum alloys [4, 23, 30]. Aluminum alloys, especially 2xxx and 7xxx series are difficult to weld because of their weak solidification and porosity in the joint area. However, these materials are relatively easily joined through FSW [8, 11].

These joints have their own advantages such as not having typical defects that can be observed in joints resulting from traditional welding methods like gas pores, shrinkage, thermal cracking and many others. Like all joining methods of this type, FSW has its limitations related to the difficulties in jointing elements with complex geometries and defects related directly to the strength of the joint and the repeatability of the process. The most common defects that can be observed from this method include contact line deformation, porosity, which results from the geometry of the tool [12-14, 16, 31].

There are very few publications concerned with the usage problems of tools used for friction welding. Most of works are focused primarily on the mechanism that cause wear in the friction welding process [22, 24, 29] and prediction tool wear with numerical methods [10]. The main problem of friction welding is tool pin wear. Wear is caused by excessive contact between the tool and welded material. The tool geometry has a significant effect on its resistance to erosive wear [3]. Without a doubt, the topics covered in the articles are valuable from the weld quality point of view, which should be characterized by identical strength parameters across the entire life of the tool. The use of PVD coatings on FSW tools is a promising approach to improve their effectiveness and lifespan, and thus improving the economics of the process. Coated tools are not as susceptible to dimensional variation as noncoated tools [1].

The research conducted by several authors aimed to present the phenomena occurring during friction stir welding with tools of various materials. The pin of the tool underwent a more detailed study because the works determined that the pin works in the most demanding conditions and is more susceptible to wear. The research does not cover topics that are very important for industrial applications like tool lifespan as a function of welding distance, which has, without a doubt, a significant meaning for manufacturing critical structural parts. When constructing an aircraft, the skin is traditionally joined using methods like resistance welding, riveting or gluing. Introducing a new sheet metal joining method like friction stir welding requires conducting several studies and attaining multiple certification that would allow for this technology to be widely used. Familiarity of the usage possibilities of FSW tools will assist in implementing this technology.

The fundamental goal of the study was determining the total welding length before reaching the critical wear criterium. Predicting the tool wear as a function of time or distance is a complex task. Having constant parameters through the entire operating range is not clear with equal tool wear. Several interferences cause variable tool lifespan. The results of tribological processes as well as heat and chemical influences affecting the tool pin, which has the greatest effect on tool lifespan. The assumptions of the study regarding the wear of the pin regard determining the welding distance for maintaining the strength parameters in a determined range. The reason for such wear criterium is the occurrence of significant tool deformation caused by the welded material affecting the tool pin. Thus, it is a technological criterium, which is wear that the tool will work in a stable manner and the weld quality meets the technological requirements. In the case of tool geometry variance caused by wear, the characteristics of the weld change, which would also be the subject of analysis in further studies.

2. Materials and Experiment Methods

2.1. Fundamental FSW concepts

Creating a weld using the FSW method is done by introducing a rotating tool with a specially designed pin into the contact area of two joined parts and then moving it along the length of the edges of the joined parts. The process of FSW being used to join two parts is illustrated in figure 1.

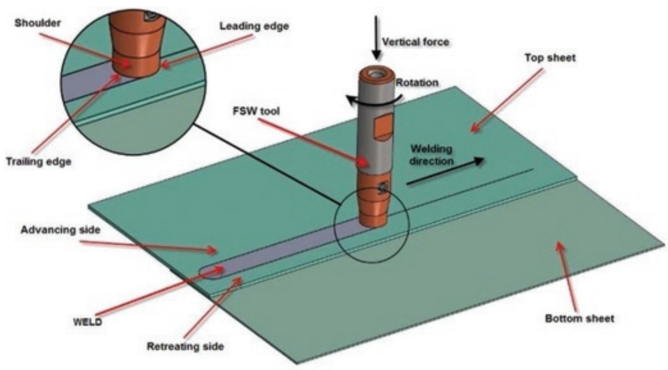

Fig. 1. The Friction Stir Welding Process

To properly complete the operation, the parts that are to be joined must be fixed securely and pressed firmly together. During the welding process, the rotating shoulder of the rotating tool heats up the parts, while the tool pin stirs the material to create a joint. When describing the friction welding process, concepts like the advancing side and retreating side should be specified. The advancing side is the side where the welding direction and rotation direction are the same. The retreating side's name suggests that the liquid material retreats in its direction. It is the side where the tool rotation direction is opposite to the welding direction.

As a result of the friction welding process, a solid weld appears where the materials were joined. The shape and properties of the weld are affect by a few factors like the shape of the tool and parameters like feed rate and rotational speed. Thermoplastic deformations can be observed in the transverse section of the weld. The effect of these process properties is the appearance of a complex microstructure that has a significant effect on the mechanical properties of the joint. A FSW weld can be divided into a few zones (Fig. 2).

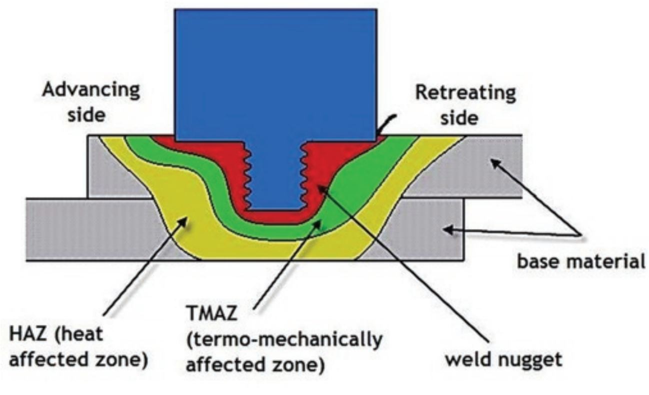

Fig. 2. The microstructure zones of the FSW process

Fig. 2. Presents the following zones of the weld:

- Parent material (PM): the part of the material that is the farthest away from the center of the weld, which does not undergo any deformation or change in a mechanically and structurally.
- Heat affected zone (HAZ): the part of the material that neighbors the weld where the material underwent the effects of heats, which resulted in a change of structure and mechanical properties. This zone does not undergo plastic deformation.
- Thermoplastic deformation zone: the zone where the material is affected by the tool resulting in mechanical and heat reactions. Aluminum alloys can undergo significant plastic deformation in this zone without the material recrystallizing. This is where the border between the non-crystallized material and weld core is found.
- Weld core: The area that undergoes full recrystallization. The weld is characterized by a small, axially distributed grain that is barely a few micrometers large (aluminum alloys). This is the area where the FSW tool pin travelled through.

The parameters of the weld like the size, shape, and zone size depend primarily on the size and shape of the tool.

2.2. Material and Samples

The experiment was conducted using 7075-T6 alloy sheet metal that was plated on both sides. The chemical composition is presented in Table 1. It was additionally examined using an X-ray spectrometer. 7xxx series aluminum alloys are characterized by high strength in comparison to other series of alloys. The compression strength and resistance to fatigue are the critical parameters in aircraft skin, wing, and empennage element design. The high strength of 7075-T6 aluminum alloy is key in using this material in aircraft structures based on its strength to weight ratio, machinability, and relative low cost [7, 26].

Aluminum alloys are susceptible to corrosion, which obviously decreases the lifespan of aircraft components. A negative phenomenon that lowers the lifespan of aircraft is corrosion and material fatigue [18]. As a result, aluminum alloy sheet metal producers use plating, a process of coating the sheet metal in pure aluminum to prevent corrosion [19]. The thickness of layer of pure aluminum is 40μm in accordance with AMS–QQ–A–250/13. The microstructure of plated Al 7075-T6 is presented in Figure 3.

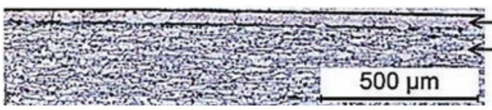

Fig. 3. The microstructure of plated 7075-T6 aluminum alloy [2].

One of the stages of tool wear analysis was determining its effect on the static strength of the joint as a function of welding distance. To conduct strength tests, samples with the dimensions presented in Figure 4. were prepared.

The thickness of the welded sheet metal was composed of a 1mm thick top sheet and a 0.8mm thick bottom sheet, which matches the thickness of an aircraft's skin and longerons respectively.

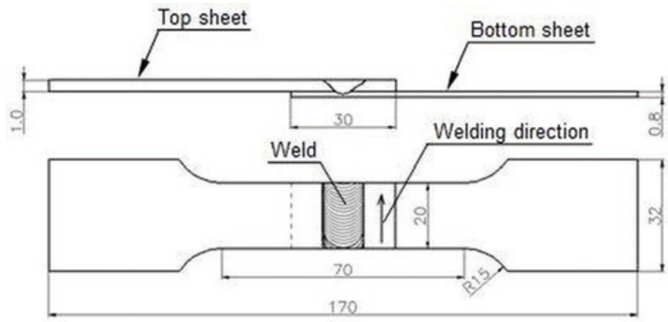

Fig. 4. Welded joint sample dimensions

3.3. Experiment

The experimental trails were conducted on a DMC 104V mill with an ISO 40 mounting system (Fig. 5a) using a commercial Schilling 10–S–4–Z–G–O tool with a hardness of 54-56HRC (Fig. 5b). The tool is characterized by a concave mainstay and cylindrical pin.

The trails were conducted on 320 mm long joints, which were cut into 4 samples for strength tests and one sample used for microscope analysis. The course of the process is presented in Fig. 6.

The following parameters were selected to perform the process:

- Rotation speed – 1000 RPM
- Feed rate – 200mm/min
- Pin extension – 1.2mm

The control samples were made every 20m up to 100m of weld, next every 40m. The geometric measurements of the pin were conducted ever 100m on a OGP Smart Scope FLASH 200 multisensory machine. To ensure repeatability of mounting the pin for making measurements, a fixture was made for indexing that precisely positions the measured pin. The measurements were conducted in two planes. After each measurement, the pin was set with an extension that accounted for the wear of the face surface (its extension was shorter than the initial value by amount defined as Δl) in comparison to the initial setting.

4. Results Analysis

The measurements showed that the wear for 100m≈2%; 200m≈4%; 300m≈10%; 400m≈12% pin material erosion. When considering the tool measurements and the wear of the face surface, there was not a significant amount of material erosion; however, the wear of the face surface was Δl≈0,06mm after 300m and Δl≈0,08 mm after 400m (Fig. 7)

Adjusting the pin extension from the mainstay of the tool allows for greater confidence and repeatability of results; however, it does not change the shape of the face surface undergoes constant advancing degradation (Fig. 8).

The wear of the tool influences the strength of the joint, which effected by the contribution of the pin (its dive depth and extension) in stirring the material (Fig. 9)

Table 1. 7075-T6 Aluminum Alloy Chemical Composition (wt.%)[2].

source	Chemical composition(wt.%)								
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	other	Al
Standard	max 0.4	max 0.5	1.2~2.0	max 0.3	2.1~2.9	0.18~0.28	5.1~6.1	0.3	0.05 0.15	remainder
Tested	–	0.10	1.35	0.06	2.61	0.26	5.6	0.05	– –	remainder

Fig. 5. (a)DMC 104V Mill, b) Schilling tool

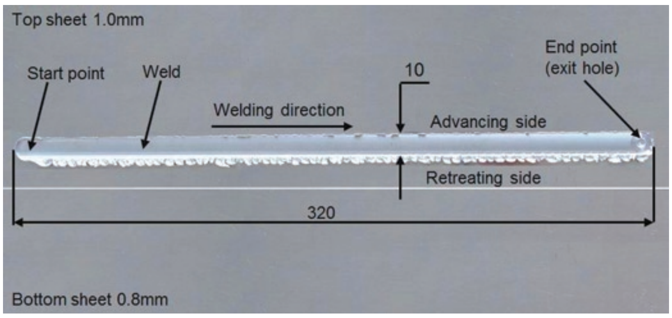

Fig. 6. FSW Process Course

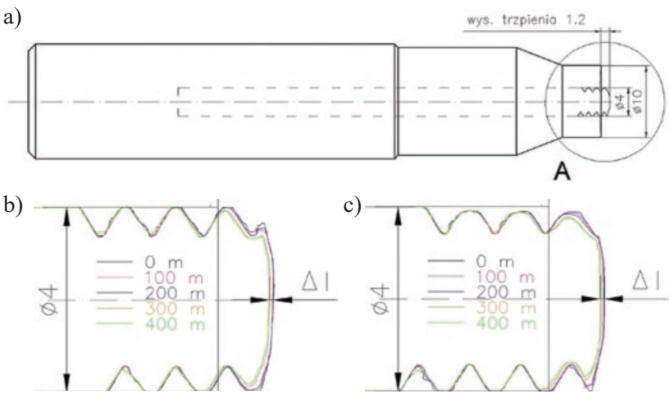

Fig. 7. The tool pin measurement results: a) characteristic dimensions b) 0°plane measurement c) 90° plane measurement

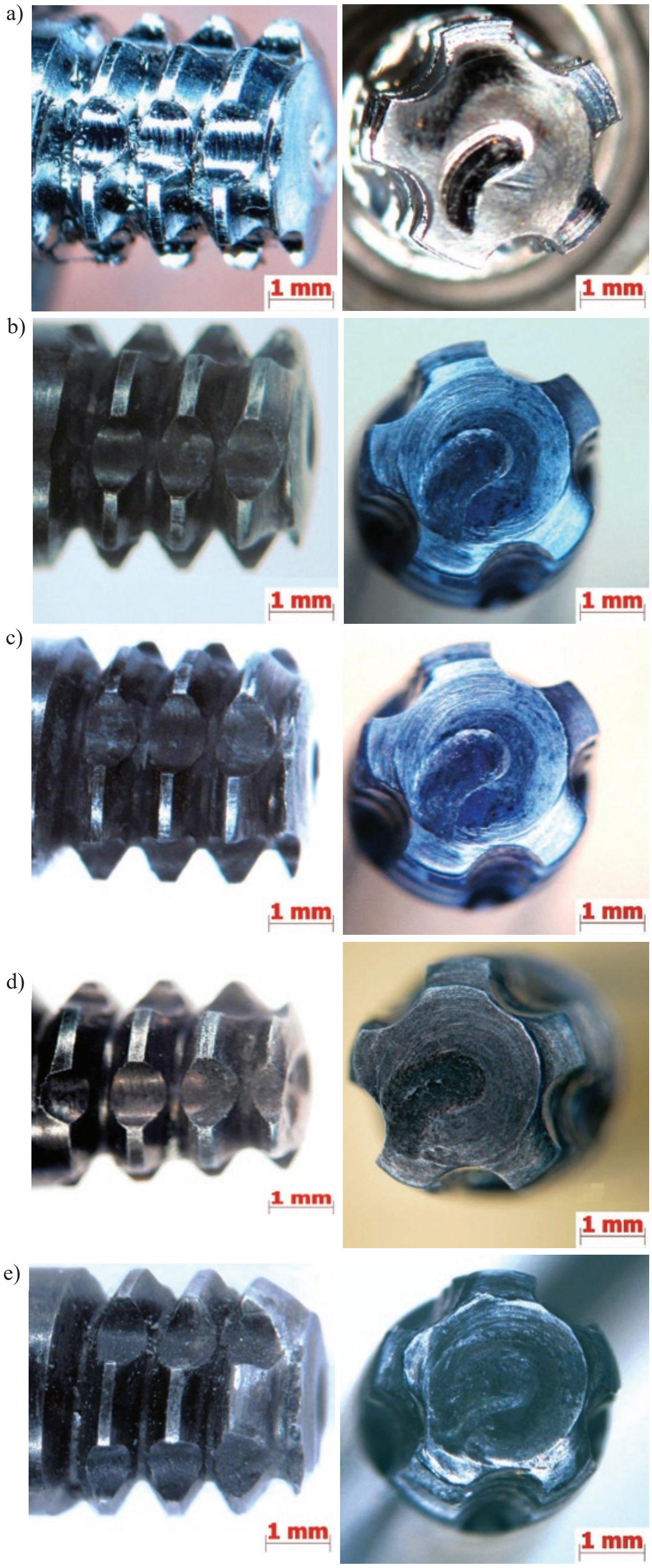

Fig. 8. Macroscopic wear analysis of the tool from the side and face for the following welding distances: a) 0m, b) 100m, c) 200m d) 300m, e) 400m.

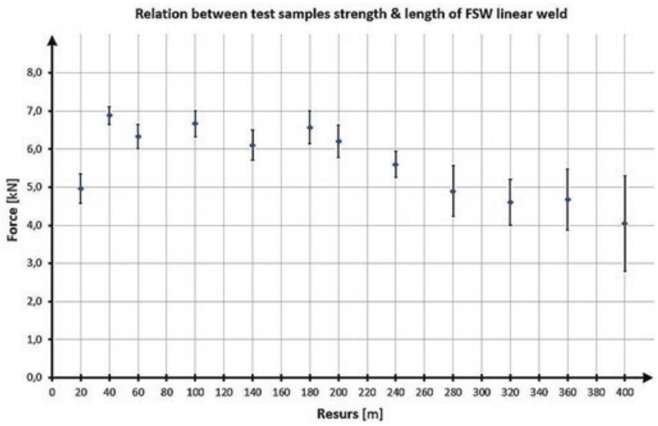

Fig. 9. The tearing force as a function of tool welding distance.

The results of the strength test trails show that the initial stage of the tool wear tests does not significantly increase the strength. This is related to the break-in period of the tool, which can be blatantly observed with an increase in strength in the 20m/40m welding distance control point. The following samples show a relatively comparable strength until reaching a welding distance of 200m. After that distance there is a decrease in strength and a lower rate of sample failure force repeatability can be observed (standard deviation value increase).

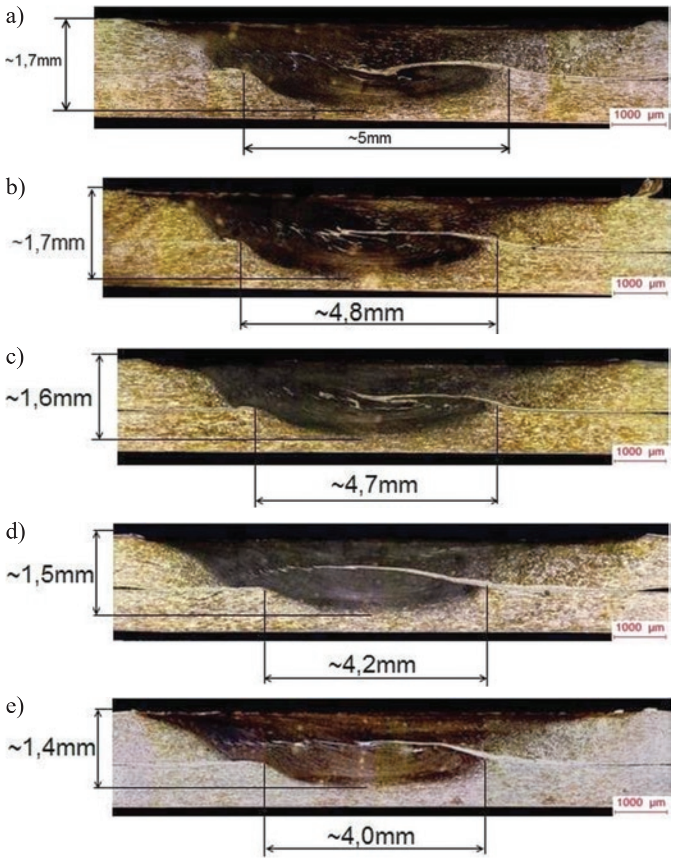

Fig. 10. Cross section and weld microstructure at: a) 40m, b) 100m, c) 200m, d) 300, e) 400m.

This is due to tool wear on the helical thread and surface face.

Thread wear also causes a decrease in stirring width on the contact line and stirring depth, which can be observed in Fig. 10.

It can be easily seen that the weld width decreases to 4mm and its depth decreases to 1.4mm after 400m of welding distance.

Based on the results, the aim of the study was to determine the welding distance where the critical wear value is reached. The wear of the pin has the greatest effect on the lifespan of the tool, which results from the tribological processes, heat, and chemical reactions. The accepted wear criterium is justified by the occurrence of significant tool deformation resulting from reactions of the welded material on the tool pin. Thus, this a technological criterium, or in other words, wear limit that the tool performs stable manner and the weld quality meets the technological requirements. The tendencies observed in this study are concurrent with those in similar publications [1, 3] concerning tool wear.

5. Conclusions

1. The tool pin performs in the most difficult conditions and is most susceptible to wear. This results from work at full dive depth in the joined material. The relatively small dimensions of the pin like its 4mm width and the large forces (5kN) that occur during process cause this part to be the most susceptible to wear. In addition, thread wear increases the chances of damage that can also weak the tool core.
2. Face surface and circumferential wear (Δl) of the tool was observed during the welding process that was proportional to the welding distance. As a result, it is paramount to control the pin extension to ensure the desired weld quality parameters during the process.
3. During the initial welding stages, the tool underwent a break in period over the first 40m of welding that was characterized by decreased strength. After this distance, the strength values stabilize at around ~6.5kN. After 200m of welding, the welds' strength begins to decrease by about 30% and the repeatability of the results also deteriorate because of a change in the stirring conditions of the material (thread wear affects the transport of the plasticized material). The repeatability of the results is critical from the aircraft construction point of view.
4. A change in the strength of the weld and tool wear is also confirmed by metallographic analysis, which confirms that the degradation of tool's dimensions results in a change in the dimensions of the characteristic thermoplastic zone that is the most significant factor of weld strength. The first 200m of welding resulted in dimensions that varied around ~1.6mm depth and ~4.8mm width.
5. The study presents the effect of tool wear on the strength parameters of welded samples. In order to perform this study, over 400m of welds had to be made, which resulting in the research being time consuming and costly.

Acknowledgements

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Rafał BUREK
Development Projects Office DTR/B
Polskie Zakłady Lotnicze Sp. z o.o.
ul. Wojska Polskiego 3, 39-300 Mielec, Poland

Dawid WYDRZYŃSKI
Jarosław SĘP
Faculty of Mechanical Engineering and Aeronautics
Rzeszow University of Technology
al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland

Wojciech Więckowski
Faculty of Mechanical Engineering and Computer Science
Czestochowa University of Technology
al. Armii Krajowej 21, 342-201 Częstochowa, Poland

E–mails: rafal.burek@lmco.com, dwydrzynski@prz.edu.pl, jsztmiop@prz.edu.pl, wieckowski@itm.pcz.pl