Article citation info:
WIĘCKOWSKI W, BUREK R, BUREK R, ŁOGIN W. Analysis of wear of tools made of 1.2344 steel and MP159 alloy in the process of friction stir welding (FSW) of 7075 T6 aluminium alloy sheet metal. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2019; 21 (1): 54–59, http://dx.doi.org/10.17531/ein.2019.1.7.

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ANALYSIS OF WEAR OF TOOLS MADE OF 1.2344 STEEL AND MP159 ALLOY IN THE PROCESS OF FRICTION STIR WELDING (FSW) OF 7075 T6 ALUMINIUM ALLOY SHEET METAL

ANALIZA PROCESU ZUŻYCIA NARZĘDZI WYKONANYCH ZE STALI 1.2344 ORAZ STOPU MP159 W PROCESIE ZGRZEWANIA TARCIOWEGO Z PRZEMIESZANIEM (FSW) BLACH ZE STOPU ALUMINIUM 7075 T6*

The study presents an analysis of wear of tools made of 1.2344 steel and MP159 alloy for the process of obtaining an overlap joint in 1.0 mm and 0.8 mm sheet metal made of 7075 T6 aluminum alloy using friction stir welding (FSW) technology. Tool geometry was designed at the Czestochowa University of Technology. Evaluation of tool wear was conducted based on the measurements of geometry of working area of tools by means of a multisensory meter system and based on the assessment of the working area by means of a stereoscope after individual stages of wear tests. Furthermore, based on the results of a static tensile strength test and metallographic examinations of the specimens sampled from the joints obtained during tool wear tests, the effect of the degree of tool wear on joint quality was also evaluated. Analysis of the results revealed that both the tool made of 1.2344 steel and that made of MP159 alloy were substantially worn, increasing the risk of further use of the tools for the joint material (7075-T6) after obtaining the joint with length of 200m, which suggests their low durability. Furthermore, modification of tool geometry caused by wear led to insignificant improvements in joint strength. Therefore, the results of wear measurement set directions for further modification of tool geometry, also due to the fact that despite a substantial wear, the tools continued to yield high-quality joints without defects. As demonstrated in the study, the type of tool material does not only impact on tool life but also, as it was the case in their geometry, has a significant effect on the quality of obtained joints. Although the tool made of MP159 alloy was worn more than the tool made of 1.2344 steel, it allowed for obtaining the joints with substantially better strength parameters.

Keywords: *wear of tools, friction stir welding, FSW, Al 7075 T6 alloy.*

W pracy przedstawiono analizę procesu zużycia narzędzi wykonanych ze stali 1.2344 oraz stopu MP159 w procesie wykonywania złączy zakładkowych z blach ze stopu aluminium 7075 T6 o grubości 1,0mm i 0,8mm technologią zgrzewania tarciowego z przemieszaniem materiału (FSW). Geometrię narzędzi użytych do badań opracowano na Politechnice Częstochowskiej. Ocenę zużycia narzędzi przeprowadzono w oparciu o pomiary geometrii części roboczej narzędzi na maszynie multisensorycznej oraz na podstawie oględzin powierzchni roboczej przy użyciu stereoskopu po kolejnych etapach badań zużycia narzędzia. Dodatkowo, w oparciu o wyniki statycznej próby rozciągania oraz badania metalograficzne próbek pobranych ze złączy wykonywanych w trakcie badań zużycia narzędzi, przeprowadzono ocenę wpływu stopnia zużycia narzędzi na jakość wykonanych złączy. Na podstawie analizy wyników można stwierdzić, że zarówno narzędzie wykonane ze stali 1.2344 oraz ze stopu MP159 ulegają intensywnemu, zagrażającemu ich dalszej eksploatacji zużyciu, we współpracy z materiałem zgrzeiny (7075-T6) już po wykonaniu złącza o długości 200m, co świadczy o ich niskiej trwałości. Przy czym zmiany geometrii narzędzia spowodowane zużyciem pozwoliły na nieznaczną poprawę wytrzymałości złączy. Uzyskane wyniki pomiarów zużycia wyznaczają zatem kierunek w procesie dalszej modyfikacji geometrii badanych narzędzi, również z uwagi na fakt, iż pomimo znaczącego zużycia badanych narzędzi, pozwalały one w dalszym ciągu uzyskać dobre jakościowo złącza pozbawione wad. Jak wykazały badania, rodzaj materiału narzędzia wpływa nie tylko na trwałość narzędzi ale również, jak ma to miejsce w przypadku ich geometrii, ma on istotny wpływ na jakość uzyskanych połączeń. Pomimo tego, że narzędzie wykonane ze stopu MP159 uległo większemu zużyciu w porównaniu z narzędziem ze stali 1.2344, to pozwoliło ono uzyskać złącza o znacznie lepszych parametrach wytrzymałościowych.

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

1. Introduction

Friction stir welding (FSW) technology was developed in the early nineties of the 20th century in the Welding Institute in the UK. An advantage of the method is that the joints are without defects, with good mechanical and structural properties. Consequently, the FSW technology started to be used on an industrial scale in the arms, aircraft and shipbuilding industries to join components of containers, decks, wings, shell plating etc. [1].

Friction stir welding (FSW) has been substantially popular in joining aluminium, its alloys and other soft metals. However, using

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** the FSW technology for joining hard metals represents an exceptional challenge due to the poor availability of tool materials that are capable of withstanding the welding process conditions, while its commercial use is limited by high costs and short life of the tools [1, 15, 16, 20, 21].

An important role in the FSW process is played by the tool. Along with process parameters, the tool is responsible for heating and mixing the material, which translates into the size of the joint zones and impacts on joint quality and properties [18].

During welding, FSW tools are exposed to wearing processes depending on interactions between the processed material, tool material, tool geometry and welding parameters. Tool wear, which is reflected by the change in geometry and caused by mechanical and thermal load to the working surface of the tool, may result from abrasion, plastic deformation, oxidation, adhesion, chipping etc. This can be prevented by using appropriately selected process parameters, right material and anti-adhesive and anti-wear coatings. Manifested by the change in the tool shape, excessive wear elevates the risk of defects and deteriorates joint quality. Particles of the tool material or a coating that remain in the joint material have an unfavourable effect on joint properties, are unacceptable and might promote formation of local corrosion cells [3, 6, 11, 15, 19, 24].

Due to the effect of high temperature and stress caused by friction and surface pressure, tools are exposed to thermal and mechanical fatigue, leading to accelerated wear. Examinations of the use of FSW tools showed that compared to the tool shoulder, elevated wear and deformation of the tool pin is observed, and tool damage occurs almost each time due to the pin damage [19].

Studies [9, 17] presented the results of examinations of 6000 aluminium alloy joints obtained using a tool made of SW7M (HS6-5-2) high-speed wolfram-molybdenum steel. It was demonstrated that with a relatively large range of process parameters, one can achieve the expected quality of joints in terms of strength and structure of the joint.

An important component of FSW tool degradation is its plastic deformation, being the most noticeable component of changes in tool geometry. Deformation leads to substantial changes in geometrical dimensions of the working part of the tool, such as length and diameter and substantial structural change in tool material. Understanding the microstructural changes that occur during welding a joint helps identify the mechanism and explain causes of tool degradation. The authors of the study [22] presented results of the examinations of wear for FSW tools made of wolfram alloys, including wolfram with rhenium, where changes in tool geometry and material microstructure that occurred during FSW welding of titanium and steel were evaluated.

The study [12] examined wear of the tool made of WC-Co material conducted for various configurations of process parameters (rotational tool speed, welding speed etc.). A tool wear index was used to evaluate tool wear quantitatively by determination of percentage changes in geometrical values of the tool compared to joint length and other process parameters. According to the authors, maximal intensity of tool wear was always observed in the initial phase of welding, whereas wear intensity reduced with the increase in joint length, with the decisive impact on wear observed for the welding velocity.

Furthermore, the authors argue [24] that excessive wear leads to changes in tool shape, thus increasing the likelihood of defects and deterioration of joint quality. Mechanisms of wear depend on interactions between the welded piece and tool material, selected tool geometry, and welding parameters. In the case of tools made of PCBN, wear at low rotational speeds of the tool is mainly caused by adhesive wear, whereas wear at high speeds results from friction wear.

The choice of the material and tool geometry is therefore an important element at the stage of planning of the process of joining materials using the FSW technology, because tool material properties determine the scope of its use for selected types of joined materials and parameters of the welding process.

The usefulness of the material for tool is mainly determined by its hardness, which should be higher than hardness of material welded under conditions typical of the process. High compression strength is also required due to the pressure on the working tool surface, and high impact and fatigue strength. Materials used in FSW tools should be characterized by resistance to abrasive, adhesive, diffusive and chemical wear. Additionally, good thermal properties are needed in the processes where substantial amount of heat is generated from tool material. An important characteristic of tool materials that determines process economy is their price [10].

Materials which are most often used for FSW tools for joining aluminium alloys are tool steels and nickel- and cobalt-based alloys [24].

High-speed alloy steels and hot work steels have been used for FSW tools for joining aluminium alloys due to their availability, easiness of processing, acceptable resistance to thermal fatigue, resistance to wear and low production costs [4,13,14]. Tool steels have been also popular for FSW tools in the process of welding of magnesium, copper and aluminium matrix composites (AMCs), for which accelerated tool wear have been observed. They can be also used for joining two different materials (e.g. copper with brass), both in overlap joints and butt joints [2, 5, 7, 8, 9, 19, 23, 24].

The material which was used to obtain FSW tools in the process of aluminium welding was cobalt-based alloy **(MP159)** with very high strength and ductility at temperature of 590 - 650°C and high resistance to corrosion and fatigue. These alloys have been also used for FSW tools for welding of Cu and Al-MMC composite materials [24].

Suitable combination of the tool material with the material of joined components and optimization of the tool shape allows for a substantial minimization of its wear, which ensures adequate tool life. Therefore, obtaining adequate quality of joints while maintaining low costs of the FSW process requires examinations of specific tool materials and design of new tools.

2. Aim and Scope of the Study

Examinations were aimed to identify a wear trend in FSW tools designed based on the geometry of the tool developed at the Częstochowa University of Technology and to gain experiences in the field of methodology of wear testing at specific parameters of the FSW technology for the selected grades and parameters of the material welded.

Two tools were used in the study, made of hot work steel (1.2344) and MP159 alloy in the Medical Devices Factory CHIRMED in Rudniki, Poland (Fig. 1). Tools have a flat shoulder and pin in the form of a truncated cone with smooth surface.

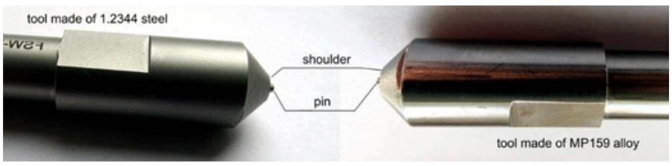

Fig. 1. FSW tools used in wear testing

During the wear tests, the overlap joints with the length of 325 mm were welded on the sheet metal with the length of 356 mm made of double-cladded aluminium alloy 7075–T6. Sheet metal thickness for the joint was 1 mm for the top sheet metal and 0.8 mm for the bottom sheet metal, see Fig. 2.

Based on the previous experimental examinations, the following parameters of welding process were determined: the tool rotational speed n = 1,000 rpm, tool feed v_3 = 200 mm/min, and the depth = 1.2 mm. Joints were welded using a DMC 104V machine in PZL Mielec.

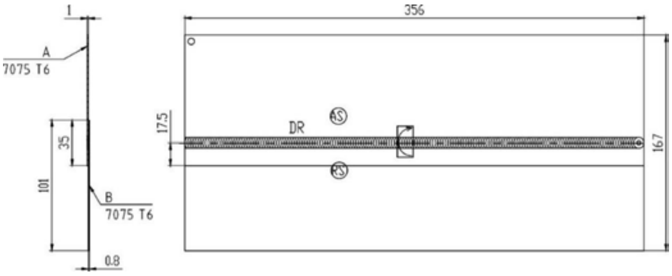

Fig. 2. The test joint welded during the FSW tool wear test

After each research stage where joints with total length of ~100 m were welded, the tool was cleaned and then the contour of the working part was measured. Furthermore, in order to evaluate the effect of tool wear on joint quality, each time after ~20 m of the joint was welded, four samples for tensile strength tests (1÷4) and three samples for metallographic tests were cut out from the test joints (5÷7). The example of a test overlap joint (1.0 7075-T6 + 0.8 7075-T6) welded during tool wear test was presented in Fig. 3.

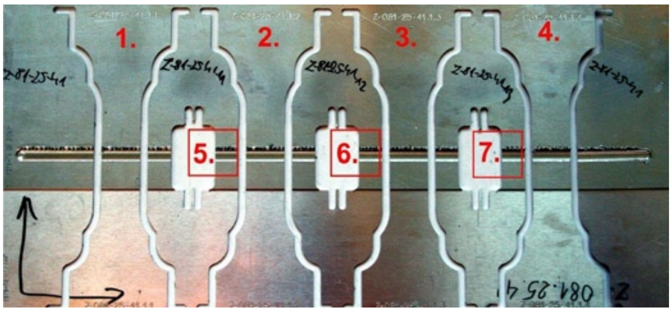

Fig. 3. Example of an FSW test joint with sample cut out for strength tests and metallographic examinations

Measurements of the geometry of the working part of the tool was made using the OGP Smart Scope FLASH 200 multisensory meter system, whereas wear of the FSW tools was evaluated based on comparisons of the contour of a new tool with the contour of the tool for which the wear was measured after individual research cycles.

In order to evaluate tool wear, absolute changes in selected geometrical values were determined with respect to the joint length (individual stages of research). As shown in the measurement design in Fig. 4, changes in the pin diameter *dp* at pin heights of 0.2mm, 0.4mm, 0.6mm, 0.8mm and 1.0 mm, measured perpendicularly to the tool axis (radial wear) and changes in pin height *hp* and shoulder height *hs* measured in the direction of the tool axis were evaluated with respect to the adopted measurement basis.

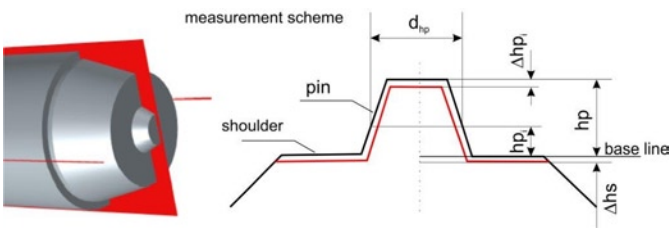

Fig. 4. Diagram of the measurements of changes in the working part contour in FSW tools

Visual inspection of the state of the working tool surface was made after completion of each cycle of tool work, based on the prepared photographic documentation from the stereoscopic examinations.

3. Results of the FSW tool wear tests

Figure 5 presents the results of measurements of the geometry of a new FSW tool made of 1.2344 steel and measurements performed after each operation (welding a joint for the expected length). The bar chart was used to present the values of absolute wear on the working surface of the tool, measured at individual research stages. Tool wear examinations were completed after obtaining the joint with total length of 202.150 m (after the 2nd research stage) due to the substantial wear of the tool working surface.

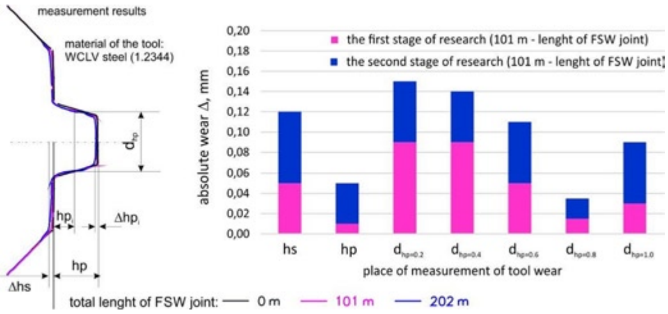

Fig. 5. The results of the wear of the FSW tool made of hot work steel (1.2344) after individual stages of wear tests

Intensive and varied wear over the entire working surface of the tool was observed during the FSW tool wear tests (1.2344), leading to changes in its shape.

Furthermore, gradual and varied wear of the lateral side of the pin was found after individual research stages. The highest radial wear of the pin occurred at the height of 0.2-0.4 mm, with wear intensity in this area greater in the first research stage and then decreasing. A substantial radial wear was also reported on the lateral surface of the pin at the height of 1.0-1.2 mm (along the edge of the front surface of the pin). Both in this case and for the front surface of the pin and shoulder, wear intensity increased during the research.

Photographic documentation of the visual inspection of the working surface of the tool made of 1.2344 steel and after completion of two consecutive stages of wear tests is presented in Fig. 6.

After the first stage of the research, noticeable marks of intensive tribological wear were observed on the working surface of the tool (both pin and shoulder). During the next research stage, a progressing increase in wear of lateral surface of the pin was observed, reflected by the change in its shape, and marks of the progressing wear on the front surfaces of the pin and shoulder, with substantial tool material depletion and numerous depressions, grooves and peripheral scratches.

The results of the measurements of working surface contour of the FSW tool made of MP159 alloy are presented in Fig. 7. Due to the substantial wear of the working surface of the tool, leading to the high risk of sudden damage at the following stages, the wear tests were terminated after the 2nd stage as it was the case for the tool made of 1.2344 steel.

The obtained results of tool measurements indicated gradual and substantially varied wear on the lateral surface of the pin. The highest radial wear was observed on the lateral surface of the pin at the height ranges of 0.2-0.4 mm and 1.0-1.2 mm. The lowest wear was observed for the lateral surface of the pin at the height of 0.8mm and the front surface of the pin. The increase in intensity of wear is noticeable on the entire working surface of the tool at the second stage of the examinations, with the only exception being the front surface of the pin, where its decline was observed.

Results of the measurements of tool wear were confirmed by the visual evaluation of the condition of the tool working surface conducted after completion of each cycle of wear tests. The appearance of the working surface of the new FSW tool made of MP159 alloy and

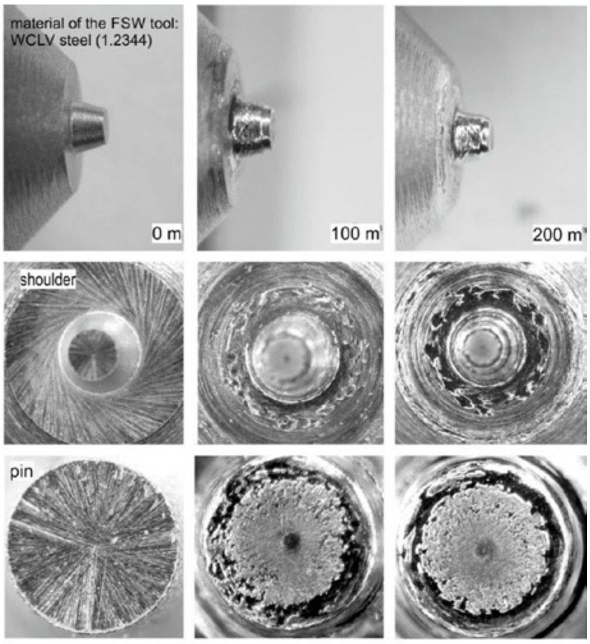

Fig. 6. Visual inspection of the working surface of the FSW tool made of 1.2344 steel following individual stages of wear tests

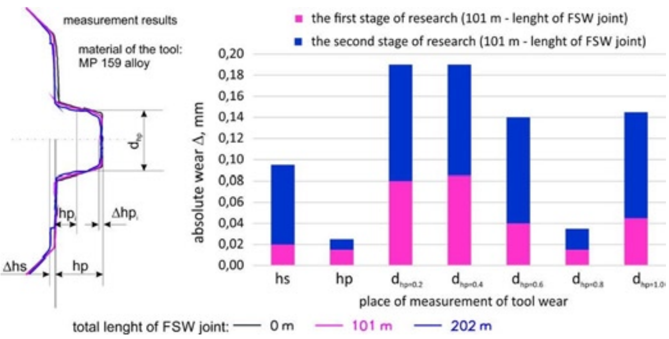

Fig. 7. The results of the wear of the FSW tool made of MP159 alloy after individual stages of wear tests

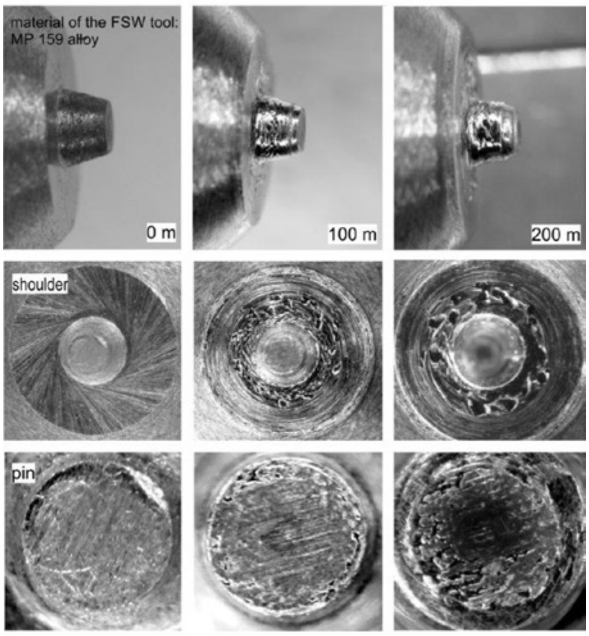

Fig. 8. Visual inspection of the working surface of the FSW tool made of MP159 alloy following individual stages of wear tests

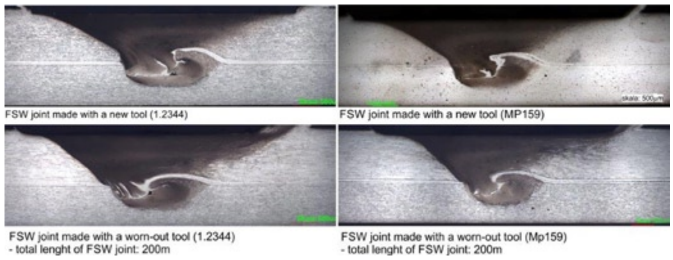

Fig. 9. Cross-section of the FSW joints welded using new and worn tools

following individual stages of the test was presented in Fig. 8. Marks of tribological wear can be noticed on the working surface of the tool, on the surface of shoulder at the pin base, its lateral surface and along the edge of the front surface of the pin. The shoulder and pin surfaces are covered with depressions and grooves of different size. Marks of peripheral scratches caused by friction were also observed on the working surface: they are considered to be the major cause of surface wear in tools for FSW processes.

A progressing increase in wear of working surface occurs with the increase in tool working time, manifested by continuous changing of its shape. Deep scratches and grooves caused by the progressing friction wear are observed on the lateral pin surface. The wear marks can be also noticed on the front surface of the pin.

The metallographic examinations of the samples of test joints showed that despite a substantial wear of the tools, it is possible to obtain joints without defects that would substantially impact on deterioration of their quality. Cross-sections of the joints obtained using the tools studied are presented in Fig. 9, for the initial and final phases of the wear tests.

Changes in geometrical parameters of the weld were observed with the change in the shape of the tool caused by its wear. Width of the joint welded with the tool made of 1.2344 steel, measured at the level of the sheet metal contact line increased from ~1.4 to ~1.5 mm, whereas mean material stirring depth in the area of the bottom sheet metal was maintained at a constant level of ~0.5mm. In the case of the tool made of MP159 alloy, the joint width increased from ~1.4 to ~1.6 mm, and an insignificant increase from ~0.4 to ~0.5 was also observed for mean material stirring depth in the bottom sheet metal.

Geometrical parameters of the joint (weld nugget width, material stirring depth in the bottom sheet metal) and type and number of defects in the joints determined the strength of the joints obtained during FSW wear tests. With the set process parameters, joint strength was also determined by accuracy of tool position with regard to the surfaces of the connected materials and geometrical changes of the working part of the tool caused by wear. The results of the strength tests of the samples from test FSW joints welded during the wear tests are presented in Fig. 10.

Compared to the FSW joints welded using the tool made of 1.2344 steel, those welded with the MP159 alloy tool had higher tensile strength. Differences in the values and substantial distribution of tensile strength of the test FSW joints obtained at the first stage of wear tests result from intensive wear (changes in geometry) of the tool and, consequently, variable conditions of the welding process. An insignificant increase in strength of the joints and reduced spread of its values were observed at the second stage of the wear tests.

Of all samples examined, 60% were broken (cut) in the joint at the level of sheet metal joining, whereas other samples were broken in the material of the lower and thinner sheet metal. An insignificant decline in the weld nugget width and depth of material stirring of the bottom sheet metal were observed for the joints with the lowest strength. Cold lap, wormholes and kissing bonds were observed in the cross-sections of these joints. Furthermore, the lack or insignificant thinning of the material of the top sheet metal in these joints may suggest too shallow

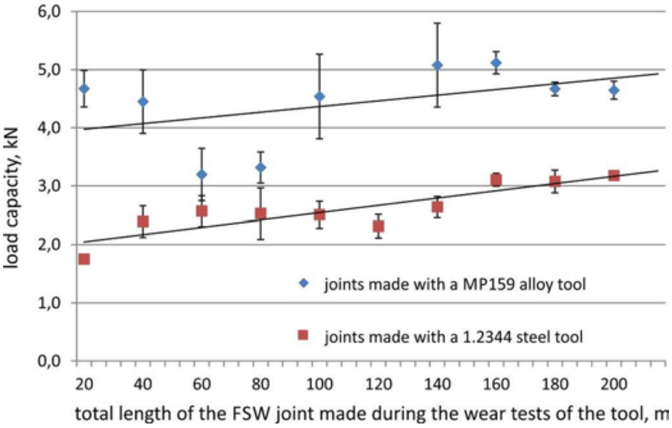

Fig. 10. Strength of test FSW joints welded during tool wear tests

tool infeed, which resulted in the lack of optimal conditions for the FSW process.

4. Conclusion

Working surfaces of FSW tools are exposed to a substantial mechanical load and high temperature during work. Therefore, the need arises for evaluation of their resistance to wear and their life. As one of main components of degradation of FSW tools, wear represents an effect of interactions between working surface of the tool and welded material. The character and intensity of the tool wear mechanism depends on interactions between welded material and tool material, and geometry of the working part of the tool and specific welding parameters. Changes in tool dimensions caused by friction suggest susceptibility of tool material to wear during contact with joint material, and its life. Therefore, symptoms of excessive tool wear should be analysed both in terms of geometrical changes and dimensions of the tool working part.

The examinations demonstrated that in addition to the set process parameters and type of joint material, an important factor that impacts on tool wear mechanisms is its geometry and type of tool material.

Changes in dimensions of the working part of the tools observed in the study that represent the measure of tool wear suggest high susceptibility of the materials used for tool tests (1.2344 steel and MP159 alloy) to wear an short life during contact with joint material (7075-T6). The tools analysed in the study were substantially worn after the second stage of the study, which virtually excludes them from further use, with the highest wear observed for the MP159 tool.

Compared to the tool shoulder, increased wear and deformations were observed for the lateral side of the pin. This was mainly due to the fact that the pin is entirely submerged in the welded material and is more exposed to the effect of the welded material during the tool movement and, consequently, to greater load.

Inspection of the worn working surfaces of the tool with particular focus on pin surface indicated that one of the mechanisms of degradation of the FSW tools was, in addition to friction and adhesive wear, their plastic deformation resulting from increased stresses in tool material over yield point reducing at elevated temperatures.

Varied intensity of wear of the tool working surface leads to changes in geometrical parameters of the joint, such as weld nugget width, material stirring depth for the bottom sheet metal or material thinning in the top sheet metal, having an effect on joint quality. Joints welded in the final phase of the examinations were characterized by an increase in weld nugget width and stirring depth for the material of bottom sheet metal compared to joints welded using new tools, which translates into increased tensile strength of the joints welded during consecutive stages of examinations of tool wear.

Changes in the geometry of the working part of the tool caused by wear and the type of tool material lead to changes in the transport of plasticized material around the tool and changes in friction conditions, responsible for amount of heat generated in the joint, which additionally impacts on joint quality (strength).

The results of the measurements of wear of the FSW tools and the results of examinations of joints obtained during wear tests can be useful in the process of modification of both shape and dimensions of the working part of the tool so that it is possible to obtain a longer and high-quality joint while limiting wear and improving tool life. Further reduction in wear of the tools may be achieved by using anti-wear coatings on working surfaces.

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", no. INNOLOT/I/4/NCBR/2013 is gratefully acknowledged.

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