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# THE INFLUENCE OF MODIFICATION OF THE FRONT SURFACE GEOMETRY OF THE RFSSW TOOL SLEEVE ON THE PLASTICIZATION EFFECT AND STIRRING MATERIALS DURING JOINING SHEETS MADE OF ALUMINUM ALLOY 2024

The paper presents the results of research and analysis of the effect of joining by the RFSSW method of alclad sheets made of Al2024 with an anodic oxide coating, with the using the tool with modified geometry of the front surface of inner sleeve. The different effects of the modifications made on the phenomenon of plasticization and stirring of materials in the process of creating a weld, microstructure of welds and mechanical strength of lap joints were shown. The tests were carried out on 1.27 mm thick sheets, with the use of an unmodified tool and modified tools with three variants of the geometry. The welds and the joints samples were subjected to metallographic and strength tests. It has been shown that the use of a properly selected modified geometry has a beneficial effect on the transport of materials to be joined in the joint zone (flow pattern of plasticized layers and the stirring effect) during the welding, which translates into the strength of the joints and the nature of the weld failure.

*Keywords:* RFSSW; RFSSW tools; joint strength; material mixing

## 1. Introduction

Although the significant increase in the share of composite materials in aviation structures is observed in recent years, metal alloys and in particular aluminum alloys, are still widely used in aircraft construction. In the form of sheets, their are used for the production of skins and structural elements (ribs, stringers, etc.). This is due to a very good knowledge of their mechanical properties and in the particular durability during the operation of the aircraft. Other aspects are relatively easy and well-known forming technologies, high specific strength and relatively good corrosion resistance in industrial and marine environments [1]. Due to their properties, and first of all, high strength and fatigue life, aluminum alloys of the 2xxx and 7xxx series are commonly used in aviation.

Sheets made of 2024 aluminum alloy in the T3 state was used in the performed research. It is characterized by good formability and increased yield point, what is particularly desirable in the design of aircraft skin elements. The main alloying element is copper, which plays a key role in the strengthening process, but has a negative effect on corrosion resistance. In order to protect the elements against unwanted pitting corrosion, the sheets are covered with a thin layer made of the alloy of the 1xxx series [2,3]. This layer of almost pure aluminum is called alclad, and its thickness according to standard is about 4% of total sheet thickness. Although the alclad may reduce the mechanical properties of the material, it improves the fatigue life in aggressive corrosive conditions, which is a desirable phenomenon in aircraft structures [4]. In addition to alclad, other types of coatings are also used to protect the surface or envelop it before applying paint layers. Among the commonly used, one can distinguish anodizing (creating an aluminum oxide layer), chromate coatings produced in the sol-gel process or alodine.

Aluminum alloys of the 2xxx and 7xxx series are included in the group of difficult-to-weld materials. In aviation structures, skins elements made of them are most often joined by riveting or using other fasteners. These processes are time-consuming and most often require dedicated tooling. In addition, there is a high risk of human error during manual riveting. Other disadvantages of fastener technologies include increased mass of the structure, occurrence of Foreign Object Damage (FOD) and high noise in the case of impact riveting. One of the joining methods of joining parts made of the aforementioned aluminum alloys is resistance welding. This process ensures a smooth surface at the

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joint. With stable process parameters, high repeatability of welds is achieved, the process can be automated, and the joints themselves have relatively good strength. The main disadvantages of the resistance welding process of aluminum alloys include high energy consumption, sensitivity of the process to all kinds of surface contamination and risk of hot cracking. Other factors influencing the formation of defects in welds are electrode wear and inaccurate process parameters [5,6].

One of the new methods of point joining of structures, which can be an alternative to the above-mentioned techniques, is the RFSSW (Refill Friction Stir Spot Welding) [7]. This process is carried out with the use of a dedicated head and tool, and the characteristic feature is obtaining a weld with a practically smooth face. The joint formation is below the melting point of the materials to be joined, i.e. without the liquid phase, and is characterized by a small heat-affected zone. The join is the result of plasticization and stirring of the joined sheets materials in the area of the influence of the tool with appropriate geometry and work parameters, which cause the above – mentioned phenomena as the result of friction. The RFSSW process enables the effective joining of not only aluminum alloys, but also steel, copper alloys and even thermoplastic composites with metals [8,9]. The tool consists of three basic elements: an outer sleeve (clamping ring), an inner sleeve and a pin. As the weld is made, the materials to be joined are compressed between the clamping ring and anvil. At the same time, the inner sleeve and the pin rotate at the same speed, while making coupled linear movements along the axis of the tool. As the outer sleeve penetrate into the materials to be joined, the pin is lifted, which creates space for moving plasticized metal streams. After obtaining the desired depth, the direction of the linear movements changes and the material from under the pin is pressed into the space on the retracting sleeve. A wider and more detailed description of the process and the RFSSW weld creation mechanism are described, among others in works [10-14].

An important issue for the correct performance of the RFSSW joint formation is the selection of process parameters, which include: tool rotational speed, welding time and the depth of penetration of the sleeve. High repeatability of welds, which are free from structural defects, can only be achieved with carefully selected parameters. As own realized research shown, this issue is particularly important in the case of joining alclad sheets, where effective fragmentation and stirring of additional material in the base material is required. Lack of stirring of the cladding material in the weld area or its excessive displacement upwards creates a structural notch and affects the load capacity of the joint [15,16]. Wide analysis of defects which can occurred during joining alclad high strength aluminum alloys sheets with RFSSW technology and influence of process parameters on joint properties can be found in [17].

The process parameters related to the tool – rotational speed, linear movement speed and geometry of the working surfaces as well as the properties of the joined materials have a direct impact on the flow of joined materials, i.e. plasticization and proper stirring in the joint area. Only their appropriate combination allows for the proper joining of metal sheets by friction stir welding technology. An additional challenge is the process in which alclad sheets are joined, due to fact that in this case additional material into the joining area is introducing, i.e. the coating material. As the results of research on the Friction Stir Welding (FSW) technology show, in order to intensify the stirring of materials, various geometric solutions of tools are used, which are characteristic for a given type of metallic material. The possibilities of changing the geometry of the working surfaces of the tool in the case of RFSSW are very limited due to the process kinematics and the design of the tool itself [18]. In the literature can be found information on the modification of tool geometry based on numerical simulations and mechanical tests. The main assumption of the applied tool modifications is to force more intensive stirring and transport of the material during the process. The results of the work show that the modifications introduced affect the joining process. A significant benefit is obtaining a high-quality connection in a much wider range of parameters than in the case of the standard tool [7,18].

The realized pilot studies showed, that the presence of the alclad has a significant impact on the load capacity of the joint. The key issue is to appropriate its stirring within the RFSSW weld, so as to ensure the least possible negative impact on the load capacity of the joint [15]. This article presents the effects of research on the influence of modification of the front surface of the inner sleeve of the RFSSW tool on the stirring process of the materials to be joined in the weld area and the impact of modifications on weld defects. When developing the geometry, the literature on the use of various geometries for FSW tools, the technological possibilities of making the developed variants and the possible impact on the process were taken into account.

## 2. Experimental work

The basic material used for the tests was a sheet of aluminum alloy 2024-T3 (according to AMS-QQ-A-250/5) with a thickness of 1.27 mm, alclad on both sides. According to the standard, the thickness of the alclad is about 4% of the material thickness per side. Additionally, the sheets were subjected to an anodizing process in sulfuric acid in order to obtain an oxide layer 5-8 µm thick. The layer arrangement on the contact of the sheets to be joined before the process is shown on Fig. 1, together with the alclad and anode layers marked.

The joining process was performed on sheets of 356×120 mm (Fig. 2a), which were joined in the rolling direction with an overlap of 30 mm. On one set, 10 welds were made from which individual joints for strength and microscopic tests were cut (Fig. 2c and d). The joints were made using the Harms & Wende RPS 100 welding machine and a dedicated jig (Fig. 2b) allowing to obtain full repeatability of the position of the welds along the longer edge of the sheet.

Tensile strength tests of the joints were carried out on the MTS Landmark machine, the breaking force [kN] was recorded

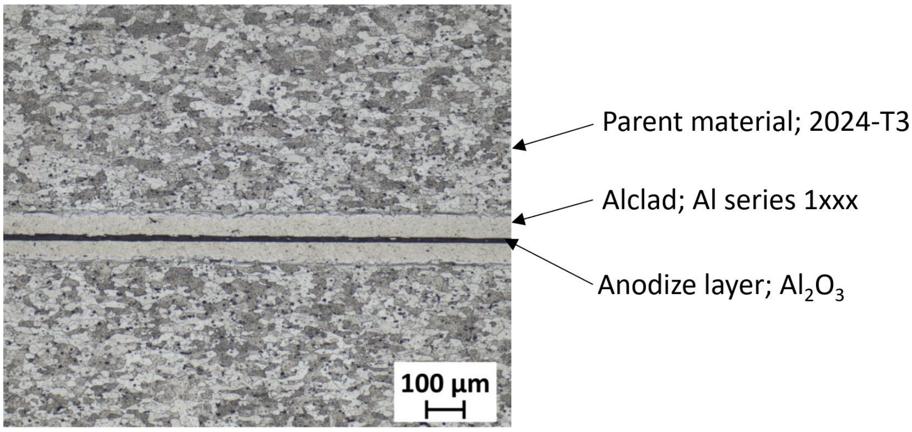

Fig. 1. View of the layer arrangement on the contact surface of the upper and lower sheets before the process

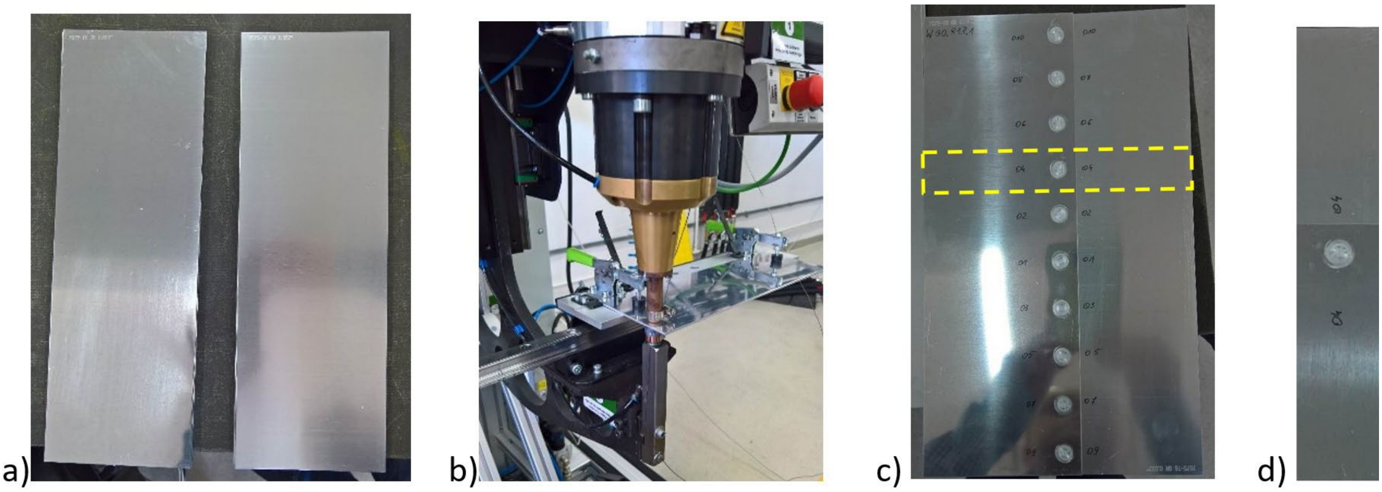

Fig. 2. Fabrication process of the samples for tests: a) sheets with dimensions of 356×120, b) joining process, c) sample with 10 joints, d) a single joint (210×30 mm)

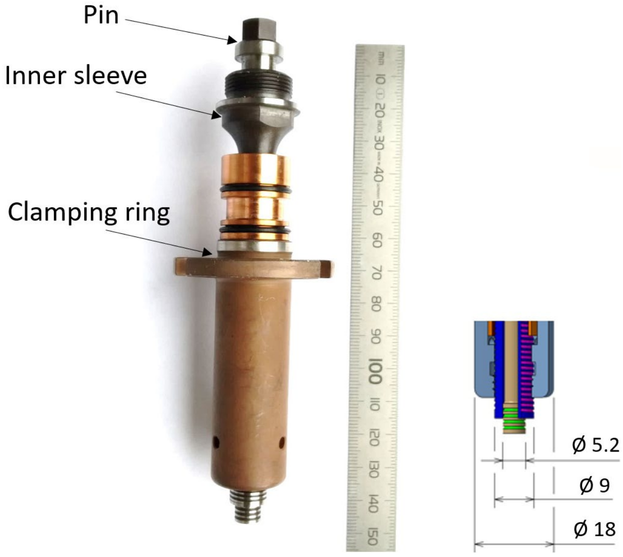

Fig. 3. WZ-12 tool dimensions

for each tested sample. The broken samples were visually inspected in order to determine the nature of the breakage of the joints. Samples intended for metallographic tests were grinded, polished and etched at ambient temperature in Keller's reagent (5 ml HF, 15 ml HCl, 25 ml HNO3, 955 ml H2O). The prepared transverse specimens cuts were subjected to microstructural observations on a digital optical microscope by Zeiss.

The joints were made with the use of a tool with the manufacturer's designation WZ-12, the outer diameter of the inner sleeve of which is 9 mm, and the pin diameter is 5.2 mm, Fig. 3.

The modification of the tools geometry, developed for the purpose of the research, consisted in making groves on the face surface of the inner sleeve with the use of milling technology. The cuts were designed as circular grooves. They were made using a spherical milling cutter with a diameter of Ø0.5 mm, in one pass, and their depth was 0.25 mm. Three geometries were developed as shown on Fig. 4.

Geometry No. 1 consists of a full groove by the outer surface of the sleeve and a single spiral passing tangentially from it, which tangentially go into the inner hole in two turns. Geometry No. 2 is consist of two spirals, of approximately 1.5 turns, not crossing the outer surfaces, rotated 180° relative to each other around the tool axis. The geometry No. 3 is 5 pcs. of the spiral, radially cut across the face of the sleeve, symmetrically arranged around the tool rotation axis.

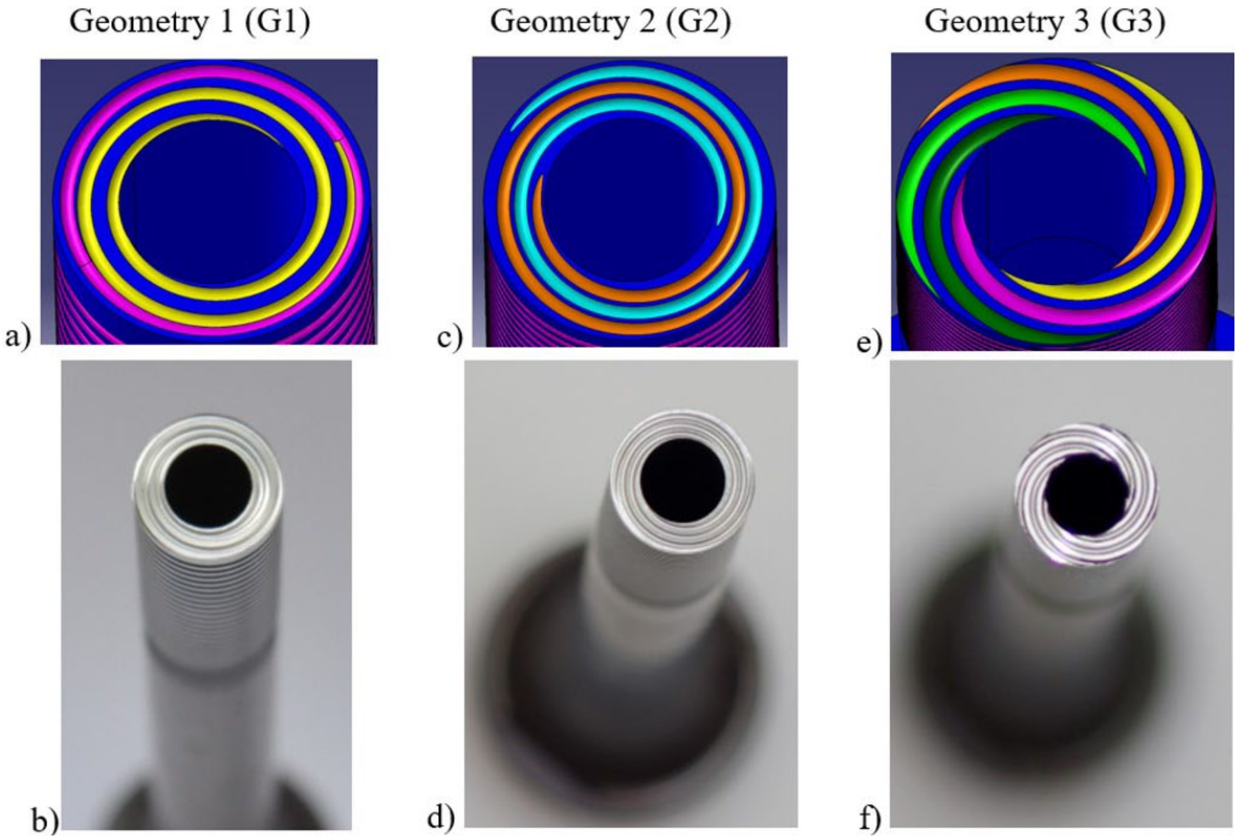

Fig. 4. Developed geometries: a) model view of geometry G1, b) photo of G1 rows made on the inner sleeve, c) model view of geometry G2, d) photo of G2 rows made on the inner sleeve, e) model view of geometry G3, f) photo of G3 rows made on the inner sleeve

The tests were carried out with the use of process parameters selected on the basis of the previous test results and they were as follows: tool rotational speed $S = 1500$ rpm, dwell depth $h = 1.3$ mm, welding time $t = 4$ s. Based on weld microstructure analysis, this parameters allowed to obtain high quality joints, without significant structural defects in form of voids or lack of connection. At the same time they gave the highest load capacity in case of joining alclad sheets with unmodified tool.

### 3. Analysis of test results

The realized research on the influence of modification of the face geometry of the RFSSW tool sleeve on the properties of the joints (static strength, the face of the joint, way of joint failure) and the stirring and fragmentation of the alclad and defects occur (microstructure analysis) allowed to determine the main purpose of the work, i.e. the impact of the modifications applied on the phenomenon of plasticization and stirring of materials.

Visual inspection of the weld face allows for quick and easy verification of the correctness of the RFSSW process immediately after its performed. Incorrectly selected parameters or an incorrectly set tool cause losses of material, craters, the formation of flashes or excessive surface roughness. The visual inspection of the welds made with the tested tools did not show any significant differences compared to those made with the basic tool (G0), Fig. 5. The central part of the weld (surface under pin) in all cases looks the same. In the area of influence of the inner sleeve, slight differences between the individual geometries are noticeable, but they are of surfacing nature and

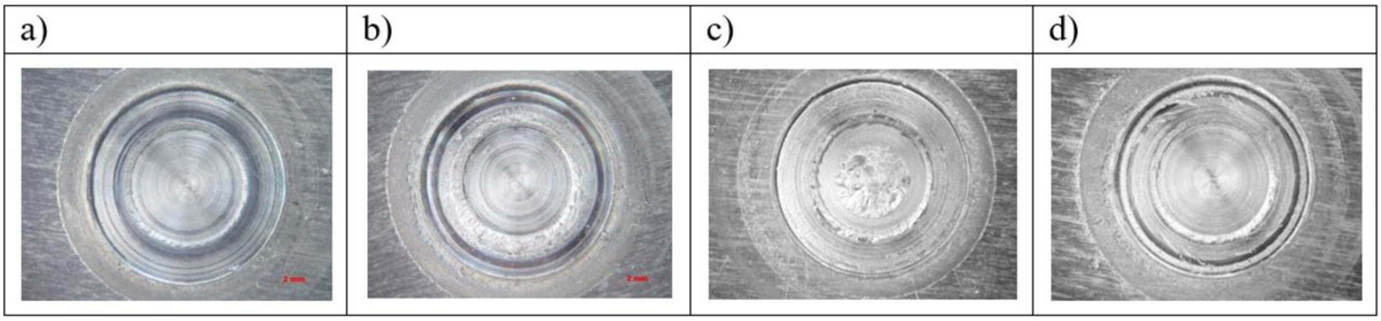

Fig. 5. The face of welds made a) with the basic tool G0 and tools with modified geometry b) G1, c) G2, d) G3

there is no significant influence of individual geometries on this feature of welds.

The significant influence of individual geometry variants on tensile shear failure load of the joints made with individual tools can be seen by analyzing the results of strength tests (Fig. 6). The presented values are the average result obtained from the examination of 7 samples.

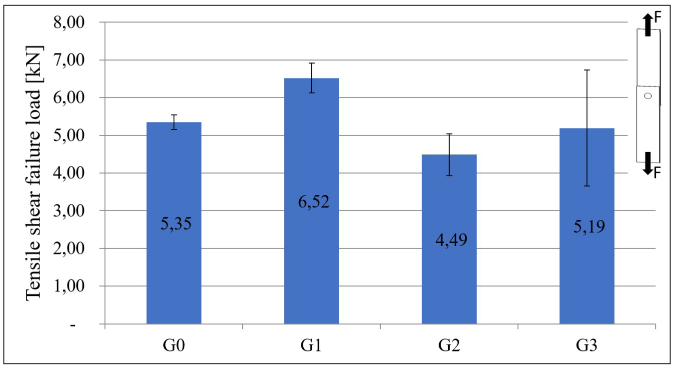

Fig. 6. The average tensile shear failure load of joints made with the basic tool G0 and with modified tools G1-G3

The reference value of the tensile shear failure load capacity of the joints was taken for the welds made with the basic geometry G0, that was 5.35 kN. The joints made with the G3 geometry tool had a similar average tensile shear failure load. In the case of the G1 geometry, the result was about 20% higher, while using the G2 tool, the tensile shear failure load of the joints was about 15% lower.

The significant impact of the studied modifications of tool geometry on the joint formation process can be seen by analyzing their microstructures, which are shown in Figs 7-10.

In the case of the G0 geometry (Fig. 7), the alclad layer is concentrated on the contact of the sheets across the entire width of the weld. The strips on the circumference are relatively thick, and in the central part of the weld its cluster is visible, both at the bottom and at the face. In the volume of the alclad material, a highly fragmented anode layer is noticeable. The material stirring of the upper and lower sheets is relatively small. The weld has no significant defects, only a slight void in the corner is visible. A good connection of materials is noticeable on the sleeve's moving path.

The microstructure of the weld made with a tool with G1 geometry is shown on Fig. 8. In this case, the alclad layer at the interface of the sheets in the central part of the weld is continuous and has a practically constant thickness. On the weld circumference the alclad material is stirred with the joined sheets material. Its scattered strips stretched upwards and swirls in the corners are visible. In a significant part of the weld, the stirring of the material of the upper and lower sheets can be noticed. The weld has no significant defects, only a slight void in the corner can be seen. There is a good material connection on the sleeve's moving path.

Analysis of the microstructure of the weld made with the G2 geometry tool (Fig. 9), similarities to that made with the G0 tool (Fig. 7) can be noticed. A continuous layer of cladding is visible along the entire width of the weld, at the sheets contact surface. The pull-outs of the alclad material at the corners are small and have the character of narrow strips. In the central part of the weld, a layered arrangement of alclad and sheet materials is visible. The stirring with the material of the bottom sheet is relatively shallow, but it occurs practically in the entire zone under the influence of the sleeve. Some voids in the corners and discontinuities in the path of the sleeve moving path can be seen in the weld.

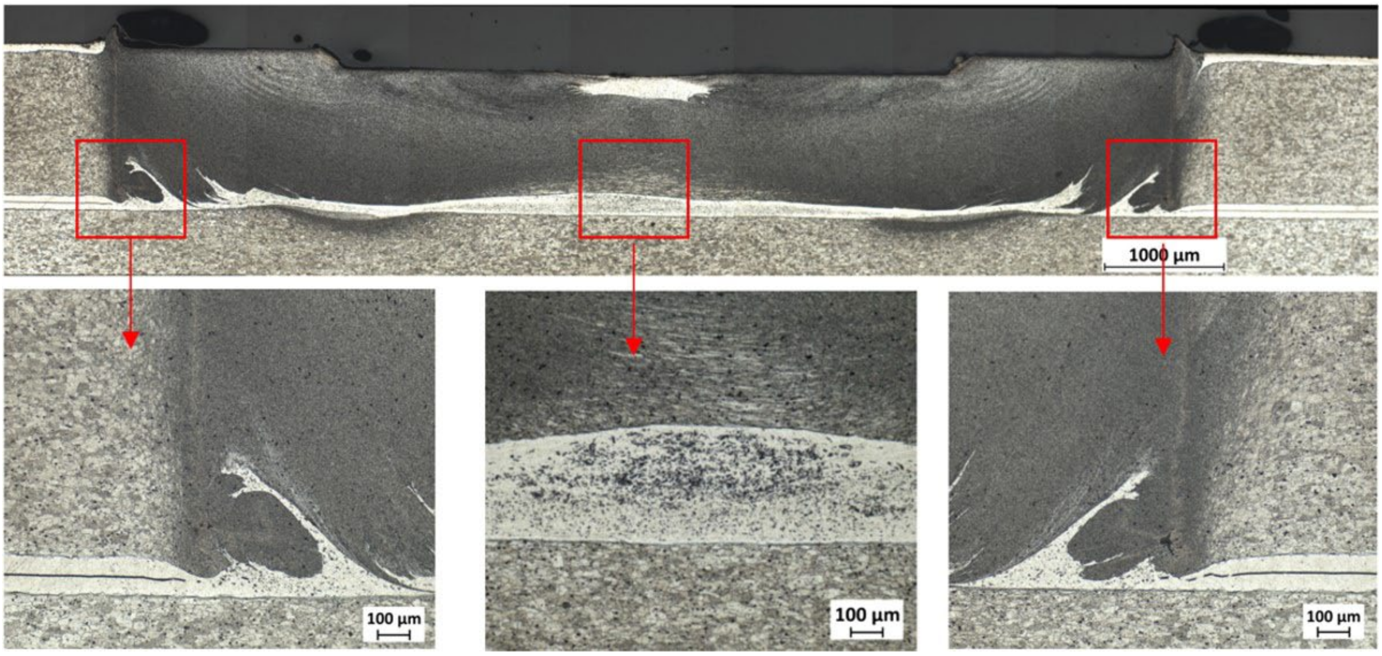

Fig. 7. Microstructure of the weld made with G0 tool

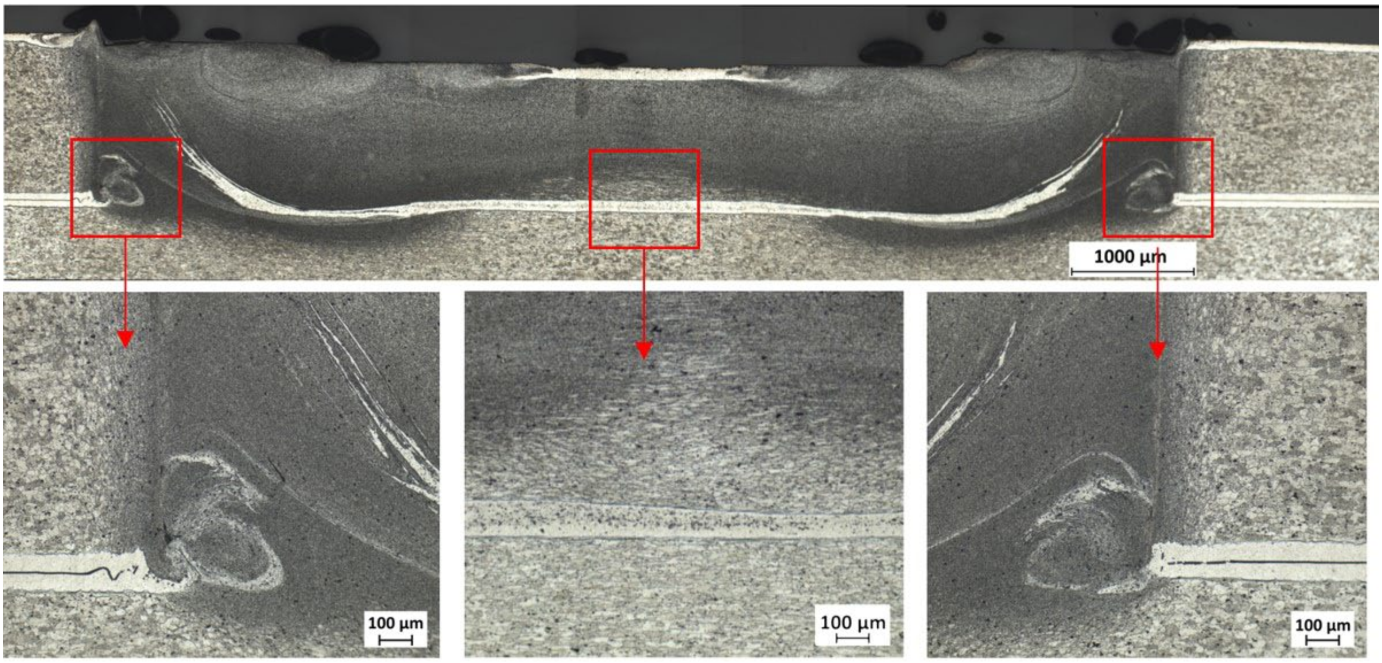

Fig. 8. Microstructure of the weld made with G1 tool

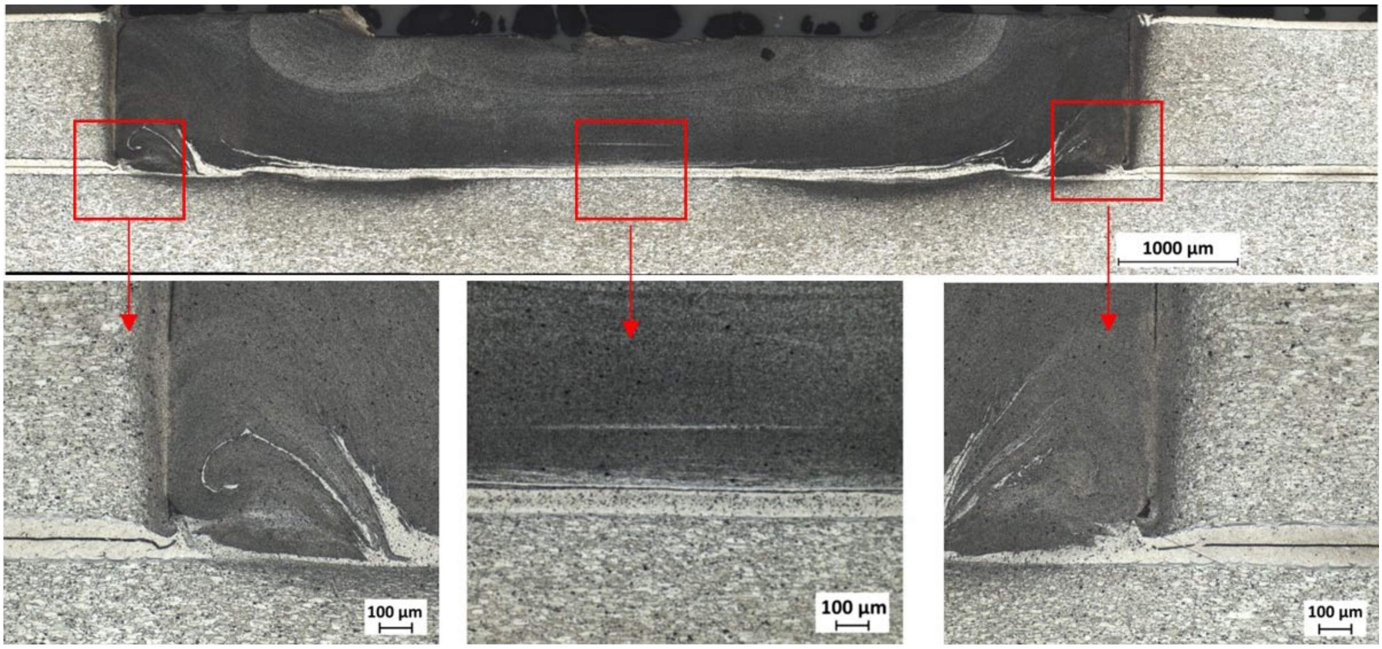

Fig. 9. Microstructure of the weld made with G2 tool

In the case of the microstructure of the weld obtained with the use of a tool with the G3 geometry (Fig. 10), the nature of the alclad arrangement is similar to that observed for the G1 tool (Fig. 8). In the central part of the weld, at the sheets contact surface, the alclad layer has an uniform thickness. In the area of operation of the sleeve, there are visible extensions of the alclad materials upwards strips, although in this case much shorter, but at the same time thicker. Swirled strips of alclad material are also visible in the corners. On the face of the weld, in its central part, a cluster of alclad is visible. The stirring with the material of the bottom sheet is relatively deep. In the case of a weld made with the G3 tool, a much wider zone of thermomechanical plasticization along the sleeve's moving path is noticeable, and at the same time discontinuities can be noticed there.

As a part of the research, the influence of the tested tool geometries on the nature of the failure of welds in the uniaxial tensile test was also analyzed. Due to the equal tensile strength of the upper and lower sheet metal (due to their equal thickness) two basic types of failure mechanism were observed – by shearing the weld and tearing the weld out of the upper sheet, Fig. 11.

All welds made with tools with G0 and G2 geometry were failure by shearing the weld. In the case of joints made with the

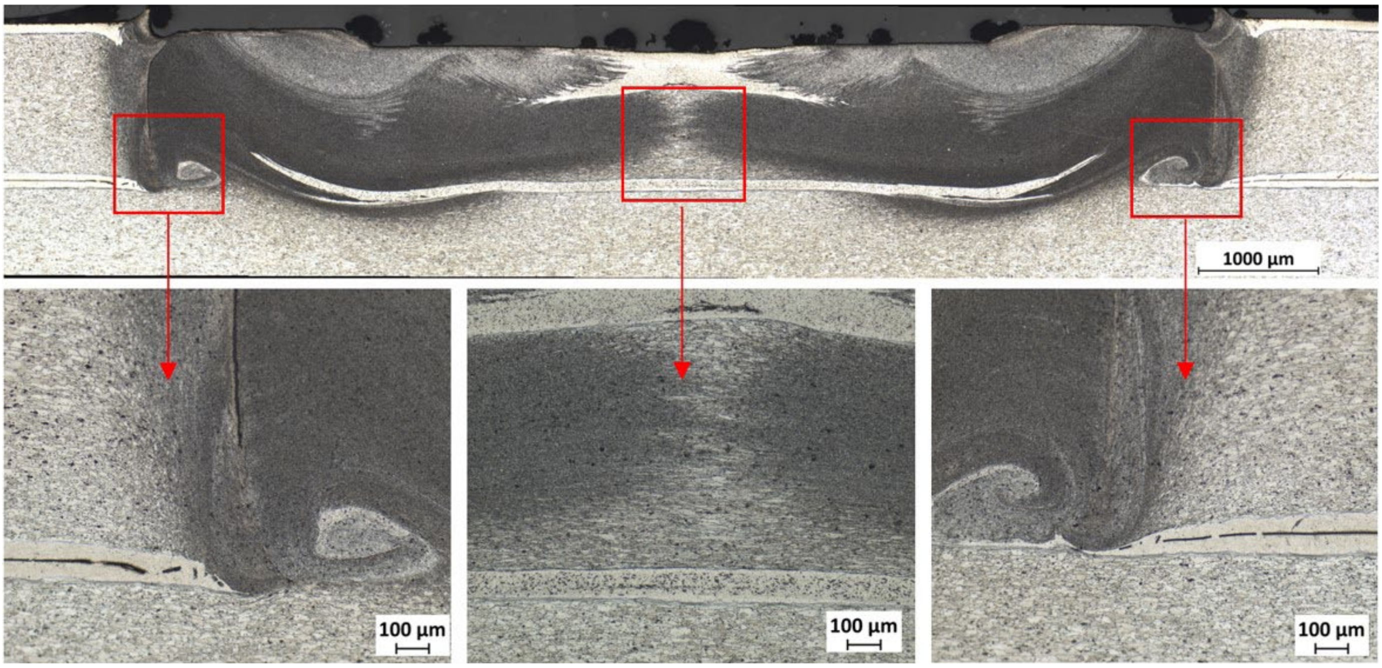

Fig. 10. Microstructure of the weld made with G3 tool

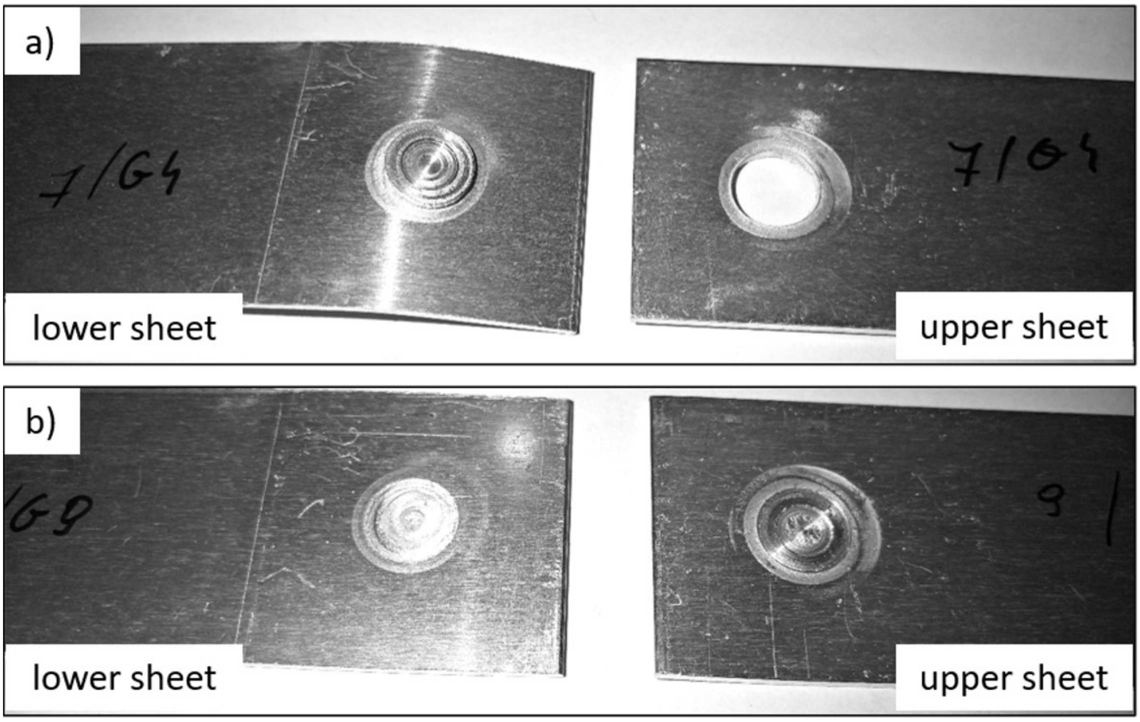

Fig. 11. Basic types of failure of RFSSW welds in the uniaxial testing of samples, a) tearing the weld from the upper sheet, b) shear the weld

G1 tool, all welds were tearing out from the top sheet. 4 welds made with the G3 tool were failure by shearing, and 3 by tearing out the weld from the upper sheet metal.

The nature of the failure of individual welds can be combined with the observed features and defects in the welds. In the case of the G0 geometry, the failure of the weld took place along the alclad layer at the joint surface of the sheets, Fig. 7. At the same time, the absence of defects in the sleeve's moving path, prevented the welds from tearing out from the upper sheet. The welds made with the G1 tool have a much better stirring of materials at the contact surface of the sheets and at the same time, no continuous alclad layer, Fig. 8. In this case, despite the lack of defects in the sleeve's moving path, this weld area was the weakest. For the welds made with the G2 tool, poor stirring of the materials at the interface of the sheets and the characteristic layered arrangement of the cladding material in the central zone of the weld, Fig. 9, were the propagation path of the failure. Despite defects in the sleeve's operating path, the welds were not torn out of from the top sheet. For the G3 tool, the failure of some of the welds by tearing out from the upper sheet may be related to defects in the sleeve's operating path, Fig. 10. At the same time, despite the stirring of materials at the contact surface of the sheets and the lack of a continuous layer of alclad, some of the welds were sheared off. This may be related to the greater than in the case of other geometries, the zone of thermomechanical plasticization in the corners of the weld, and visible swirls of the materials in this area, which act as crack initiator.

## 4. Conclusions

Based on the analysis of the obtained results, it can be concluded that the change in the geometry of the front face of the inner sleeve of the RFSSW tool affects the properties of the weld. The obtained results shown that the use of a properly selected geometry allows to obtain higher mechanical strength of the joint in relation to joint made with the basic tool. For the tested material configuration and the tools used, the load capacity of the connection increased by over 20% (1.17 kN).

The analysis of the microstructure of the welds shown that the modification of tools geometry resulted in better stirring of the alclad material and more intensive stirring of the joined materials. At the same time, no deterioration in the quality of the weld face and no effect on the formation of defects in the form of voids was observed. Among the tested geometries, the configuration with a continuous groove by the outer surface of the sleeve and with a spiral (G1 geometry) turned out to be the most advantageous.

There was no observed clear relationship between the load capacity of the connection and the type of joint failure. In order to define the most advantageous geometry for the application of the RFSSW technology for the joining of anodized and alclad sheets made of aluminum alloy 2024, it is necessary to conduct further research, also taking into account the optimization of the process parameters.

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