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EFFECT OF TOOL PIN LENGTH ON MICROSTRUCTURE AND MECHANICAL STRENGTH OF THE FSW JOINTS OF AL 7075 METAL SHEETS

The Friction stir welding (FSW) is a complex process, depending on many factors: machine, clamping device, material and tools. Parameters that have a direct impact on the quality of the joint include the rotational speed, welding speed, clamping force, geometry and tool plunging depth. The paper presents the results of experimental studies concerning the effect of tool pin length on the microstructure and mechanical strength of joints of thin sheets made of Al 7075 alloy. A tool with an adjustable pin with concave shoulder was used to weld the joints. Different pin lengths were used, which were selected with respect to the thickness of the welded joint. The specimens were subjected to visual evaluation, metallographic tests and mechanical strength testing. The results indicate that the pin length has a decisive effect on the microstructural changes in the joint and thus influencing the strength of the FSW joints.

Keywords: *FSW lap joints, aluminium alloys, transportation industry*

1. Introduction

The Friction stir welding (FSW) is a relatively new technology for materials joining. Constantly developing, technology is becoming more and more widely used in many sectors of industry, e.g. in the automotive industry, railway, shipbuilding, aviation and space industry [1-2]. At present, Polskie Zaklady Lotnicze / A Sikorsky Company in Mielec, as part of the INNOLOT sector programme, perform the R&D work to develop and adapt the FSW technology to joining the structures of currently built aircrafts.

Compared to conventional joining technologies, the FSW has a number of unquestionable advantages, such as no need for transforming the material into the liquid state because the welded parts are joined together in a solid state [3-4]. This prevents from shrinkage, hot cracking, pores, inclusions and other defects typical of welding or resistance welding. Therefore, the method allows for joining, among others, components made of metal alloys, considered to be weldable or hardly weldable, i.e. Al alloys of 2xxx and 7xxx series. Furthermore, this method does not require the use of connectors, does not emit noise, does not generate welding dusts and gases and is considered to be energy efficient [5-10]. Friction welded joints are characterized by very good metallurgical quality, mechanical strength and repeatability, but only if the process is automated and fully controlled. It should be emphasized that despite a relatively small number of parameters of the FSW process (rotational speed, welding line speed, forces in the x and z axes, angle of inclination of the tool, shoulder plunging depth, depth of pin plunging into the lower sheet metal in overlapping joints), the choice of the best combination is representing a challenge. For comparison, in the case of the MIG, TIG and plasma welding, good joint quality depends on cca. 13, 15 and 24 parameters, respectively [11-13].

The above mentioned parameters and the FSW tool, or rather the geometry of its basic elements (pin and shoulder), have a direct effect on the flow of deformed metal within the weld [1, 14-17].

In the FSW overlapping joints, the material of the joined components is mixed as a result of the rotary motion of the tool. The main difficulty in obtaining joints with high mechanical strength is mainly the formation of hooking on the advancing side and cold lap on the retreating side. These are defects associated with contact line deformation, which very often constitute the initial points for breaking the joint. They also cause thinning of the sheet metal, which also adversely affects the joint strength. These defects result from the upward flow of the material, caused by too high a temperature and excessive plasticization of the material [18-20]. The authors of the studies [19-20] agree that the rising movement of the material in the weld can be limited by using a lower rotational speed of the tool or higher feed rate. Depending on the set process parameters, contact line deformation on the advancing side can be directed upwards or downwards, whereas on the retreating side, the contact line deviates upwards. Furthermore, a characteristic feature of hooking is a rapid change in shape, while the contact line on the retreating side usually has a milder course [19-20]. The defects are determined by the work of the tool, which, with each rotation, "cuts off" new portions of material on the advancing side and pushes them to the retreating side. A parameter that has an equally important effect on material mixing in the weld and the level of its characteristic features (e.g. hooking and cold lap) is the length of the tool pin, which directly impacts the depth of the material mixing in the joint. Few publications have described the effect of this factor on the properties and microstructure of welds, e.g. [17, 20-22]. As

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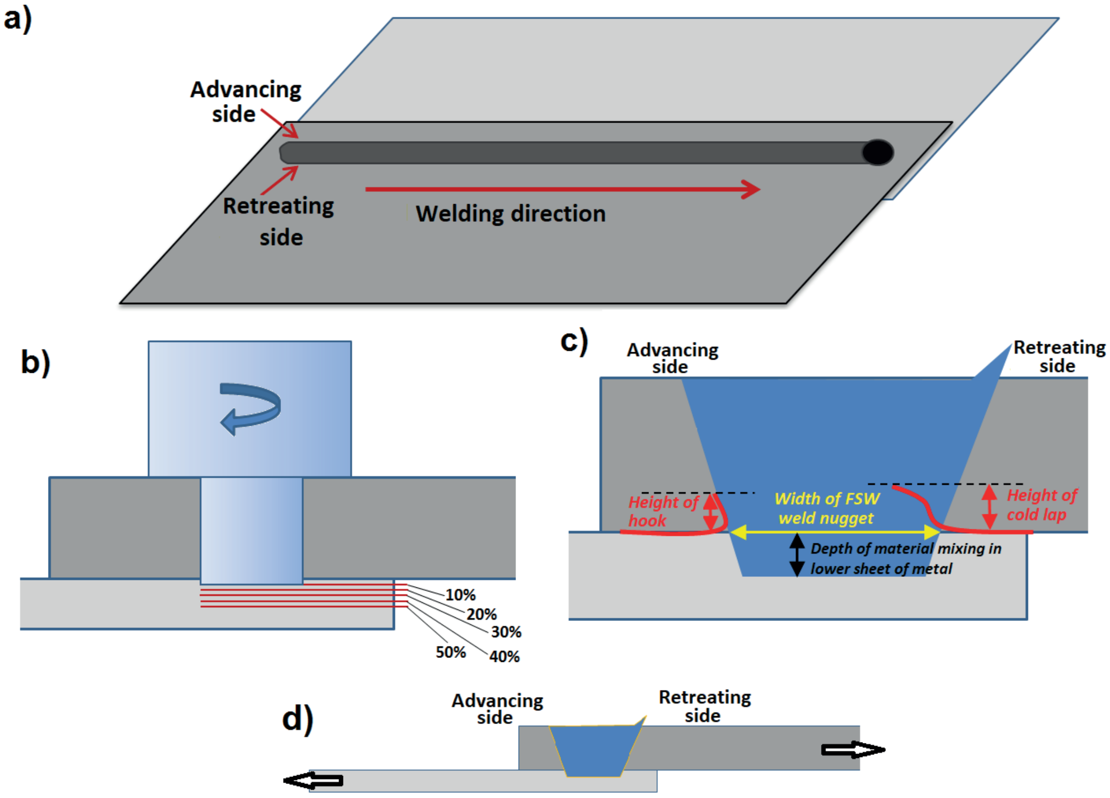


Figure 1 *FSW lap joint: a) general view, b) applied tool plunging in lower sheet, c) methodology of measurement of characteristic features of the FSW lap joint, d) lap orientation in the FSW joint and tensile force direction during strength tests*

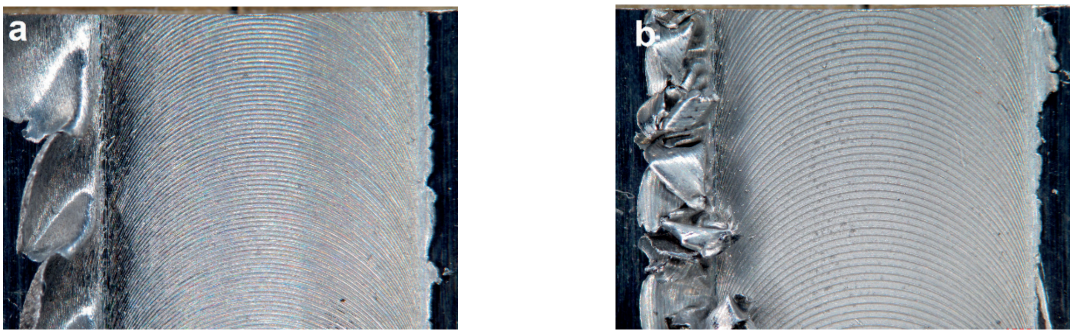
emphasized by the authors, the pin length should be chosen while taking into account the specific rotational speed and feed rate of the tool. The pin length, which, for one set of rotational speed and feed rate, is sufficient to connect the welded component, may prove to be too small for another set. Furthermore, this parameter has a direct effect on the contact line deformation: when the mixing depth is small, i.e. when the pin length corresponds approximately to the thickness of the upper sheet metal of the overlapping joint, the upward flow of material is small. Therefore, the contact line deformation is also limited, but it is likely that the mixing of material at the contact point of the connected elements will be negligible. By increasing the pin length, the height of the hook and cold lap is also increased, leading to increased thinning of the upper sheet metal and weakening of the entire joint [17, 20]. Furthermore, the studies [21-22] proved that the strength of the joint is higher for the longer pin lengths, even exceeding 40 % of the thickness of the lower sheet metal.

In conclusion, the problem of the effect of the pin length on the microstructure and strength of overlapping joints made of Al alloys remains insufficiently described in the literature. It should be stressed that this topic is complex and the discrepancies in the effect of the pin length on the strength of welds result from the fact that the tests have been performed using different tool geometries, different thickness and grades of materials. Therefore, the authors of this paper conducted an experiment, whose aim was to clarify how a change in a pin length affects the formation of the FSW weld when joining the thin-walled components (up to 1.6 mm) used in aircraft structures.

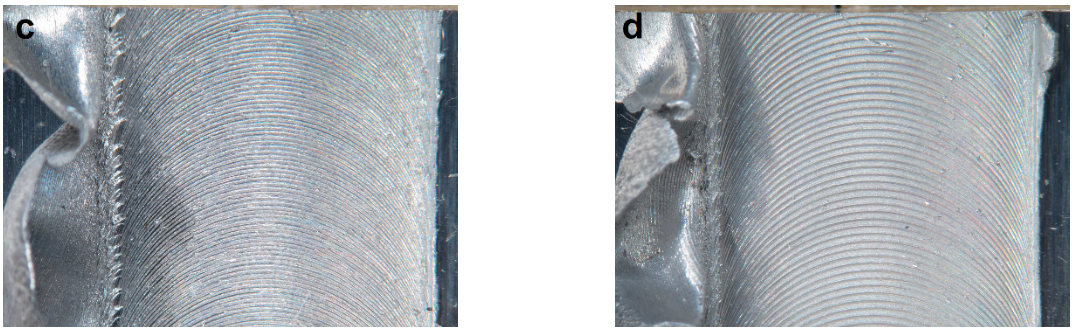
2. Material and research methodology

Sheets of Al 7075 T6 alloy (chemical composition according to AMS-QQ-A-250_13), coated on both sides with a plating layer with thickness corresponding to 4 % of the workpiece thickness were used in the study.

Sheets of 356 mm x 10 mm, with thickness of 1.6 mm (upper sheet) and 0.8 mm (lower sheet), were welded. The sheets were joined in the overlapping rolling direction, with the overlap of 30 mm. The welded sheet metal was fixed with a special device to prevent it from moving during the welding process. The FSW lap joint is shown in Figure 1a. The FSW process was performed by means of a CNC machine using a concave shoulder and a threaded cylindrical pin. This pin geometry provides a more efficient mixing of the plasticized weld material. Welding was performed for two different sets of rotational speed and feed rate: a) ω = 700 rpm / v = 100 mm min^{-1} and b) ω = 1300 rpm / v = 300 mm min^{-1}. Further part of the study used the following denotation of the specimen sets: 700/100 and 1300/300. Five different pin lengths were used for each set of rotational speed and feed rates, corresponding to the sum of the upper sheet metal thickness and the percentage of the lower sheet metal thickness fraction: 10, 20, 30, 40, 50 % (corresponding to 1.68; 1.76; 1.84; 1.92; 2.0 mm) (Figure 1b). This approach allowed not only for verification of the effect of the pin length on weld properties (and therefore material mixing depth), but also made it possible to determine whether the effects were similar at different linear and rotational speeds.



Plunging depth in the lower sheet metal: 10%



Plunging depth in the lower sheet metal: 50%

Figure 2 *Weld face view of the FSW joints prepared using tool pin plunge depth of 10% and 50% and process parameters: a, b) ω = 700 rpm; v = 100 mm min^{-1}, c, d) ω = 1300 rpm; v = 300 mm min^{-1}*

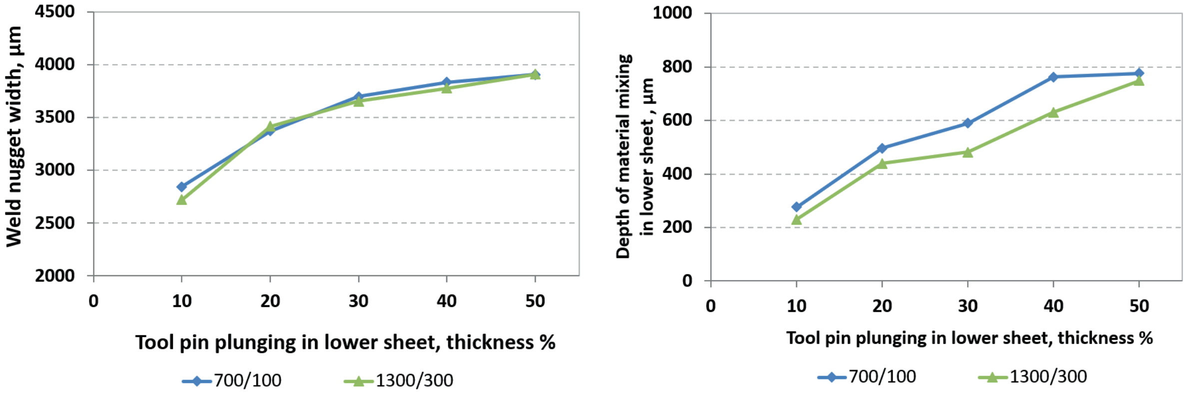


Figure 3 *Effect of the FSW process parameters on: a) weld nugget width, b) material mixing depth in the lower sheet*

The joints were assessed visually: the face of the welds was evaluated for defects, mainly discontinuities. Four specimens for the static strength testing and three specimens for microscopic tests were cut out from each joint.

Specimens for metallographic testing were ground, polished and etched at ambient temperature in Keller's reagent (5 ml HF, 15 ml HCl, 25 ml HNO_3, 955 ml H_2O). The prepared microsections were subjected to microstructural observations by means of the Zeiss digital optical microscope. On the recorded images, the width of the weld nugget and mixing depth were measured and the heights of the so-called hook and cold lap were determined. The measurement diagram is shown in Figure 1c.

The tensile strength tests were performed by means of a Landmark MTS machine equipped by the force and displacement sensors. Arrows in Figure 1d show the direction of specimen extending in relation to the position of the advancing and retracting sides. A breaking strength [kN] was recorded for each specimen. The broken specimens were visually assessed in order to determine the joint breaking point.

3. Results and discussion

The joints were visually inspected. All the welds were characterized by an acceptable face and no discontinuities were found. Figures 2a÷d illustrate the examples of welding faces made at different parameters. Different density of characteristic rings on the faces of welds can be observed depending on the applied rotational speed and feed rate. In the case of welded specimens with the depth of pin plunging into lower sheet of 50%, the upset metal was greater than in the case of specimens with a 10% pin plunge depth, even though the same shoulder plunging depth was ensured. This is due to the fact that with a larger pin plunge, a larger volume of the plasticised weld material is mixed and

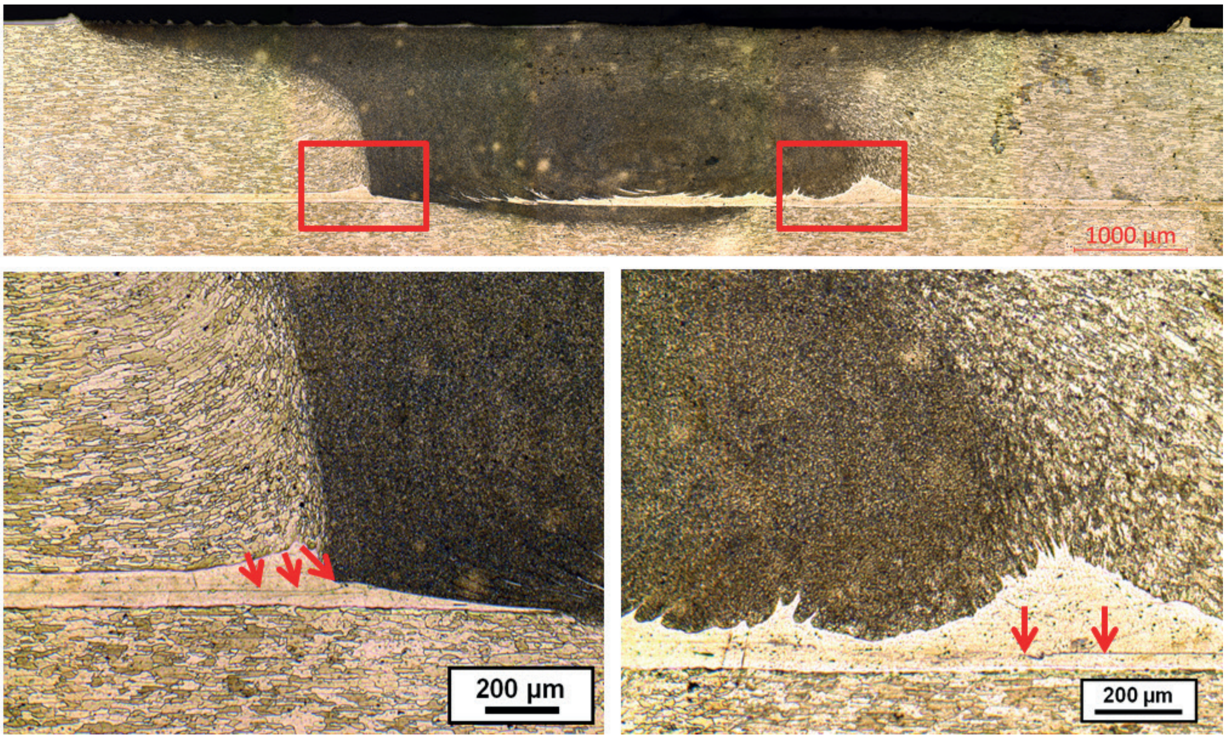


Figure 4 *Microstructure of the joint welded according to the parameters: ω = 1300 rpm; v = 300 mm min^{-1}; tool plunging in the lower sheet of 10 %: a) total view of the weld cross section, b) contact line at advancing side, c) contact line on retreating side*

transported to the surface of the upper sheet metal. The material is then pressed through the shoulder into the weld area. However, a certain volume remains on the weld surface on the retreating side.

Figure 3 shows the results of measurements of the weld nugget width and mixing depth of the lower sheet metal depending on the welding parameters. For the linear and rotational speed range used, the measured values for the individual tool plunging depths are comparable. However, the larger the pin plunging depth, the larger the mixing zone. Therefore, it can be expected that the amount of heat supplied to the joint is also higher, thus increasing the risk of joint deformation.

With the literature data, e.g. [15, 20], increasing the pin plunging depth intensifies the vertical movement of the weld material and the formation of the hook and cold lap. Those observations are also confirmed by the analysed joints. Figures 4÷6 show the microstructure of selected joints welded at a rotational speed of ω = 1300 rpm and a linear velocity of v = 300 mm min^{-1} and a pin length of 10 %, 30 % and 50 %. Figure 7 shows the relationship between the height of the hook and cold lap and the tool pin plunging depth. With a pin plunging depth of 10 % of the lower sheet thickness, the hook and cold lap are not observed. The contact line retains a straight line character throughout the joint until it is interrupted at the boundary of the weld nugget and the heat-affected zone on both sides of the weld (Figure 4). When using a pin plunging depth equal to 20 % of the lower sheet thickness, the hook still does not occur, while on the retreating side, the contact line is deformed upwards, reaching a height of cca. 50 µm (Figure 7). With the plunging depth of 30 %, an increase in contact line deformation is already noticeable on both sides of the weld (Figure 5). The hook height reaches ~ 70÷180 µm, while the cold lap height exceeds 350 µm (Figure 7). With plunging depths of 40 % and 50 % (Figure 6), the cold lap height is similar to the case of plunging depth of 30 % (~ 250÷350 µm), but the hook is much higher (in most specimens its height exceeds 200 µm) (Figure 7). Microstructural observations also revealed that the increase in pin plunging depth also leads to changes in the character of the weld material mixing. This is particularly noticeable in the specimens analysed in the study because a threaded pin was used. Thus, increasing its depth of plunging into the joined set of metal sheets results in increase of the effect of thread coils on material mixing. Comparison of the microstructure of the tested joints (Figures 4÷6) reveals that for larger depths, the plating layer is broken down and is distributed in the weld nugget. Furthermore, the shape of the weld also changes: for the small pin plunging depths, the weld nugget retains its oval shape (Figure 4a), while for min. 30 %, the areas corresponding to the effect of individual thread edges can be clearly distinguished. Figure 6a illustrates the shape of these areas indicated by a dashed line. Special attention should be paid to the fact that both the hook and cold lap, "trapped" in the plating layer, actually occur in the area of the effect of the last coil (Figures 5, 6). The next coil, mixing the material in the area of the upper sheet metal, limited contact line deformation, thus preventing the upper sheet thinning. Perhaps the use of a smooth pin without thread for the same plunging depth values would lead to the formation of a much higher hook and cold lap.

Figure 8 shows the results of the static strength tests of the joint, while the images of selected broken specimens are presented in Figure 9a÷d. The high strength values (~ 7 kN) were recorded for all the analysed sets of rotational speed and feed rate at the depth of plunging into the lower sheet of 10 % of its thickness.

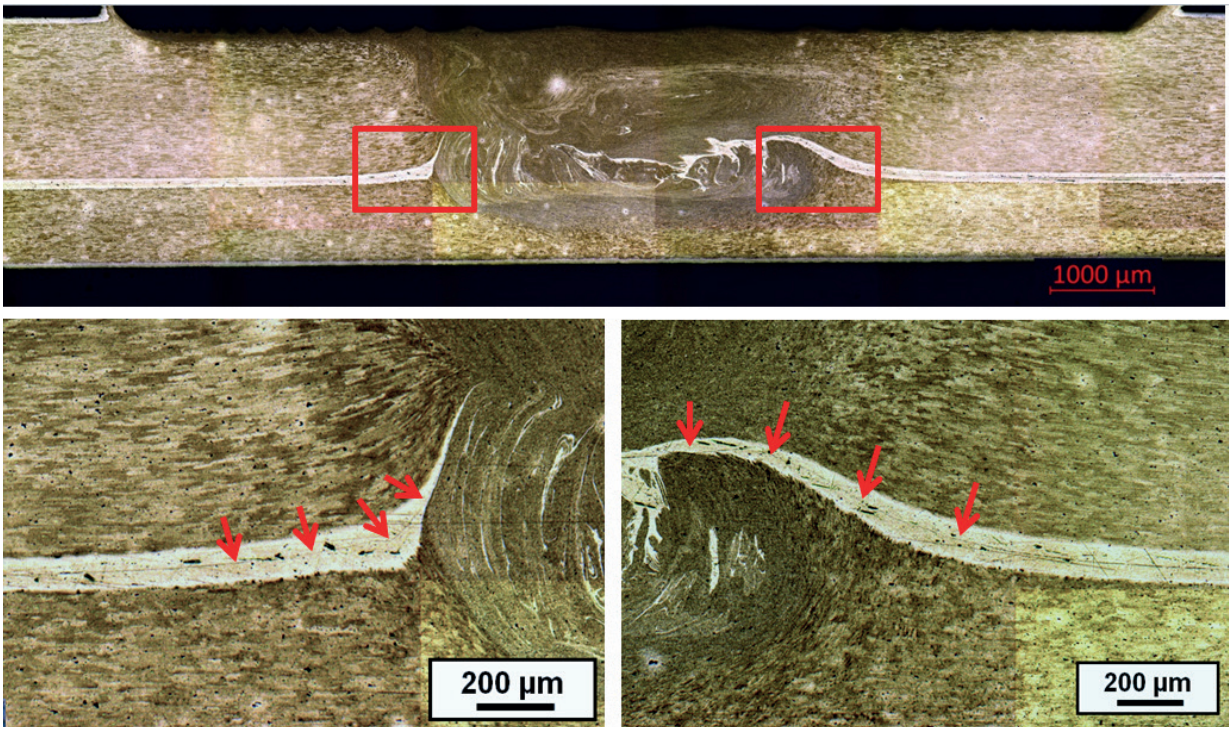


Figure 5 *Microstructure of the joint welded according to the parameters:* ω *= 1300 rpm;* v *= 300 mm* min^{-1}*; tool plunging in the lower sheet of 30%: a) total view of the weld cross section, b) contact line at advancing side, c) contact line at retreating side*

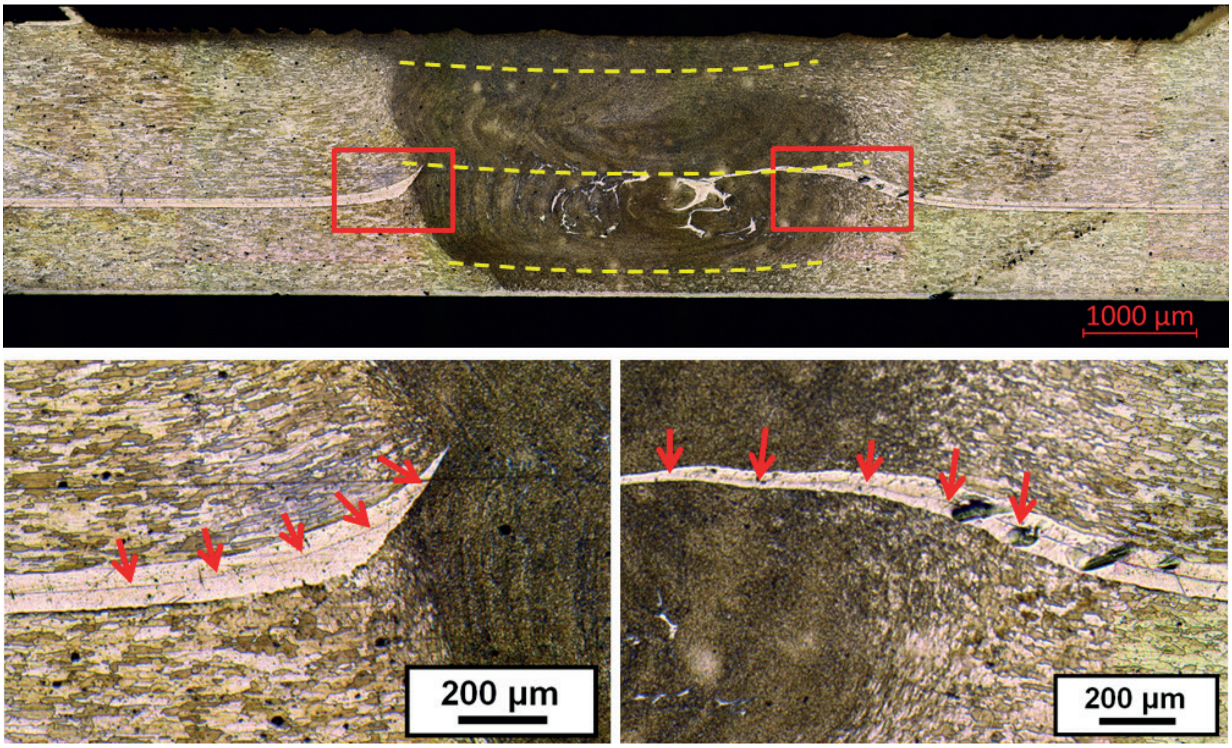


Figure 6 *Microstructure of the joint welded according to the parameters:* ω *= 1300 rpm;* v *= 300 mm* min^{-1}*; tool plunging in the lower sheet of 50%: a) total view of the weld cross section, b) contact line at advancing side, c) contact line at retreating side*

No contact line deformations were found in these joints, and the specimens were broken outside the weld in the lower sheet in the heat affected zone or by shear (sheet delamination) (Figure 7).

Welded specimens for the tool plunging depth of 20% were destroyed in the upper (thicker) sheet metal in the weld area on the retreating side, where the cold lap occurs. Although the cold lap height did not exceed 60 µm, this defect contributed significantly to the weakening of the joints, as it was characterized by a sharp tip pointing towards the surface of the upper sheet, similar to the case of the hook. During the tensile test, the cold lap apex was

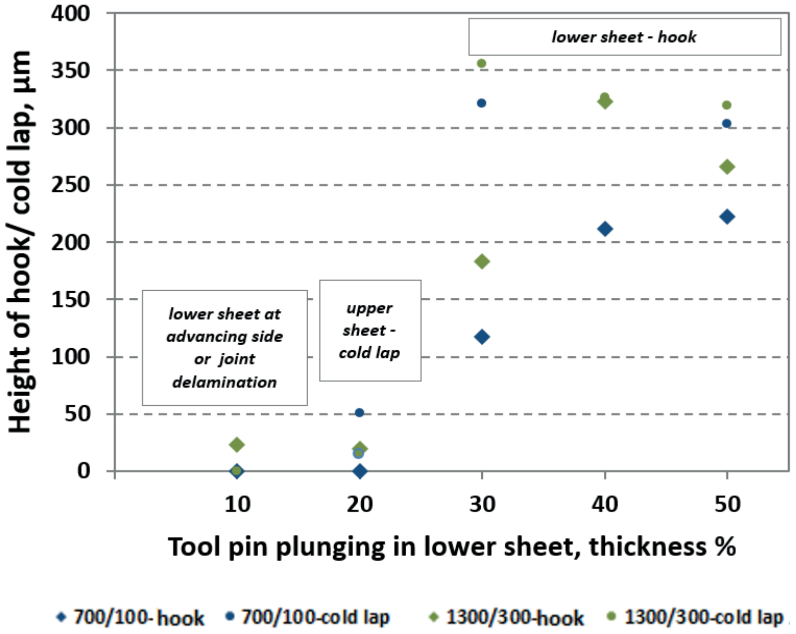


Figure 7 Effect of the tool pin plunging depth on defects size

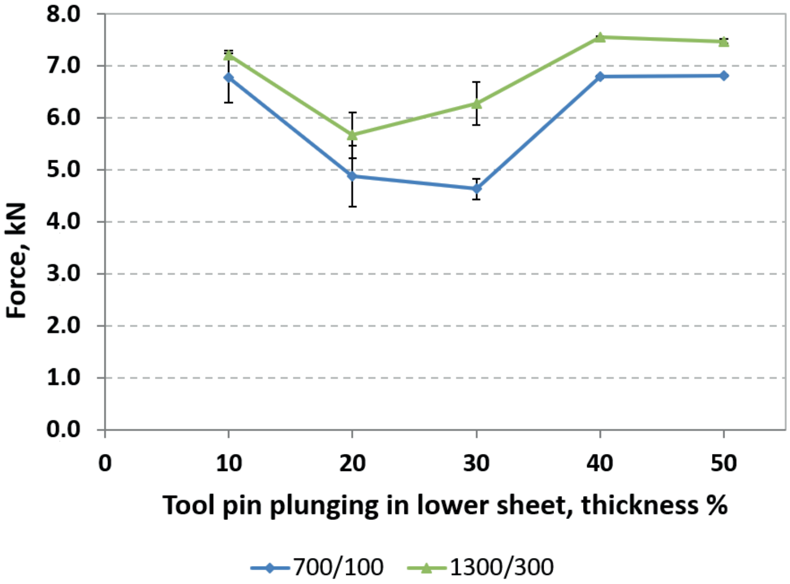


Figure 8 Effect of the FSW process parameters on mechanical strength of the joints

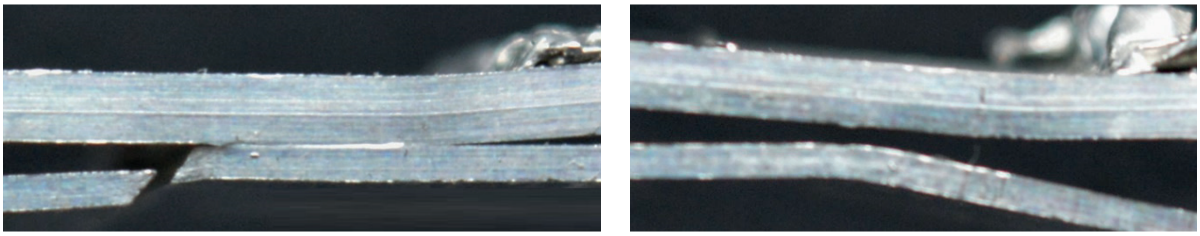
a particularly stress-sensitive site and initiated cracking of the upper sheet metal (Figure 9c).

Joints welded with a pin plunging depth of 30÷50 % were in the majority of cases broken in the thinner sheet metal in the location of the hook (Figure 9d). Breaking of the joint occurred along the line of contact between the sheet metal and the hook and then through the lower sheet metal, along the boundary between the weld nugget (recrystallization zone) and the thermomechanical deformation zone. In other words, the lower sheet metal was pulled from the weld.

Welded specimens with plunging depths of 40 % and 50 % and parameters ω = 700 rpm, v = 100 mm min^{-1} and ω = 1300 rpm, v = 300 mm min-1 were broken at ˜ 7 kN (Figure 8). Despite the significant height of the cold lap defect (Figure 7), these specimens were destroyed due to the presence of the hook on the advancing side. Comparison of the shapes of both defects reveals that the cold lap was characterized by a much smoother shape (Figure 6b), while the hook represented a sharp geometric notch (Figure 6a), sensitive to mechanical stresses and thus initiating breaking of the joint.

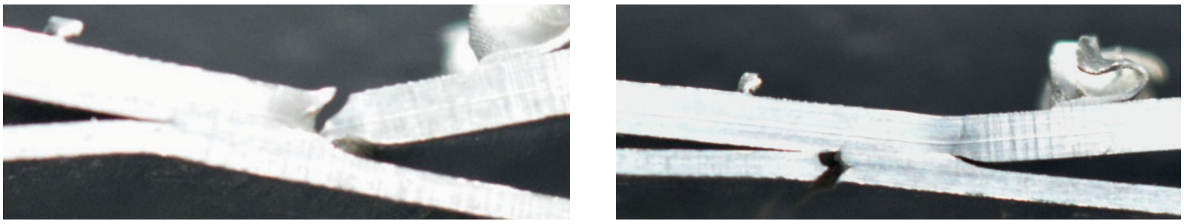
4. Conclusion

The results of examinations presented in this study lead to the following conclusions:



a) breaking of the lower sheet metal in the heat affected zone

b) delamination of the sheet metal



c) breaking of the joint on the retreating side of the upper sheet metal, initiated along the cold lap

d) breaking of the joint on the advancing side of the lower sheet metal, initiated along the hook

Figure 9 *The FSW lap joints breaking sites*

- Length of the pin, which is involved in mixing of the material of the overlap joint is a parameter determining the quality of the joint: the occurrence of geometric defects or their lack and the joint strength,
- Increased pin exposure intensifies the vertical movement of the weld material. This leads to increase in the contact line deformation (increasing the hook and cold lap, which is accompanied by increasingly high thinning),
- The results of the strength testing showed that for the tested set of sheets there are two ranges of pin plunging depths, ensuring high strength of the joint: 10%, and 40% and 50%. The recommended plunging depth of the tool is 10%, because regardless of the rotational speed and feed rate used, the strength of the joints reaches ~ 7 kN and the hook and cold lap do not occur. The specimens are broken in the lower sheet metal outside the weld or by shear. In the case of the plunging depths of 40% and 50%, breaking of the specimens occurred in most cases in the lower sheet metal as a result of the presence of a hook,
- In the case of a cold lap defect, it is recommended that it has a smooth shape (as in the case of joints welded with plunging depth of 40÷50 %). This defect does not represent a sharp geometric notch and the joints can carry high loads (~ 7 kN). If the contact line on the retreating side is clearly pointing upwards despite its low height, it causes the joint to break at low load values (as in the case of joints welded with pin plunging depth of 20 %).

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