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The Use of a Bobbin Tool in the Friction Stir Welding of Plates Made of Aluminium Alloy EN AW 6082 –T6

Abstract: The article presents test results concerning the friction stir welding of 6 mm thick plates made of aluminium EN AW – 6082. The welding process was performed using a tool consisting of two shoulders and a probe. The tests were concerned with the effect of welding parameters in the process of welding and the quality of joints. Related visual test results enabled the assessment of the effect of a bobbin tool on the formation of a weld, the presence of surface imperfections and the continuity of material in welds (based on metallographic tests). Mechanical properties of the joints were identified in static tensile tests and in hardness measurements. The effect of welding conditions on the welding process and weld formation was determined through measurements of temperature on the weld surface, performed using a thermographic camera, and measurements of force and torque affecting the tool, performed using a LowStir device. The test results revealed that the use of the bobbin tool enabled the obtainment of joints characterised by the compact structure of welds, material continuity, strength and repeatability comparable with those obtained using the conventional tool.

Keywords: FSW, Friction Stir Welding, bobbin tool, aluminium alloys

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Introduction

The friction stir welding (FSW) method performed using a conventional tool primarily enables the welding of structures made aluminium alloys. The use of a bobbin tool has extended the potential of the method making it applicable in industrial sectors where the use of the FSW method based on the conventional tool was difficult or impossible, e.g. because of the problematic shape of elements in the joining area such as long hollow sections used in the ship-building industry.

In the FSW method, the heating and plasticisation of a material is performed by special rotating tools having various shapes and dimensions. During the joining process the tool set into rotation penetrates material(s) in the joining area of elements to be welded. After heating and plasticising the material by friction heat, the tool moves along the line of interface. Before cooling, the material is concentrated through upsetting. A weld formed behind the moving tool is linear.

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Primary tasks of FSW tools include the generation of friction heat, the plasticisation of the material, the squeezing of the material in the welding area around the probe, the stirring of the material(s) of elements being joined, the destruction and dispersive application of an oxide coating around the probe as well as the consolidation and upsetting kneading of the stirred material in the weld nugget.

Usually, the FSW-based process involves the use of the so-called conventional tool, composed of one shoulder and one probe (Fig. 1a). Another type of a tool used in FSW processes is a bobbin tool consisting of two shoulders and one probe (Fig. 1b) [1-4]. The FSW process performed using the conventional tool and the bobbin tool is presented schematically in Figure 1.

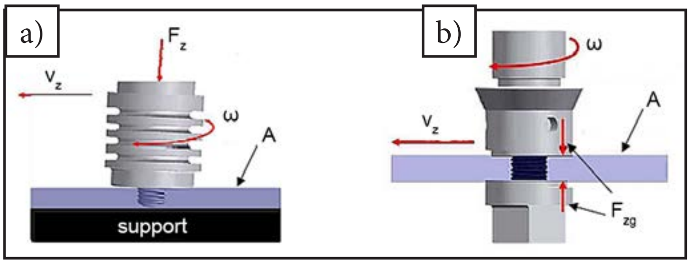

Fig. 1. FSW process performed using: a) conventional tool, b) bobbin tool. *A* – materials to be welded, v_z – welding rate, ω - tool rotation rate, F_z – tool (pressure) force, F_{zg} – strain force [1]

In comparison with the conventional tool, the advantages accompanying the use of the bobbin tool are the following [2 - 4]:

- lack of need for using the support of the joint on the root side and the elimination or significant limitation of welding pressure,
- elimination of the lack of joining ("no weld") of elements on the root side,
- possibility of welding long hollow sections,
- lower strains of elements subjected to welding,
- possibility of performing butt welding and overlap welding.

Research on the FSW process involving the use of the bobbin tool is performed at a number of research centres in the world. Research works include tests concerned with the welding of elements made of aluminium alloys having thicknesses restricted within the range of 1.8 mm to 38 mm [1-9]. Researchers admit that, because of the volume of a material, it is easier to perform the welding process involving elements having walls of thicknesses exceeding 6.0 mm [2, 5]. Below the above-named thickness it might be difficult to properly initiate the welding process, where the aforesaid initiation is manifested by the formation of a groove in the weld formation area, related to the "plugging" of the space between the shoulders and the materials of the plates being joined [2].

Factors decisive for successful welding include dimensions and shapes of the shoulders and those of the probe as well as parameters of the welding process such as the initial rotation rate of the tool and the welding rate accompanying application (plunging) of the tool [3].

However, the lack of a support on the root side does not exclude the necessity of using fixtures ensuring the rigid fixing of elements to be welded. The foregoing results from the fact that the use of the bobbin tool does not eliminate the generation of resistance accompanying the process of welding or forces acting transversely in relation to the welding direction, potentially leading to the formation of a gap between elements being joined [10].

Shapes and dimensions of the shoulder(s) and the probe may vary in both types of the tool, depending, e.g. on aluminium alloy grades being joined, thicknesses of plates being welded or types of joints to be obtained. The use of a cylindrical probe with the incused thread enables the obtainment of joints characterised by high mechanical properties. A conical probe with vertically incused planes enables the use of the lower shoulder having a smaller diameter, and, consequently, reducing the torque and force in the direction of welding [9]. Where elements to be joined are characterised by deviations in surface flatness, it is recommendable to use a conical shoulder with the spirally notched work surface [2].

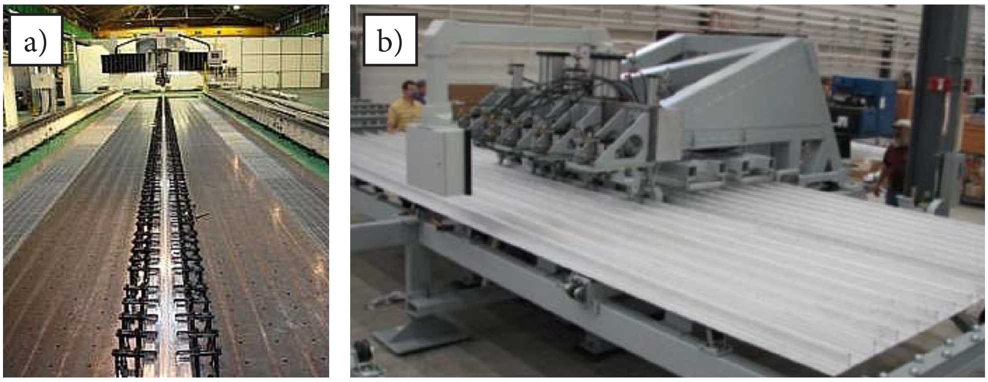

Fig. 2. Aluminium sections welded using the FSW method: a) length of 25 m and a wall thickness (in the joint area) of 2.5 mm, b) for the ship-building industry [2, 3]

The bobbin tool has two primary variants, i.e. the fixed gap bobbin tool, where the distance between the shoulders is constant and the so-called self-reacting bobbin tool [11], where the lower shoulder is mounted mechanically on the probe, whereas the upper shoulder can move along the probe (upwards and downwards) by changing the length of the probe. Because of this, the self-reacting bobbin tool is characterised by the possibility of automatically adjusting the distance between the shoulders, depending on the thickness of elements being joined. A desired result is achieved by controlling the force at which the shoulders are pressed against the surfaces of element being joined. The foregoing is a significant advantage, particularly when elements to be joined are characterised by locally varying thicknesses, e.g. either as a result of irregular surfaces or intentional changes in thicknesses.

The FSW method involving the use of the bobbin tool can be successfully used when welding hollow sections made of various aluminium alloy grades. The use of the above-named method and the tool enables the joining of small-sized pressed sections into products of significantly greater lengths and/or widths. The exemplary application of the FSW method and the bobbin tool is presented in Figure 2.

Fsw elements find applications in:
- railway industry,
- ship-building industry,
- automotive industry,
- aviation industry,
- civil engineering etc.

Individual tests and testing methodology

The tests aimed to assess the effect of FSW conditions and the use of a bobbin tool on the quality of welded joints made of 6 mm thick aluminium alloy EN AW 6082 T6. The tests were performed using a station based on a FYF32JU2 vertical milling machine. The performance of the welding process was preceded by the preparation of special fixtures enabling the joining of plates without the use of a support on the side of the weld root. The fixtures were also used to ensure the rigid fixing of the plates preventing their deformation during the welding process. The welding station provided with the bobbin tool is presented in Figure 3.

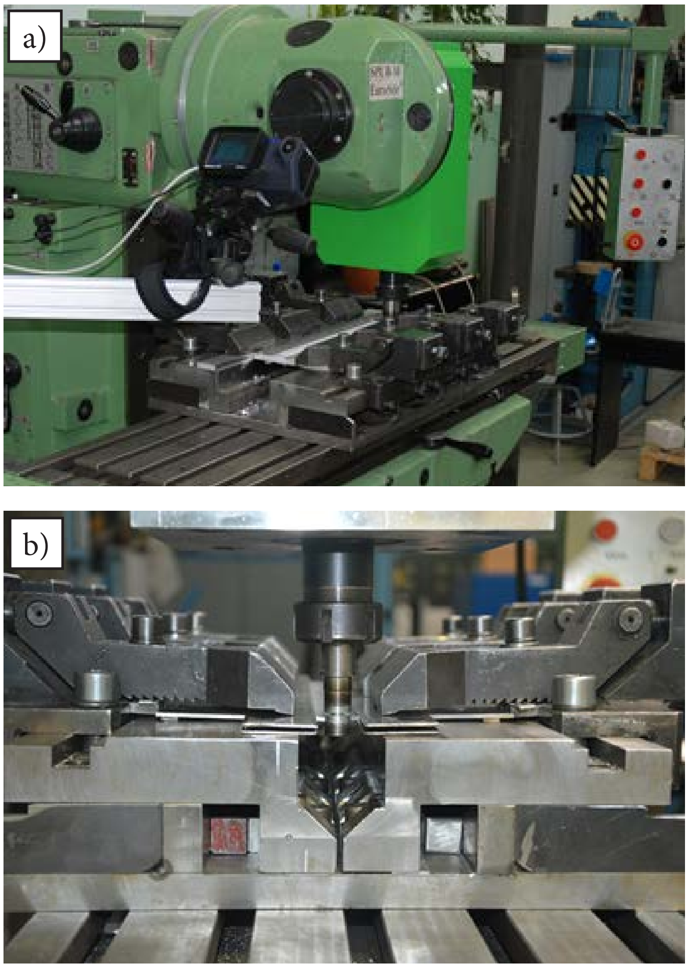

Fig. 3. Welding station and the bobbin tool: a) welding machine built on the basis of the FYF32JU2 vertical milling machine, b) welding performed using the bobbin tool

Table 1. Chemical composition of aluminium ally EN AW – 6082 T6

Alloy designation		Chemical element content, %							
Numerical designation	Symbol	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn
EN AW – 6082	EN AW – AlSi1MgMn	1.028	0.281	0.036	0.652	0.867	0.008	0.002	0.007

Ti	B	Bi	Co	Ga	V	Zr	Pb	Sn	Al
0.014	0.001	<0.003	<0.001	0.008	0.015	<0.002	<0.005	0.002	rest

The tests involved the use of 6 mm thick plates made of aluminium alloy En aw – 6082 t6. The chemical composition of the alloy used in the tests is presented in Table 1. Selected properties of aluminium alloy En aw – 6082 t6 are presented in Table 2.

Table 2. Selected properties of aluminium alloy EN AW – 6082 T6

Alloy designation	Mechanical properties		Plastic properties	
Numerical designation	$R_{0,2}$, MPa	R_m, MPa	L_u, mm	A_5, %
EN AW – 6082	260.0	310.0	101.0	12.2

The analysis of the process involved measurements of the temperature field of the welding area as well as measurements of force in the welding direction and torque affecting the tool. The temperature field measurements were performed using a VigoCam thermographic camera (model v50). The measurements were performed on the surface of the upper face of the weld, directly behind the shoulder of the tool. The emissivity factor amounting to 0.6 was adopted on the basis of previously gained research experience. The measurement results were used to calculate the mean value of temperature on the surface of the upper face of the weld during the stabilised phase of the process.

Measurements concerning force in the welding direction and the torque affecting the tool during the process were performed using a LowStir sensor head. The measurement results were used to calculate the mean force in the direction of welding and the mean friction torque during the stabilised process.

All of the joints were subjected to visual tests. The research also involved metallographic tests of the joints in relation to selected welding conditions. The tests were performed using an MeF4M optical microscope (Leica). Mechanical properties of the joints were assessed on the basis of tensile test results. Specimens used in the tests were prepared in accordance with the requirements specified in Pn-en iso 4136: 2013-05e Destructive Tests of Metallic Welded Joints – Tensile tests of Transverse Specimens [12]. Vickers hardness tests were performed using a kb50byz-fa testing machine and a load of 9.81 N. The tests were performed in accordance with the Pn-en iso 9015-1: 2011 standard.

Welding parameters used in the tests, i.e. a tool rotation rate *ω, rpm* and *a* welding rate v_{zg}, mm/min are presented in Table 3.

Table 3. Parameters of the FSW process performed using the bobbin tool

Tool rotation rate ω, rpm \ Welding rate vzg, mm/min	280	355	450	560
560	•	•	•	•
450	•	•	•	-
355	•	•	-	-

To prevent the breaking of the tool probe at the beginning of the process, the welding rate applied during the penetration of the plates by the tool amounted to 56 mm/min. After the obtainment of a proper joint being several centimetres in length, the movement of the tool was stopped and the welding rate was adjusted to the initially assumed (target) value.

The tests involved the use of a rigid bobbin tool made of steel hs 6-5-2 (sw7m) and composed of two shoulders and one probe. The working part of the shoulders had a notched spiral. The diameter of the upper shoulder amounted to 22.0 mm, the diameter of the lower shoulder amounted to 16.0 mm whereas the diameter of the probe amounted to 10.0 mm. The surface of the probe had horizontal notches. The distance between the shoulders amounted to 5.5 mm. The design and dimensions of the tool are presented in Figure 4.

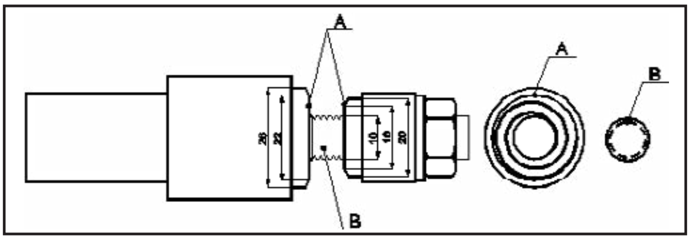

Fig. 4. Design of the bobbin tool

Test results, analysis and conclusions

Both at the beginning and during the welding process the bobbin tool did not get clogged by the plasticised material of the plates. Visual tests revealed the material continuity of the joints in cases of all of the welding parameters used in the tests. The upper and the lower face of the weld did not reveal the presence of welding imperfections. Figure 5 presents selected joints. As can be seen, the process was performed from the left to the right side. At the end of the joint (on the right) reveals the lack of fusion resulting from the tool leaving the material of the plates.

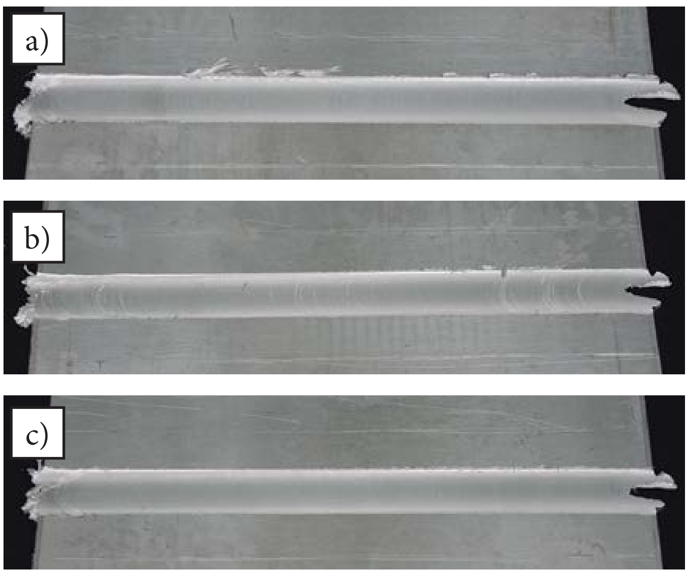

Fig. 5. Joints obtained using selected welding parameters: a) 355 rpm, 280 mm/min, b) 450 rpm, 450 mm/min, c) 560 rpm, 560 mm/min

The results of the metallographic tests revealed the clearly visible stirring of the material in the welds of the joints (Fig. 6 and 7). The weld adopted the shape of an hourglass. In the central part, the weld nugget was narrower and grew wider in the direction of plate surfaces. This phenomenon resulted from the effect of shoulders on the heat generation process. The analysis of the metallographic test results revealed that, on the advancing side, the interface between the heat affected zone (HAZ) and the base material was clearly visible. The material adopted the shape of concentrically arranged "onion-like" rings. The "ring-like" arrangement of the material resulted from

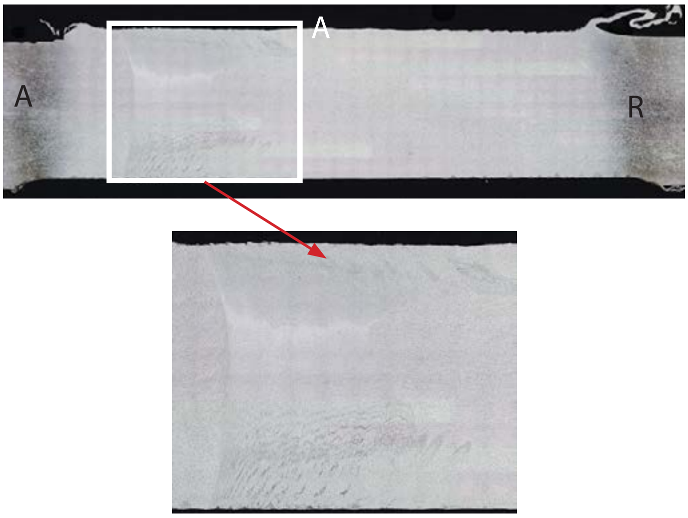

Fig. 6. Macrostructure of the joint welding area; welding parameters: ω = 450 rpm, v_{zg} = 280 mm/min. A – advancing side, R – retreating side

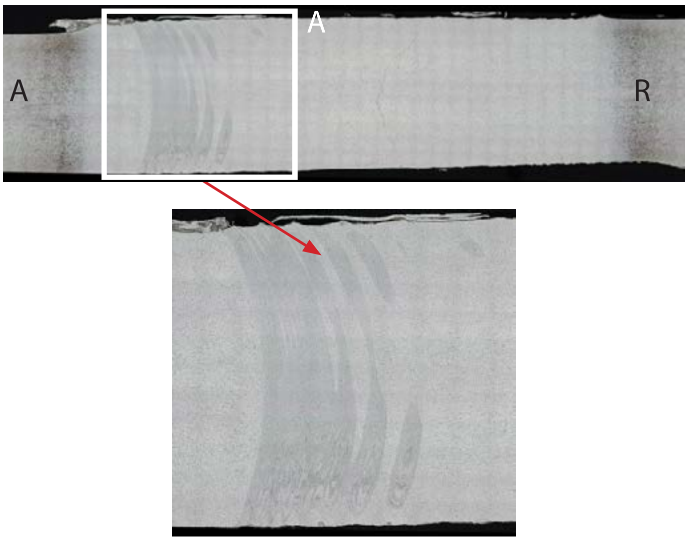

Fig. 7. Macrostructure of the joint welding area; welding parameters: ω = 450 rpm, v_{zg} = 450 mm/min. A – advancing side, R – retreating side

the effect of shoulders. The rings were more concentrated under the smaller shoulder having a shorter diameter. In addition, the rings were more concentrated as a result of a higher welding rate. The heat affected zone was less clearly visible on the retreating side.

The analysis of the test results concerning the strength of the joints revealed that the joints characterised by the highest strength could be obtained by using the following welding parameters: ω = 450 rpm and v_{zg} = 280-450 mm/min (Fig. 8). The strength of the joints constituted between 75% and 77% of the base material strength (BM). The above-named tool rotation rate adopted during welding resulted in the obtainment of the highest repeatability. In turn, the lowest repeatability was obtained at a rotation rate of 560 rpm and a low welding rate of 280 mm/min. All of the joints tended to rupture in the HAZ, on the retreating side. The maximum strength obtained during welding performed using the tool provided with one shoulder constituted approximately 77% of the base material strength and was comparable with the strength obtained during welding performed using the bobbin tool. The above-named strength was obtained using a Triflute device, a welding rate of 1120 mm/min (ω = 560 rpm) and 710 mm/min (ω = 710 rpm) (Table. 7.2). The use of the conventional tool enabled the obtainment of joints, the strength of which constituted approximately 68% of the BM strength, yet at a lower welding rate of 224 mm/min [13].

The hardness tests involved the specimens made using the following welding parameters: joint no. 1, welding parameters: ω = 450 rpm, vzg = 280 mm/min and joint no. 2, parameters:

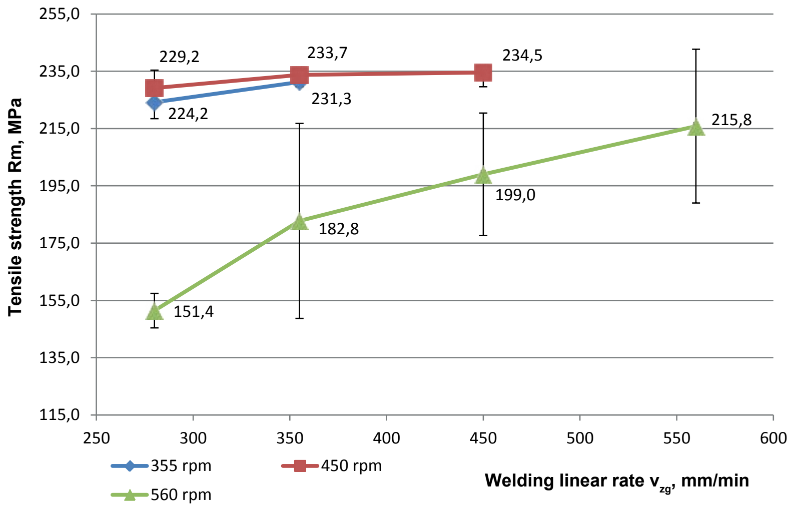

Fig. 8. Effect of linear welding rate on the strength of joints in the static tensile test

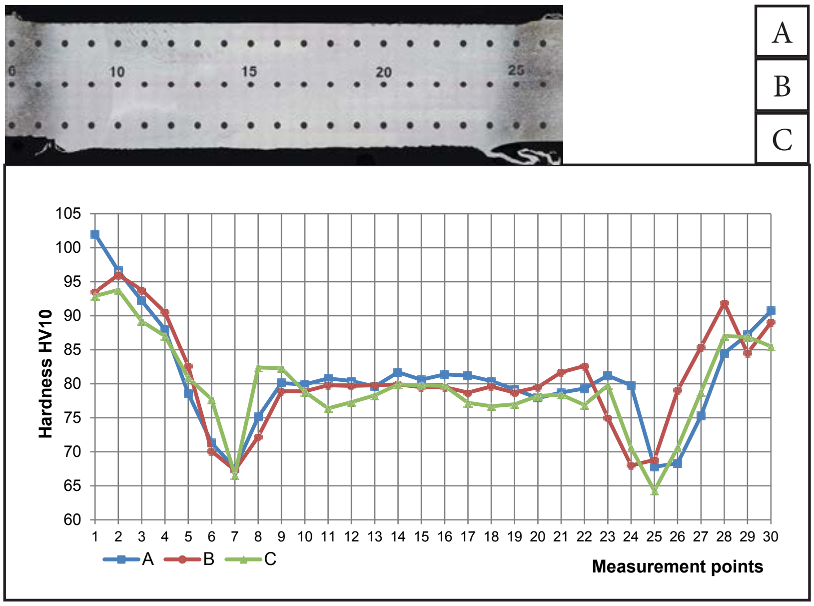

Fig. 9. Hardness distribution in cross-section of join no. 1; welding parameters: ω = 450 rpm, vzg = 280 mm/min

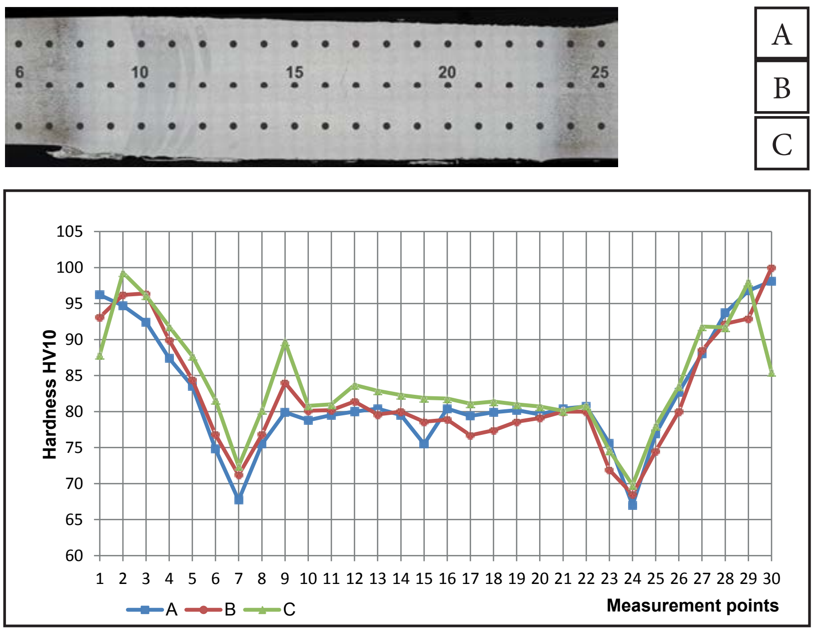

Fig. 10. Hardness distribution in cross-section of join no. 2; welding parameters: ω = 450 rpm, vzg = 450 mm/min

ω = 450 rpm, vzg = 450 mm/min. The test results in the form of hardness distribution graphs are presented in Figures 9 and 10. Areas where measurements were performed are marked in the macrostructures of the joints. The analysis of hardness distribution in the joints revealed that a decrease in hardness related to the base material involved the weld nugget, the zone deformed thermomechanically and the heat affected zone (HAZ). The hardness amounted to approximately 80 HV, where the greatest hardness decrease was observed in the HAZ (to approximately 67 HV). The above-named hardness distribution was typical of FSW joints made using a tool provided with a one shoulder.

The tests included measurements of force in the direction of welding and the friction torque affecting the tool. The analysis of the measurement results involved the calculation of the mean values of the above-named parameters during the stabilised phase of the process. Exemplary courses of the torque and the force in the direction of welding direction recorded during the welding process as well as the stabilised phase of the process are presented in Figure 11.

Measurements of temperature in the welding area were performed on the surface of the upper face of the weld. The mean temperature on the weld face was calculated by mapping (in the thermograph) a 25 mm long measurement line (Fig. 12) located 2.5 mm away behind the upper should of the tool. The course of the mean temperature during the welding process along with the phase of the stabilised process is presented in Figure 13. The results related to the measurements of temperature performed on the weld face, the measurement of force in the welding direction and the friction torque affecting the tool are presented in Table 4.

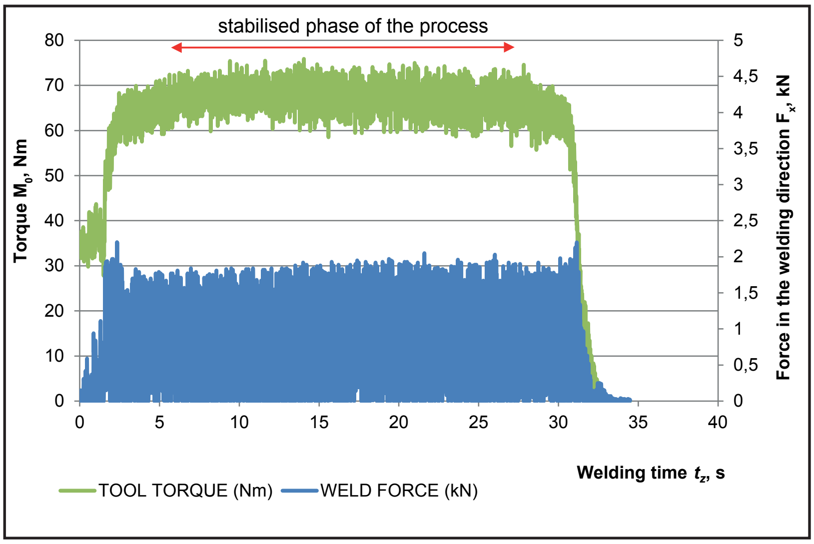

Fig. 11. Force in the welding direction and the tool torque during welding; welding parameters: ω = 560 rpm, vzg = 560 mm/min

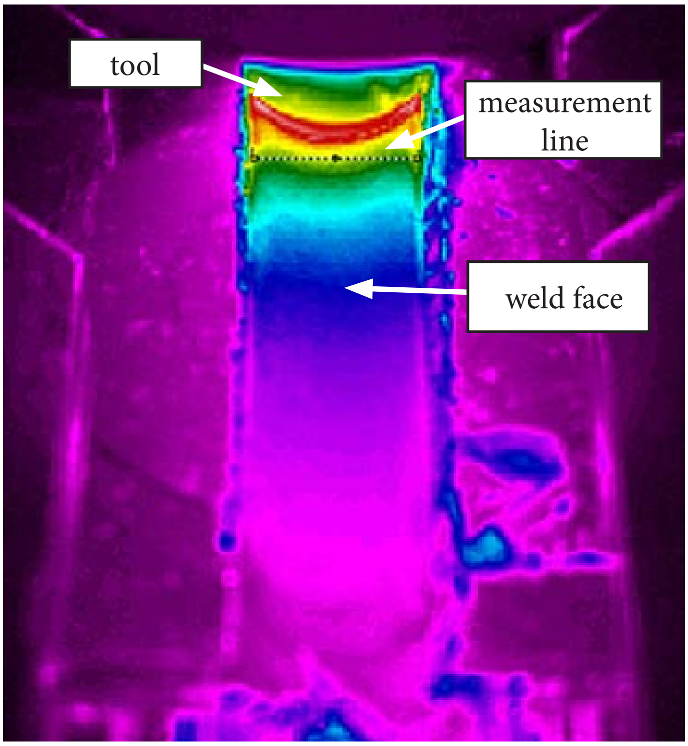

Fig. 12. Exemplary thermograph of the welding area with the marked measurement line

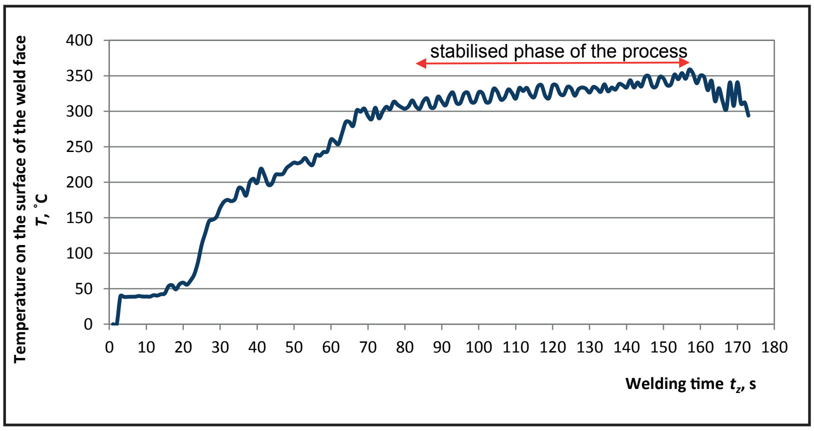

Fig. 13. Changes in temperature during the process of welding; welding parameters ω = 450 rpm, vzg = 355 mm/min

The temperature measurement results revealed that an increase in the linear welding rate combined with the constant rate of tool rotation led to a decrease in temperature on the surface of the weld face. In turn, the constant linear welding rate combined with an increase in the tool rotation rate led to an increase in temperature on the surface of the weld face. The highest temperature restricted within the range of 345°C to 350°C was obtained using a low welding rate of 280 mm/min. At the same time it was ascertained that the higher the material temperature in the tool operation area, the lower the forces in the welding direction and the friction torque.

Table. 4. Results of measurement of forces, friction torque and temperature on the weld face recorded during the process of welding

Welding parameters		Mean friction torque $M_{ośr}$, Nm	Mean force in the welding direction $F_{xśr}$, kN	Mean temperature measured on the weld face $T_{śr}$, °C
ω, rpm	v_{zg}, mm/min			
355	280	76.0	0.6	345.0
	355	81.0	0.5	305.0
450	280	60.0	0.5	345.0
	355	66.0	0.6	325.0
	450	72.0	0.7	310.0
560	280	47.0	0.7	350.0
	355	52.0	0.7	345.0
	450	57.0	0.8	325.0
	560	67.0	0.9	305.0

The research-related tests justified the formulation of the following conclusions:

1. The use of the bobbin tool enabled the friction stir welding of the 6 mm thick plates made of aluminium alloy EN AW 6082 T6 without the use of the lower backing bar. During welding the tool did not clogged with the plate material but underwent self-cleaning.

2. The bobbin tool enabled the proper heating of the material within its operation area, which favourably affected the course of the welding process and the quality of the welds.

3. Welding parameters affected heat generation and friction torque:
- the lower the welding rate and the higher the tool rotation rate, the higher the temperature in the welding area;
- the higher the welding rate and the lower the tool rotation rate, the higher the friction torque; force in the direction of welding changed negligibly.

4. The welds adopted the shape of an hourglass and were characterised by the compact structure, material continuity and the lack of visible welding imperfections. On the side of shoulder operation the material was placed in the form of concentrically arranged "rings".

5. The hardness of the weld dropped to approximately 80 HV, which is typical of FSW joints.

6. The joints made using the bobbin tool were characterised by high strength constituting up to 75-77% of the base material strength (using the following welding parameters: ω = 450 rpm and v_{zg} = 280 – 450 mm/min) and by high repeatability.

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