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The Application of the Bobbin Tool in the Friction Stir Welding of Aluminium Sheets

Abstract: The article presents the effect of the technological parameters of the friction stir welding of 2 mm thick aluminium sheets made of aluminium alloy EN AW 6082 performed using of the bobbin tool. The tests included static tensile tests, hardness tests and macroscopic metallographic tests. The tests revealed that properly selected welding parameters enabled the obtainment of joints characterised by material continuity, compact structure and the lack of welding imperfections in the welding area. The application of the bobbin tool made it possible to obtain joints of aluminium sheets characterised by high strength, i.e. amounting to 61% of the base material strength.

Keywords: bobbin tool, Friction Stir Welding, FSW, EN AW 6082, welding of aluminium, aluminium joints

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Introduction

The development of design methods makes it possible to decrease the weight of the structure by using thin-walled structural elements, including those made of aluminium alloys. As a result, the costs related to the whole investment process may also be reduced. However, in order to make the application of thin-walled structural elements widespread, it is necessary to develop technologies enabling their permanent joining, for instance using welding technologies. One of the possibilities is the use of solid state joining, i.e. the FSW method and the bobbin tool.

The FSW method involving the use of the bobbin tool is applied to the welding of elements more than 1.8 mm thick [1-5]. This method is most often used to join closed-shape aluminium sections with products having much greater widths and/or lengths, used in the railway, shipbuilding and automotive industries as well as in building engineering and other sectors.

The bobbin tool is composed of two shoulders connected with a probe [1-11]. Depending on the thickness of sheets to be welded and grades of welded materials, the shapes and dimensions of both the shoulders and the probe may vary. Figure 1 presents the welding station for the welding of sheets involving the use of the bobbin tool.

During the welding of sheets, because of a small volume of material and the lacking sufficient rigidity of the entire system, the beginning of the welding process may prove problematic. The gap between the shoulders and the sheets may be filled with the plasticized material from

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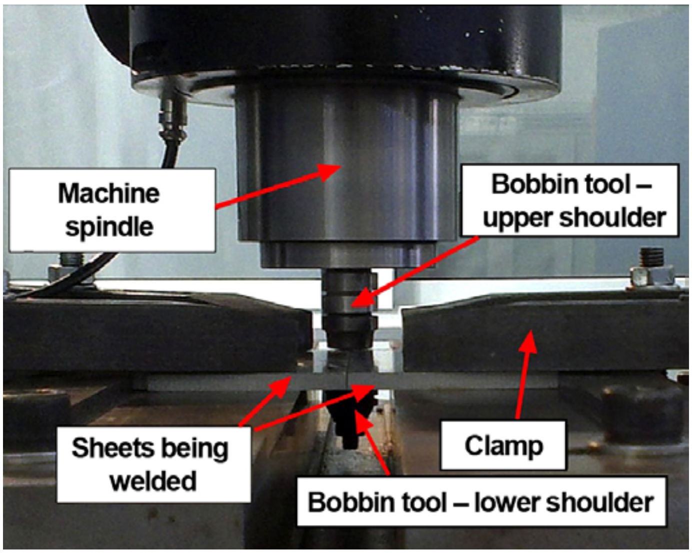


Fig. 1 Station for the butt welding of sheets using the FSW method and the bobbin tool [1]

the sheets. As a result, the material will not be correctly stirred and upset by the tool [2]. Factors decisive for the proper course of the joining process involving the use of the bobbin tool include the shape and dimensions of the shoulders and the probe as well as the parameters of welding and proper equipment [2, 3].

During the friction stir welding performed without the lower support it is essential to use equipment which will provide not only proper rigidity of the elements to be joined, but also prevent their deformation in the tool working area. If the clamps of the equipment are located overly close to the welding line or are excessively far from it, the elements may be deformed up or down [2, 3] (see Figures 2 and 3). In addition, non-uniform fixing may trigger the movement of sheets in relation to each other [4].

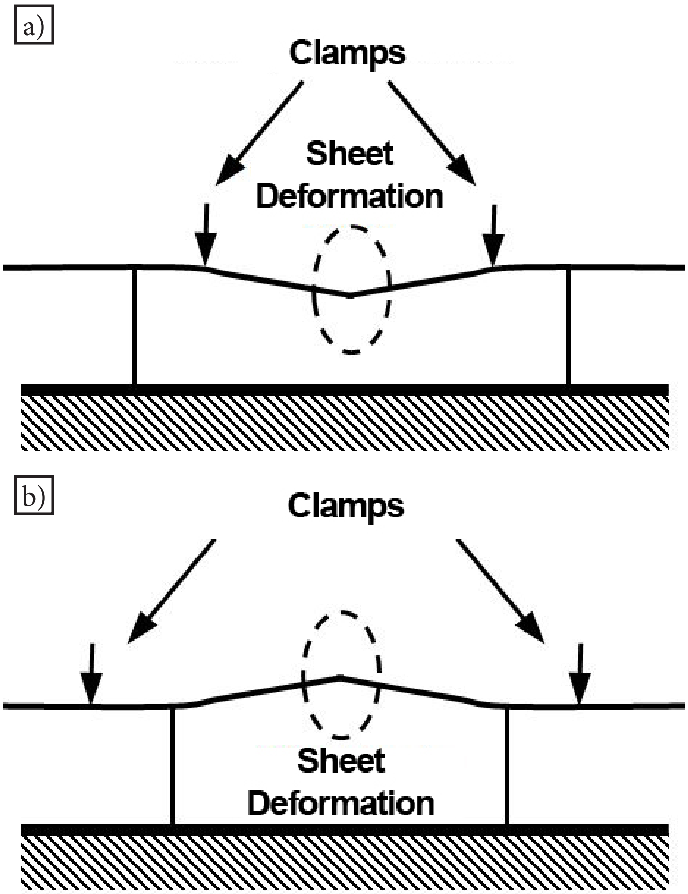


Fig. 2. Possible deformation of elements at the interface triggered by the incorrect fixing of the elements to be welded, a) clamps of the equipment are overly close to the welding line welding, b) clamps of the equipment are excessively far from the welding line [3]

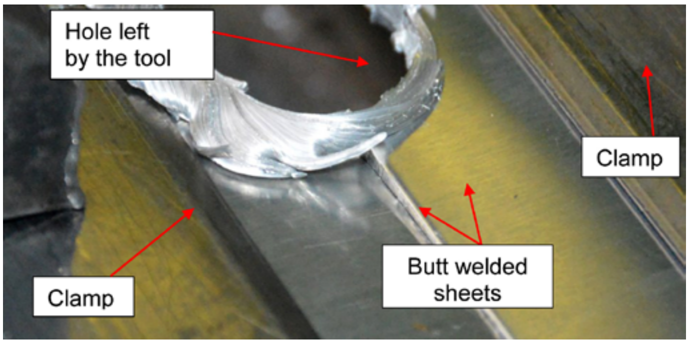


Fig. 3. Deformation of sheets after the welding process performed with the bobbin tool [4]

Another important factor involves the preparation of sheet edges. As can be seen in reference publications, in terms of sheets having a thickness restricted within the range of 3.0 mm to 5.0 mm, the maximum width of the gap at the interface not reducing the mechanical properties of joints amounts to 0.75 mm [2]. The above results were obtained in the welding of sheets made of 5xxx and 6xxx series aluminium alloy. An excessively large gap between the sheets and an improperly selected tool may lead to the formation of welding imperfections in the joints or result in the lack of the weld [3].

The tests [5] revealed that the quality of welded joints is influenced by the rate of rotation and welding rate. The welding of 4.0 mm thick sheets made of aluminium alloy EN AW6061-T6 involved the use of a tool consisting of shoulders of different diameters (18.0 and 16.0 mm) and a probe having a diameter of 8.0 mm [5]. In comparison with a constant rate of rotation, an increase in the rotation rate of the tool up to 600 rpm resulted in an increase in the strength of the joints in the static tensile test, whereas a rate of 700 rpm resulted in the dramatic deterioration of quality because of material discontinuities in the weld nugget on the advancing side.

It was noticed that at the rotation rate of the tool amounting to 600 rpm was accompanied by the clear effect of the probe – the width of the weld in its central part was larger than the diameter of the probe and amounted to 10.0 mm, whereas at a rotation rate of 700 rpm, the weld width corresponded to the probe diameter (approximately 8.0 mm) and the weld nugget (in the thermomechanically affected zone) contained welding imperfections on the advancing side [5].

In addition, the tests also concerned the impact of the linear welding rate on the strength of joints in relation to a constant tool rotation rate of 600 rpm, i.e. the rate at which the highest quality of the joints was obtained. The tests revealed that an increase in the welding rate up to 200 mm/min led to an increase in the strength of the joints (up to approximately 80% of the strength of the base material), whereas a rate of 250 mm/min was accompanied by a dramatic decrease in the strength because of material discontinuities formed in the weld nugget on the advancing side [6]. The tests of microhardness confirmed that the highest decrease in hardness occurred on the advancing side in the area between the heat affected zone and the thermomechanically deformed area [5].

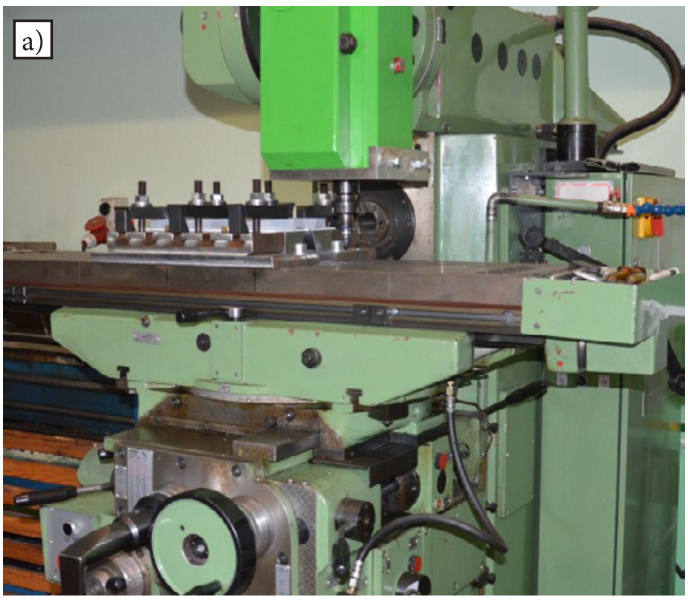
The research also involved tests concerning the effect of the probe shape on the quality of joints in 4.0 mm thick sheets made of aluminium alloy EN AW 6082-T6 [7]. The application of the tool with a threaded probe, a probe with horizontal notches as well as a probe with the right thread and the left thread resulted in the formation of welding imperfections in the joints, including excess flash, weld face surface irregularities or the linear discontinuity of the material visible on the weld face surface (the effect of gouging). On the other hand, the joints without any imperfections were obtained using the tool featuring the threaded probe and three notched vertical planes. The thread on the probe enforced vertical movement, whereas the notched vertical planes enforced the horizontal movement of the material. The authors emphasised that if the volume of the material between the shoulders was small, as was the case with the welding of sheets, a proper joint could be obtained by involving the vertical movement of the material (enforced by the movement of rotating shoulders).

The FSW method involving the use of the bobbin tool may be also applied at different rotation rates of the shoulders. The authors of publication [8] welded 3.2 mm thick sheets made of aluminium alloy AA2198-T851. The surface of the shoulders was concave and had a diameter of 11.0 mm, whereas and the smooth probe had a diameter of 4.0 mm. The welding rate amounted to v_{zg} = 42 mm/min, whereas the rotation rate of the tool was ω = 400–1200 rpm. In comparison with the classic bobbin tool, the use of the tool with the shoulders rotating at different rates enabled the better mixing of materials in the weld. In addition, it was revealed that the joints without imperfections could be obtained within a wider range of welding parameters. It was observed that the application of different rotation rates of the shoulders resulted in the asymmetric flow of the material in the weld. This led to the filling of cavities (appearing in the material behind the tool, on the advancing side) with the plasticized material. The distance between subsequent layers of material λ, resulting from the proportion of the welding rate to the rotation rate of the tool, also referred to as the step, was different in relation to two rotation rates of the shoulders. At the preset welding rate, the lower shoulder made a smaller step because of a higher rotation rate. As a result, the layers of the material deposited interchangeably by the lower and upper shoulder had different widths, thus preventing the formation of cavities in the weld.

There are also applications involving the use of bobbin tools provided with the fixed (not moving) upper shoulder. The authors of publication [9] demonstrated that during the welding of 3.0 mm thick sheets made of aluminium alloy AA2198-T851 [9], the fixed shoulder acted as a moving support stabilising the welding process.

Previously conducted research was also concerned with the effect of an oxide layer and welding parameters on the properties of FSW joints. The authors of publication [10] presented results obtained in tests involving the welding of 3.2 mm thick sheets made of aluminium alloy AA2198. The tests involved the use of a bobbin tool provided with the shoulders having a diameter of 11.0 mm and a smooth probe having a diameter of 4.0 mm. The distance between the shoulders amounted to 3.0 mm. The tests were concerned with the effect of the rotation rate on the structure of the welding area and the strength of the joints. The tool rotation rate was restricted within the range of tool 400 rpm to 1000 rpm, whereas the welding rate was constant and amounted to 42 mm/min. The test results (concerning all of the joints) revealed the presence of an oxide layer in the weld nugget. The deposition of the oxide layer was related to the rotation rate of the tool. At a rate of 400 rpm, the above-named layer was present nearly across the entire thickness of the joint. However, the higher the rotation rate, the narrower and the shorter the layer. The results of the static tensile test revealed that the failure of the joints made at a low rotation rate of 400 and that of 600 rpm took place usually in the weld and overlapped with the line of oxides. In terms of higher rotation rates, specimen ruptured as above, in the heat affected zone in relation to a rate of 800 rpm or at the interface between the thermo-mechanically affected zone (TMAZ) and the stirring zone (SZ – Stirring Zone) – in relation to a rate of 1000 rpm. When analysing the results of the tests concerning the mechanical properties of the joints it was ascertained that the strength of the joints increased along with an increase in the rotation rate of the tool of up to 800 rpm, leading to the obtainment of the maximum strength of approximately 380 MPa (80% of the base material strength). In turn, at a rate of 1000 rpm the strength decreased to approximately 325 MPa (68% of the base material).

The work presents the results of tests concerning the friction stir welding (involving the use of a bobbin tool) of 2 mm thick sheets made of aluminium alloy EN AW 6082. The research-related tests involved visual tests of joints, macroscopic metallographic tests, strength tests and hardness measurements.



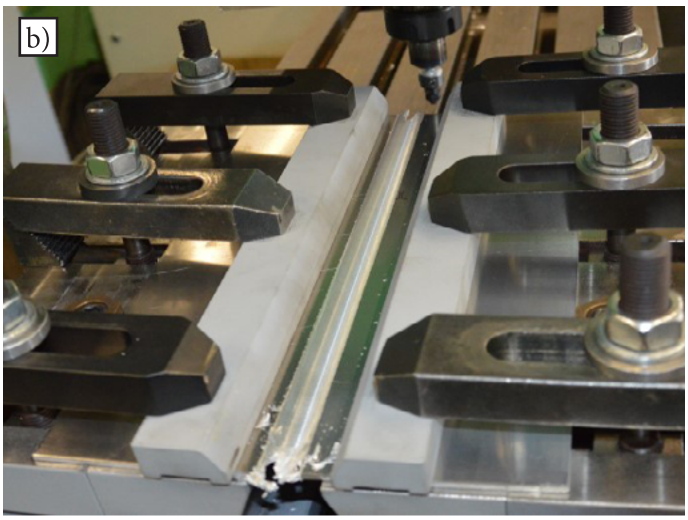


Fig. 4 FSW station with the bobbin tool, a) main view and b) fixtures

Methodology of the experiments

The tests aimed to assess the effect of the conditions of the FSW method-based process (performed using a tool with two shoulders) on the quality of joints of 2.0 mm thick sheets made of aluminium alloy EN AW 6082.

The tests were performed using a station composed of an FYF32JU2 vertical milling machine (Fig. 4) equipped with special tooling enabling the joining of sheets having a thickness restricted within the range of 2.0 mm to 4.0 mm, without the application of a support on the weld root side. The tests involved the use of adjustable bobbin tools allowing the modification of the distance between the shoulders (to the thickness of sheets). The material of the tool was steel HS 6-5-2 (SW7M).

The chemical composition of the alloy is presented in Table 1, whereas selected properties of aluminium alloy EN AW-6082 are presented in Table 2. The welding of sheets involved the use of tools having different shapes and dimensions of the shoulders and probes. The diameter of shoulders (upper / lower shoulder) amounted to 11/10 mm with a notched spiral. The diameter of the probe with a notched thread amounted to 5.0 mm. Table 3 presents parameters used in the welding process.

Table 1 Chemical composition of aluminium alloy EN AW-6082 T6

Content of elements, %									
Si	Fe	Cu	Mn	Mg	Ti	Cr	Ni	Zn	Al
1.028	0.281	0.036	0.652	0.867	0.014	0.008	0.002	0.007	rest

Table 2 Selected properties of aluminium alloy EN AW-6082

Mechanical properties		Plastic properties	
$R_{0.2}$, MPa	R_m, MPa	L_u, mm	A_5, %
273.9	368.7	44.0	10.1

The visual tests of the welded joints were performed along their entire length. The macroscopic metallographic tests of the joints were performed in relation to selected welding parameters. The tests were performed using an Eclipse MA 200 optical microscope (Nikon).

Mechanical properties of the joints were identified on the basis of the results a static tensile test. The test specimens were prepared in accordance with PN-EN ISO 4136 [11]. The hardness measurements were based on the Vickers hardness test and performed using a KB50BYZ-FA testing machine in accordance with PN-EN ISO 9015-1: 2011 [12]. The applied load amounted to 9.81 N.

Test results and analysis

The visual tests of all of the joints revealed that at the beginning of the joint some material was present in the form of flash, squeezed out of the line of the sheets when the tool was penetrating the material. The end of the joint contained a characteristic gap, i.e. a mark left by the tool.

The making of the joints using the following welding parameters: ω = 900 and 1400 rpm and v_{zg} = 140 mm/min led to the formation of linear discontinuities in the material, visible on the weld face (Figs. 5 and 6).

In turn, it was impossible to obtain a proper joint using of the following welding parameters: ω = 1800 rpm and v_{zg} = 355 mm/min. The tool got plugged with the material of the sheets (during welding); after the stoppage of the feed, the tool got cleaned and subsequently got plugged again after the feed was switched on. The fragments of the weld also contained linear discontinuities (Fig. 6).

Table 3 List of parameters used in the welding of 2.0-mm-thick sheets

	Welding rate v_{zg}, mm/min						
Tool rotation rate ω, rpm	71	90	112	140	180	280	355
710	●	●	●	-	-	-	-
900	-	●	●	●	-	-	-
1120	●	●	●	-	-	-	-
1400	-	●	●	●	-	-	-
1800	-	-	●	-	●	●	●

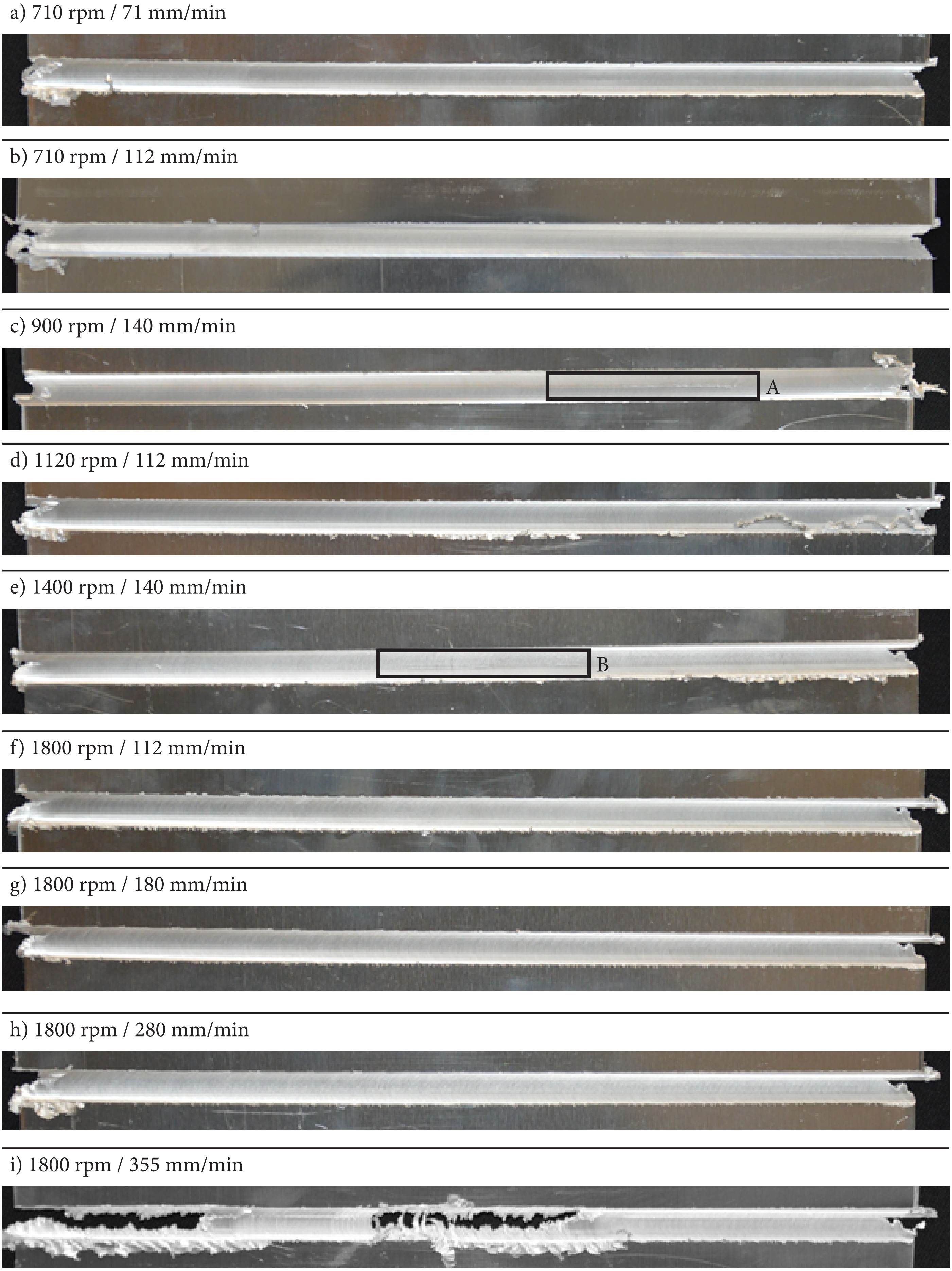


Fig. 5 Joints made of 2.0 mm thick sheets in relation to selected welding parameters

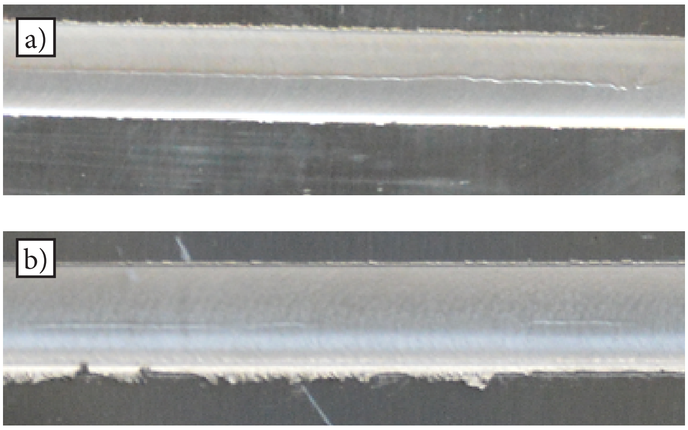


Fig. 6 Linear discontinuity of the joint – fragment A from Fig. 5c and fragment B from Fig. 5 e)

All of the joints were subjected to tests of mechanical properties in a static tensile test. Each joint was sampled for three specimens. In terms of the joints made of 2.0 mm thick sheets using the following parameters: ω = 1800 rpm ivzg = 355 mm/min, specimens were not sampled because material discontinuity. The results of the tensile tests are presented in Table 4.

The analysis of the tensile strength test results revealed that, depending on the welding parameters, the joints made using the bobbin tool reached the maximum strength amounting to 61% of the strength of the base material (BM).

The hardness tests involved the 2.0 mm thick joints made using the following welding parameters:

- ω = 710 rpm; v_{zg} = 112 mm/min (Fig. 7)
- ω = 1400 rpm; v_{zg} = 112 mm/min (Fig. 8)

The analysis of the results obtained in the hardness tests revealed that the distribution of hardness was typical of the FSW joints. The reduction of hardness in relation to the base material was observed in the heat affected zone (HAZ), the thermo-mechanically affected (deformed) zone (TMAZ) and in the weld nugget. The hardness in the weld nugget dropped to approximately 70HV, whereas the hardness in the HAZ decreased to approximately 60 HV.

The macroscopic metallographic tests involved the joints made using selected technological process parameters. The results of the tests are presented in Fig. 9. The analysis of the results obtained in the metallographic tests

Table 4 Results of tensile strength tests of joints of 2.0-mm-thick sheets

No.	Welding parameters		Tensile strength		Area of rupture
	ω, rpm	v_{zg},mm/min	R_m, MPa	$R_{mśr}$, MPa	
1.1	710	71	187.8	199.7	Rupture in the weld axis
1.2			215.9		
1.3			195.4		
2.1		90	218.4	218.5	Rupture in the weld axis
2.2			218.6		
2.3			218.4		
3.1		112	223.5	223.4	Rupture in the weld axis
3.2			223.5		
3.3			223.3		
4.1	900	90	195.8	211.1	Rupture in the weld axis
4.2			218.4		
4.3			219.0		
5.1		112	225.0	225.2	Rupture in the weld axis
5.2			225.4		
5.3			225.1		
6.1		140	222.4	213.5	Rupture in the weld axis
6.2			210.0		
6.3			208.1		
7.1	1120	71	229.1	200.4	Rupture in the weld axis
7.2			149.0		
7.3			223.1		
8.1		90	212.3	206.7	Rupture in the weld axis
8.2			227.6		
8.3			180.2		
9.1		112	211.6	219.2	Rupture in the weld axis
9.2			220.3		
9.3			225.7		
10.1	1400	90	224.1	215.2	Rupture in the weld axis
10.2			201.0		
10.3			220.5		
11.1		112	208.1	214.0	Rupture in the weld axis
11.2			220.3		
11.3			213.5		
12.1		140	237.9	223.3	Rupture in the weld axis
12.2			193.5		
12.3			238.4		
13.1	1800	112	186.0	198.8	Rupture in the weld axis
13.2			199.7		
13.3			229.9		
14.1		180	241.4	222.1	Rupture in the weld axis
14.2			189.3		
14.3			220.5		
15.1		280	199.7	210.4	Rupture in the weld axis
15.2			199.9		
15.3			242.1		

revealed that the material in the weld was stirred. The weld adopted the shape of a sandglass (typical of this tool), i.e. narrow in the central part of the weld and widening towards the surface of the sheets. The above-presented shape of the weld resulted from the operation of two shoulders. On the advancing side, interface between the heat-affected zone and the weld nugget was clearly visible, whereas on the retreating side the above-named boundary was less visible. The material in the weld nugget, on the advancing side, adopted the shape of concentrically arranged circles or layers. The above-named manner of material deposition was triggered by the shoulders and by the enforced movement of the material. It was also possible to observe the line of oxides, particularly in relation to higher welding rate values (independent of the rotation rate of the tool). The 2.0 mm thick joint, made using ω = 1800 rpm and v_{zg} = 112 mm/min, contained some imperfections in the weld nugget, on the advancing side.

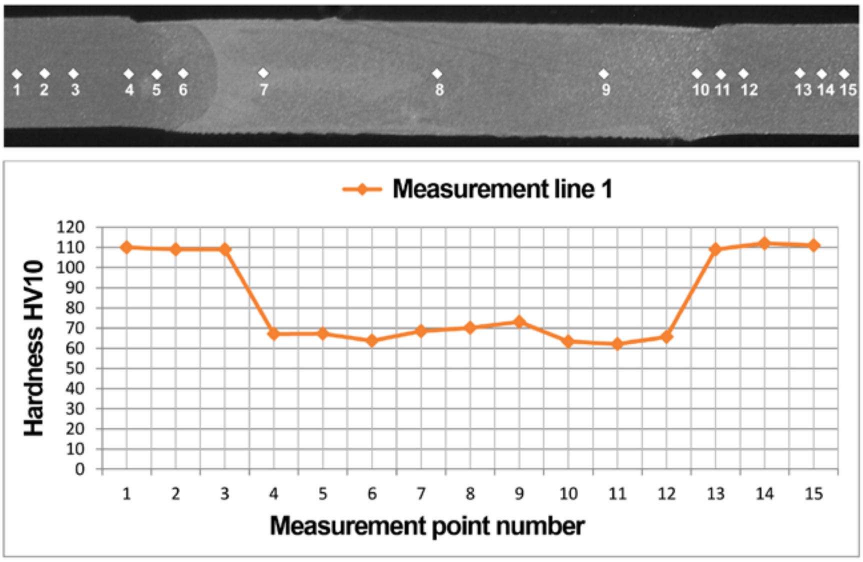


Fig. 7 Hardness distribution in the cross-section of the 2.0 mm thick joint; welding parameters: ω = 710 rpm; v_{zg} = 112 mm/min

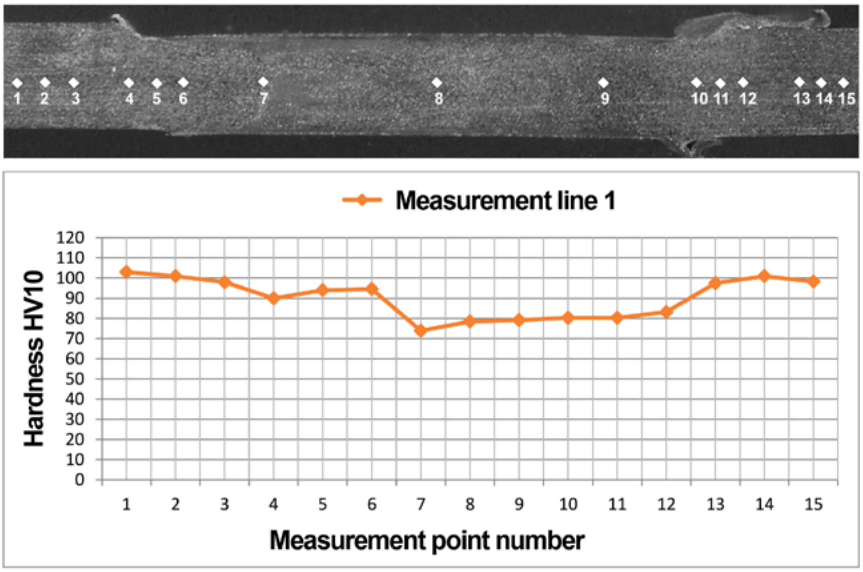
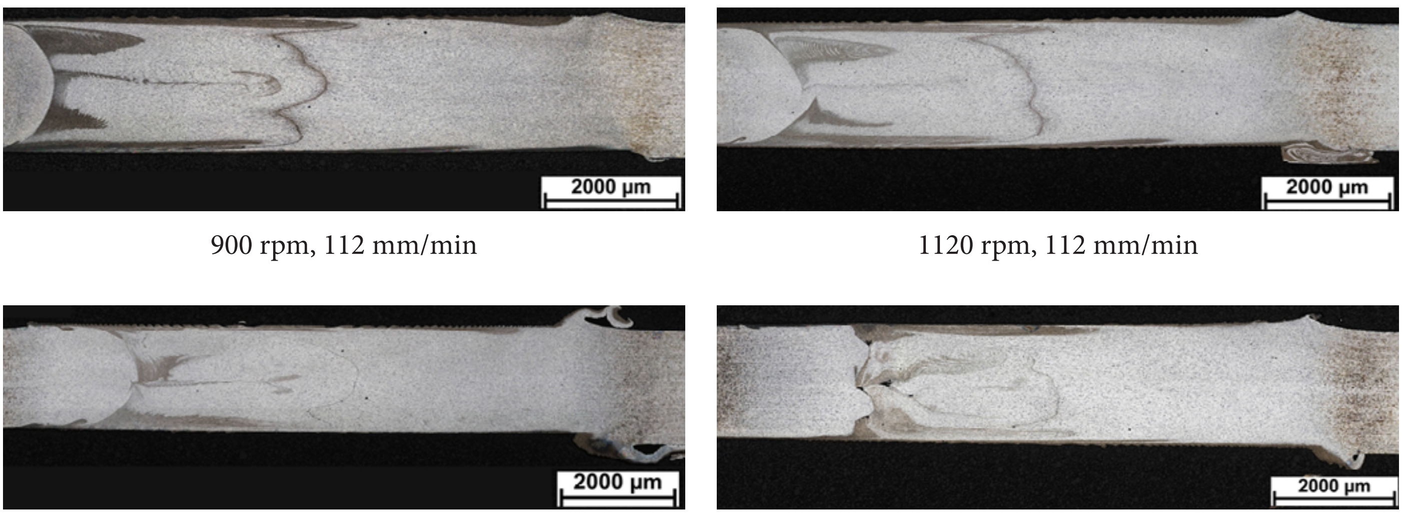


Fig. 8 Hardness distribution in the cross-section of the 2.0 mm thick joint; welding parameters: ω = 1400 rpm; v_{zg} = 112 mm/min



900 rpm, 112 mm/min

1120 rpm, 112 mm/min

1400 rpm, 112 mm/min

1800 rpm, 112 mm/min

Fig. 9 Results of the macroscopic metallographic tests

Conclusions:

The analysis of the above-presented results justified the formulation of the following conclusions:

1. The making of FSW joints in aluminium sheets using a bobbin tool requires the application of special equipment ensuring the proper positioning of elements before and during the welding process.
2. To obtain high-quality joints in aluminium sheets it is indispensable to use tools having proper shapes and dimensions.
3. It is possible to make joints in 2.0 mm thick sheets by using a tool characterised by small diameters of the shoulders and probe (W: Ø11/10 mm, T: Ø 5.0 mm). It is necessary to use a high rotation rate of the tool (restricted within the range of 710 rpm to 1800 rpm) and a low linear welding rate (restricted within the range of 71 mm/min to 280 mm/min).
4. Properly adjusted welding parameters enable the obtainment of joints characterised by material continuity, compact structure and the lack of welding imperfections in the welding area.
5. The application of the bobbin tool enables the obtainment of high-strength joints. The maximum strength of the 2.0 mm thick joints amounted to 61% of the base material strength (ω = 900 rpm, vzg= 112 mm/min).

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