

# THE FSW TECHNOLOGY OF NON-FERROUS METALS — PROCESS CONDITIONS AND EXAMPLES OF APPLICATION

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The paper presents welding conditions and the process of creating a FSW weld during welding elements made of wrought aluminium alloys and cast aluminium alloy. Investigations were conducted at Institute of Welding, Gliwice (Instytut Spawalnictwa), on the FSW stands equipped with vertical milling machine adapted for friction stir welding process. Influence of the tool's dimension and shapes on the plasticization process of welded material and formation of a weld behind the tool, at different welding set of parameters were studied. During the investigations it was noticed, that forces and torque occurring during FSW and stiffness of the clamping system influence the temperature of the welding area, the plasticity of the material, the particles fragmentation and the quality of the joints. On the basis of research correct welding conditions were selected and process of welding was conduct using specially designed instrumentation. The views of exemplary friction stir welded elements and macrosections from the welding areas are shown. 14 Ref., 4 Tables, 16 Figures.

**Keywords:** Friction stir welding, wrought and cast aluminium alloys, copper tool dimension

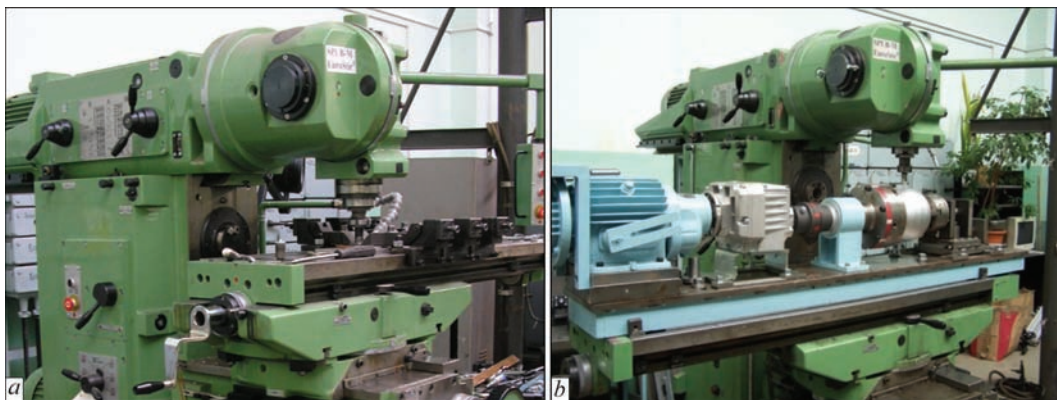
**Introduction.** FSW (Friction Stir Welding) is the method that makes it possible to successfully join aluminium alloys, including casting alloys and copper alloys, which are difficult to weld using known welding techniques. This method is increasingly used in the world mainly in the shipbuilding, rail, automotive and building industries.

In FSW process the stirring and rotating tool penetrating material along the line of welding is applied for the friction heating and softening of the material. After the tool is put into rotation and frictional heating is softening the material around the probe, the tool is traversed along the joint line. The heated and plasticised materials of the components being welded are extruded around the tool probe backwards, where before cooling down they are stirred and upset by the shoulder. In the centre of the weld the zone called «nugget» is formed behind the tool in the result of the stirring of the softened metals of both parts being welded [1, 2].

The shape and dimensions of the weld depend on the shape and size of the stirring tool and applied welding parameters. The tool penetrating welding zone has three basic functions: heating metal in the area of joining, stirring of materials and upsetting of plasticised metal behind the tool in the phase of weld forming. Basic parameters of FSW process comprise:

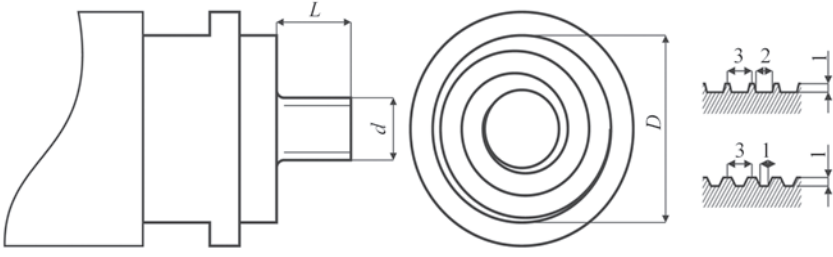
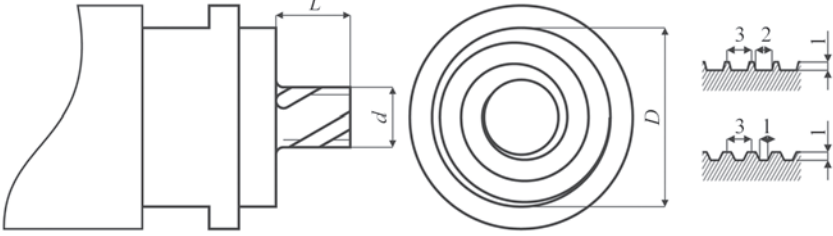
- tool rotation speed —  $\omega$  ( $\text{mm}^{-1}$ );
- welding speed —  $V_{zg}$  (mm/min);
- tilt angle —  $\alpha$  [ $^{\circ}$ ];
- tool type and size of the tool: probe diameter —  $d$  (mm), shoulder diameter —  $D$  (mm), probe length —  $l$  (mm).

During FSW process, material of the workpiece subjected to mechanical stirring and intensive plastic deformation at higher temperature, spreads out also outside the stirring zone (thermomechanically affected zone). Additionally, the significant temperature gradient occurs across the weld outside the thermomechanically affected zone (in the heat affected zone). As the



**Figure 1.** Station for FSW welding process: *a* — tooling for plate welding; *b* — tooling for cylindrical elements

**Table 1.** Tools used during studies

Type	Shape of a tool working part	Dimensions		
		$D$ , mm	$d$ , mm	$L$ , mm
K (1)		20.0	8.0	5.8
		11.0	5.0	3.8
T (1)		20.0	8.0	5.8
		11.0	5.0	3.8

K — conventional tool, T — Triflute tool.

result of those factors more complex structure is being formed in the cross-section of the weld, which influences directly its mechanical properties [3–5]. In case of aluminium casting alloys welding, the changes in the microstructure are associated both with processes of deforming, recovery and recrystallization and also with microstructure component phase changes, e.g. with precipitation or dissolving of intermetallic phases [6]. The aim of this research was finding the relation between welding conditions: welding parameters, a tool shape, the process of forming of friction welded joint and welding quality.

**Research station.** The investigation into FSW process was conducted at Instytut Spawalnictwa on the vertical milling machine FYF32JU2 equipped with special clamps fixing the welded parts and special ISstir head constructed at Instytut Spawalnictwa for the measuring of torque and friction force. The station for testing of linear welding of plates is shown in Figure 1, *a*, while Figure 1b presents the station for welding of cylindrical or spherical elements, equipped with a special positioner. Some of the testing was con-

ducted on the station build on the basis of numerical milling machine FNC 50NC.

**Tools.** During research, the impact of several tools having different shapes and dimensions of working parts, on the process and welding quality was tested for various configuration of components being welded. The tools were made of high-speed steel S 6-5-2 [7]. The shapes and dimensions of the tools used in research are shown in Table 1.

**Tested material.** During FSW, forces and weld forming process were tested for wrought aluminium alloys, casting alloy and copper M1. Chemical composition of aluminium alloys used in the research is presented in Table 2.

**Research into FSW process.** *Testing of the tool effect on welding quality.* Research into the influence of tool shape and dimensions on FSW quality was conducted using tools for various welding parameters, enumerated in Table 1. Tests were conducted for wrought aluminium alloys, casting alloys, copper M1 as well as wrought alloy welded together with casting alloy. Obtainment of the correct weld is difficult, in

**Table 2.** Chemical composition of aluminium alloys used during studies [8, 9]

No.	Alloy denotation		Content of chemical elements, %								
	Numerical	Chemical symbol	Si	Cu	Mg	Mn	Fe	Ti	Zn	Ni	Al
1	EN AC-43200 (AK9)*	EN AC–Al Si10Mg(Cu)	9.0–11.0	0.35	0.20–0.45	0.55	0.65	0.20	0.35	0.15	Rest
2	EN AW-2017A (PA6)**	EN AW–Al Cu4MgSi	0.2–0.8	3.5–4.5	0.40–1.00	0.40–1.00	0.70	0.15	0.25	–	Same
3	EN AW-6082 (PA4)	EN AW–Al SiMgMn	0.7–1.3	0.1	0.60–1.20	0.40–1.00	0.50	0.10	0.20	–	»

\*Aluminium casting alloy.

\*\*Wrought aluminium alloy.

**Table 3.** Welding parameters

Parameter No.	Material from advancing side	Tool movement parameters		Notes
		$\omega$ , min <sup>-1</sup>	$V_{zg}$ , mm/min	
1	EN AC-43200	560	280	Correct weld face. Linear discontinuity
3	EN AC-43200	900	180	Correct weld face and structure
6	EN AW-2017A	560	280	Correct weld face. Linear discontinuity
9	EN AW-2017A	450	560	Correct weld face and structure. Very small imperfections
10	EN AW-2017A	900	560	Correct weld face. Linear discontinuity
11	EN AW-2017A	560	280	Uneven weld surface. Correct weld structure
14	EN AW-2017A	450	180	Correct weld face and structure
15	EN AW-2017A	900	560	Correct weld face. Linear discontinuity
16	EN AC-43200	900	180	Correct weld face. Linear discontinuity
19	EN AC-43200	900	560	Incorrect weld material stirring. Large wormhole cavity

particular in case of welding of dissimilar materials. Selected sets of parameters used while welding of wrought alloy EN AW-2017A + casting alloy EN AC-43200 are shown in Table 3.

During testing the process of weld face forming, material subjected to the strains and deformations, quality of the surface and weld structure were analysed. The example of a weld surface is shown in Figure 2.

*Testing of friction forces.* In FSW process the change of mechanical energy into friction heat occurs, what makes it possible to create the conditions for welding in solid state. In this case the coefficient of friction between the tool metal and the welded plates surface is essential.

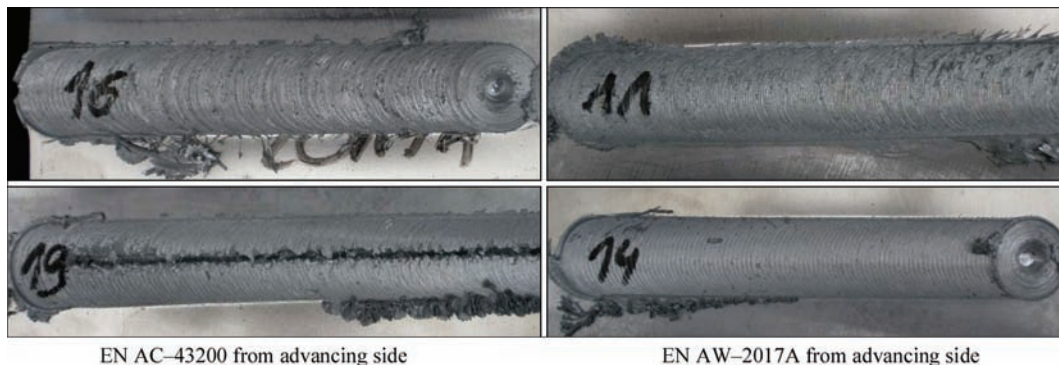
During the first stage of research into the friction phenomenon in the FSW process the impact of friction speed on friction coefficient was tested. Aluminium plates were initially preheated up to the temperature of: 350, 450, 500 and 550 °C, i.e. up to the temperature occurring in the FSW process. While measuring, the tool having a pipe shape in the working part was pressed down to the plate surface and the down force and friction torque for different tool rates of rotation were measured. The tool was made of the same tool steel as FSW tools. For the known geometrical shapes of the tool and rotational speed, it is possible to calculate the distribution of friction coefficient depending on frictional speed for various temperatures of pre-heated plates. The tests were conducted on the numerically controlled station (build on the basis of milling machine FNC 50NC) at the same times of approach-

ing and retracting the tool ( $t_{wst} = 3.0$  s) and the same friction time  $t_f = 1.0$  s.

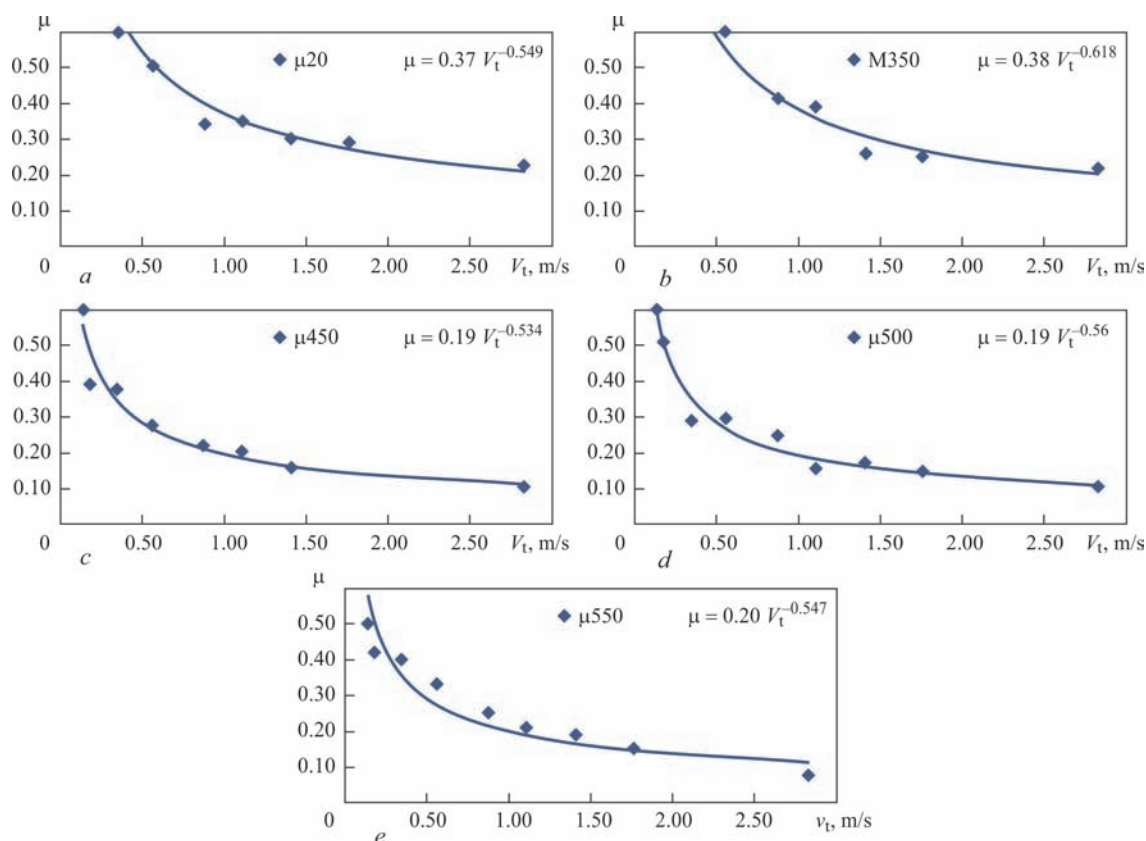
The test results for EN AW-2017A alloy are presented in Figure 3. For the remaining alloys being tested, the dependence of friction coefficient on friction speed was similar.

Similar research was conducted for FSW process in which a conventional tool, having a tool shoulder  $\varnothing 11.0$  mm and a probe  $\varnothing 5.0$  mm, was used on 4 mm thick plates of EN AW-2017A alloy, and a tool rotational speed  $\omega$  was being changed while welding speed  $V_{zg}$  remained on the same level of 200 mm/min. During making of a single longitudinal weld, the sequence of three different rotational speeds was changed twice, as in Figure 4 ( $\omega = 350, 550$  and  $750$  min<sup>-1</sup>), while measuring down force and friction torque using ISstir head. After the production of the first weld, the plates have been heated to the temperature up to 150 °C and the second welding cycle was performed with changing the rotational speed of a tool and then the plates were heated up to the temperature of 250 °C and the third welding cycle was done. The results of the measured friction torque and down force are presented in Table 4.

*Testing of metal structure in the area of tool friction during FSW process.* During this testing, friction torque (down force), that resulted from summarized frictional resistance coming from two sources was recorded. One of the source was external friction, i.e. from force of shearing micro-joints and irregularities in local friction points and second source was internal



**Figure 2.** View of the surfaces of the selected welds EN AC-43200 + EN AW-2017A obtained for various process parameters



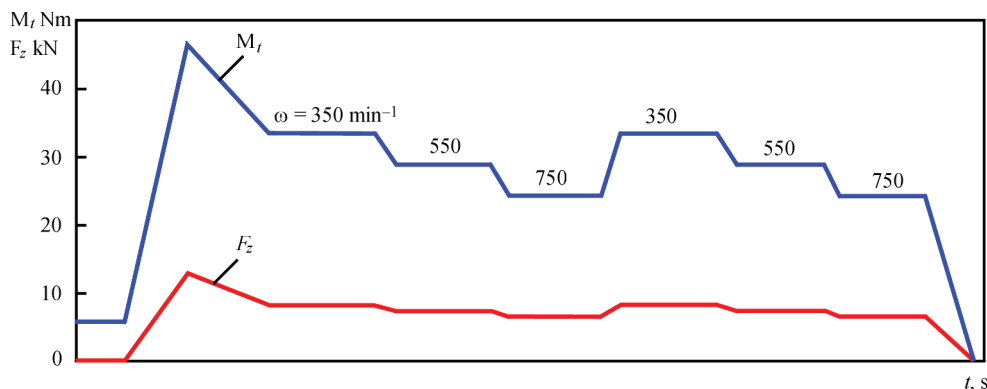
**Figure 3.** The change of friction coefficient depending on friction speed at various temperatures: *a* — 20 °C; *b* — 350 °C; *c* — 450 °C; *d* — 500 °C; *e* — 550 °C [10]

friction, i.e. from forces connected with plastic strain of the metal layer up to the certain depth.

For samples undergoing friction both phenomena are clearly visible. During testing of friction coefficient and FSW process, it can be noticed that both friction forces and thickness of material layers undergoing plastic straining depend on friction speed. The structure of a layer being modified using friction is different from that of parent material. Figures 5 and 6 shows metal deformed during the process in the area of a tool action. The area under observation includes a modified by friction layer of EN AC 43200 alloy in the cross-section parallel to the plane of welded plates, on the depth of 1 mm, in the area of tool action after its

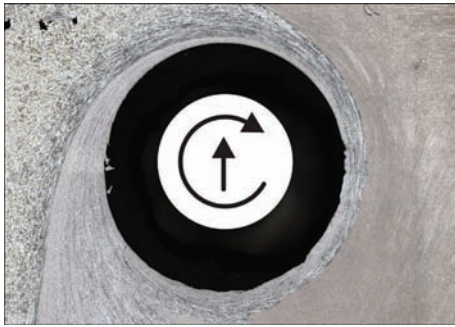
retracting. Welded plates were of EN AC-43200 + EN AW-6082, 6.0 mm in thickness.

The image of the process of metal movement around a tool and creating a weld behind a tool observed from above (from a welding machine spindle) is shown in Figure 7. Those images present cross-section of a weld made parallel to the surface of welded plates on the depth of 1.5, 3.0 and 4.5 mm below a tool shoulder, i.e. in the location of primary action of a tool probe. The shown image of a welding process has been obtained after adequate preparation of the samples in the place of rapid stoppage of a tool movement and retracting it from a weld region. The direction of rotation and translation movement of a tool is marked schematically in its position.

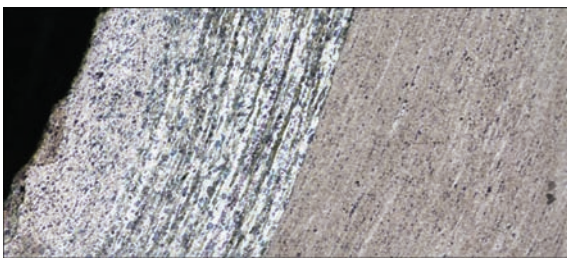


**Figure 4.** Diagram of changes of friction torque  $M_t$  and down force  $F_z$  during testing of welding process with changing of frictional rotation speed of a tool [10]





**Figure 5.** Metal layers around a tool. Friction modified layer located in the direct vicinity of a probe. EN AW 6082 alloy from a retreating side (right side), EN AC 43200 alloy from advancing side (left side) extruded around a tool probe during FSW. The direction of rotation and translation movement of the tool is marked schematically



**Figure 6.** Fragment of the modified layer of Figure 5 on retreating side

As can be seen in the above images, material is extruded around a tool on the retreating side, in accordance with the tool probe rotation. Along the tool probe the material from retreating side penetrates into the material from the advancing side on various depth. The observed image of the structure being created is obtained after stoppage of a translation movement and rapid retraction of a tool from the welding area.

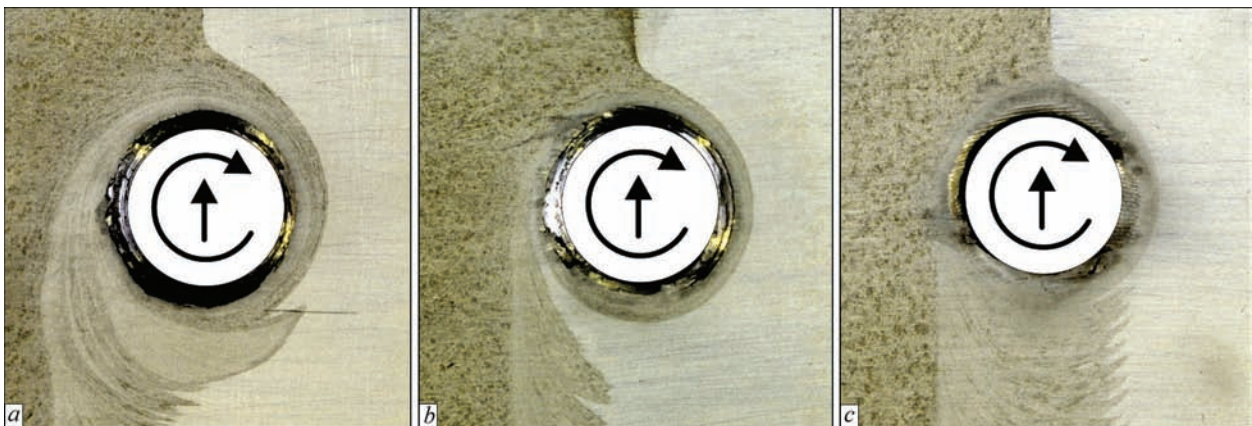
Around the tool, on the retreating side, the material is moved backwards through a relatively wide area of plasticised layer towards the weld being created. This phenomenon is clearly visible at low tool rotational speeds (low friction speeds) which is accompanied by high friction forces. In the case of high tool rotational

**Table 4.** Results of measuring friction torque and down force recorded while testing of FSW using preheated plates [10]

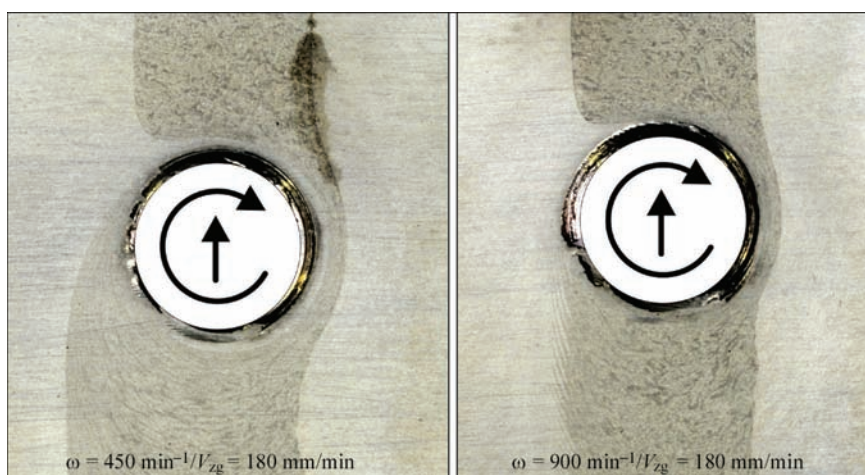
Measure No.	Temperature of plates prior to the process, °C	Tool rotation speed $\omega$ , $\text{min}^{-1}$	Friction torque $M_f$ , Nm	Down force $F_z$ , kN
1	20	350	35.4	8.7
2	20	550	30.5	7.8
3	20	750	25.7	6.9
4	20	350	37.1	9.0
5	20	550	29.2	7.3
6	20	750	25.1	7.1
7	150	350	33.8	8.0
8	150	550	29.0	6.9
9	150	750	23.4	6.6
10	150	350	33.7	7.7
11	150	550	28.0	6.8
12	150	750	24.8	6.7
13	250	350	35.1	8.3
14	250	550	27.4	6.9
15	250	750	22.8	6.3
16	250	350	33.8	7.7
17	250	550	26.9	6.7
18	250	750	23.1	6.6

speeds (high friction speeds) the forces are noticeably lower and the thickness of a layer being modified is also lower (Figure 8). Material is extruded backwards on retreating side, however is not deformed that strongly in large volume. Practically, at those high friction speeds only material from the front of a specimen is being moved backwards (in this case EN AC 43200). This phenomenon was clearly revealed while testing of FSW process using EN AC 43200 material of tool probe width, being implemented into AW 6082.

As can be seen in Figures 7 and 8, the thickness of the modified and plasticised layer during friction depends on the friction conditions and is of great significance during generating of friction heat. This friction modified layer takes part in the creation of a weld of specific structure and properties.



**Figure 7.** The image of a weld formed around a tool, observed on the depth of: *a* — 1.5 mm; *b* — 3.0 mm; *c* — 4.5 mm from weld face surface. From advancing side (left side) is located EN AC 43200 alloy, while from retreating side (right side) EN AW 6082 alloy. Welding parameters:  $\omega = 450 \text{ min}^{-1}/V_{zg} = 224 \text{ mm/min}$



**Figure 8.** A weld being created around the tool with implemented EN AC 43200 material of a tool probe width. Rotation of a tool and direction of the movement is marked in the photographs. On the right side: retracting, on the left side: advancing

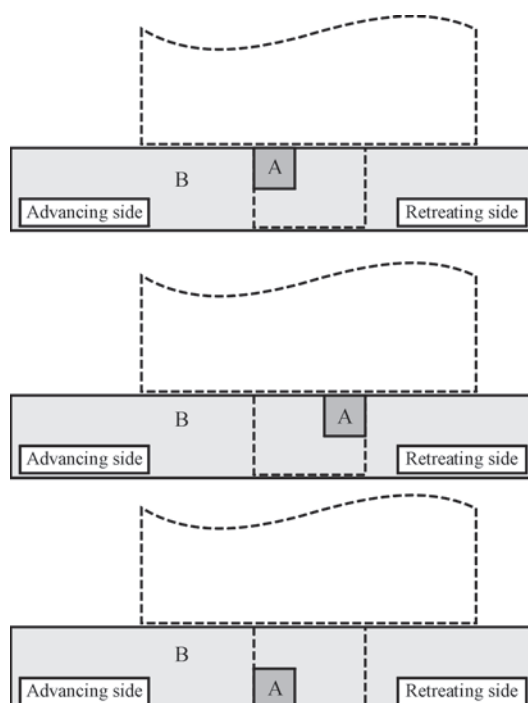
While welding material is extruded around a weld backwards, not changing its position behind the tool relative to the weld line. This phenomenon is clearly visible in the testing of FSW process using so called marker made of casting alloy. A rod of EN AC 43200 casting alloy having a dimensions of 3.0×3.0 mm was included into the material of EN AW 6082 alloy, 6 mm thick, as in Figure 9.

After welding, the location of the rod of EN AC 43200 is visible on the weld cross-sections in the separate welding areas. In case of location of a rod A on the advancing side before welding (Figure 9, a), during the process its material is moved around the tool and after welding is situated in a weld, as in Figure 10.

As can be seen in the weld structure, despite extruding material through the narrow area around the tool, the EN AC 43200 alloy (material A) is located approximately in the same weld area as before the process completion.

In case of location of a rod on the retreating side before welding (Figure 9, b), during the process its material is moved around the tool and after welding is situated in a weld, as in Figure 11. In case of location of a rod in the root area on the advancing side before welding (Figure 9, c) after welding the weld structure is obtained as shown in Figure 12.

In spite of the fact that in welding process the material being implemented was strongly heated and deformed while extruding around the tool (as in Figures 5 and 7) it successfully recreated its previous lo-



**Figure 9.** Diagram of the distribution of a «marker» of EN AC 43200 alloy (A) in the material of EN AW 6082 alloy (B) before welding using FSW process

calisation. Dissimilar physical properties of materials do not prevent localisation of material in such a way after extruding around the tool.

Some molecules coming from the material being included can be moved in a random way and injected into



**Figure 10.** Structure of FSW weld in case of location EN AC 43200 rod (A) on the advancing side (as in Figure 9, a). Welding parameters:  $\omega = 450 \text{ min}^{-1}$ ,  $V = 224 \text{ mm/min}$ . Triflute tool. Keller etching





**Figure 11.** Structure of a weld in case of location of a rod of EN AC 43200 on retreating side (as in Figure 9, *b*). Welding parameters:  $\omega = 450 \text{ min}^{-1}$ ,  $V = 224 \text{ mm/min}$ . Keller etching



**Figure 12.** Structure of a weld in case of location of a rod of EN AC 43200 in the root on the advancing side (as in Figure 9, *c*). Welding parameters:  $\omega = 450 \text{ min}^{-1}$ ,  $V_{zg} = 224 \text{ mm/min}$ . Keller etching

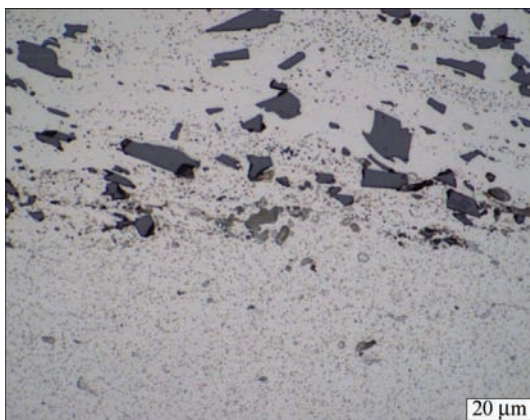
the metal matrix, however in the whole mass the substantial part of the included material do not change its location after FSW completion. Such phenomenon occurs during welding with relatively low frictional speeds of a tool. For high rotational speeds, especially while using a tool with screwed probe the process of metal extruding is more complex [3, 6, 11, 12].

The structure (Figure 13) reveals a good metallic bonding between EN AC 43200 alloy layer (from the top) and material matrix of EN AW 6082 alloy. For many places in the weld structure from Figs. 10–12 the SEM-EDS analysis was conducted. The exemplary results of the analysis are shown in Figure 14.

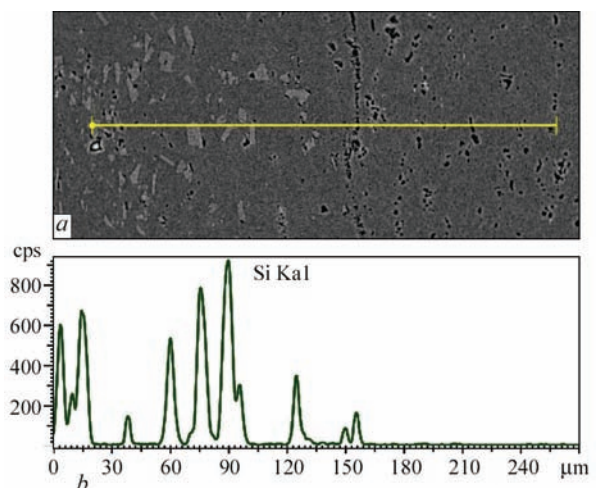
The area subjected to the significant strains and deformations was tested from the viewpoint of the average size of the particle and shape factor. In Figure 15 histograms of the particles occurrence frequency in separate intervals of shape factor are presented. In parent material (Figure 15, *a*) very elongated particles dominate — 12.8 % particles have shape factor below 0.1 and 54 % particles below 0.3. For the tested area

of a weld (Figure 15) only 13.5% particles have the shape factor below 0.3, whereas the particles of shape factor between 0.3–0.8 are the dominant (68.4 %). The research results have indicated that plastic deformation occurring while welding caused very high refinement of particles and changed their shape towards particles being more equiaxial.

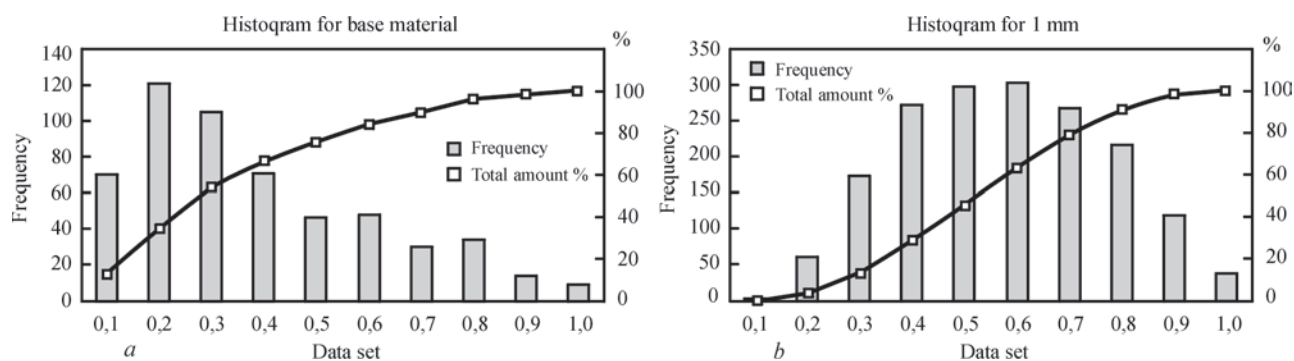
The results of conducted research into the process of friction welded joints forming together with testing of their mechanical properties were used while developing FSW process conditions for welding components in the industrial practice. Such elements, for which FSW technology was developed at Instytut Spawalnictwa, basing among other things on the research mentioned above, are the following (Figure 16): components of pneumatic cylinder of EN AW-2017A alloy, heat exchangers of EN AC 43200 casting alloy



**Figure 13.** Fragment of a structure from Figure 9. Bonding of metal layer of EN AC 43200 with EN AW 6082 alloy



**Figure 14.** Boundary between EN AC 43200 alloy (on the left side), and EN AW 6082 alloy (on the right side); *a* — line, along which the analysis of chemical content SEM-EDS was conducted; *b* — Si concentration along measuring line



**Figure 15.** The measurement of grain size in parent material of casting alloy (*a*) and in material subjected to the strains and deformations (*b*)

and EN AW-6082 alloy as well as copper M1, balls for check valves of EN AC 43200 casting alloy, M1 copper contact rails and others [13].

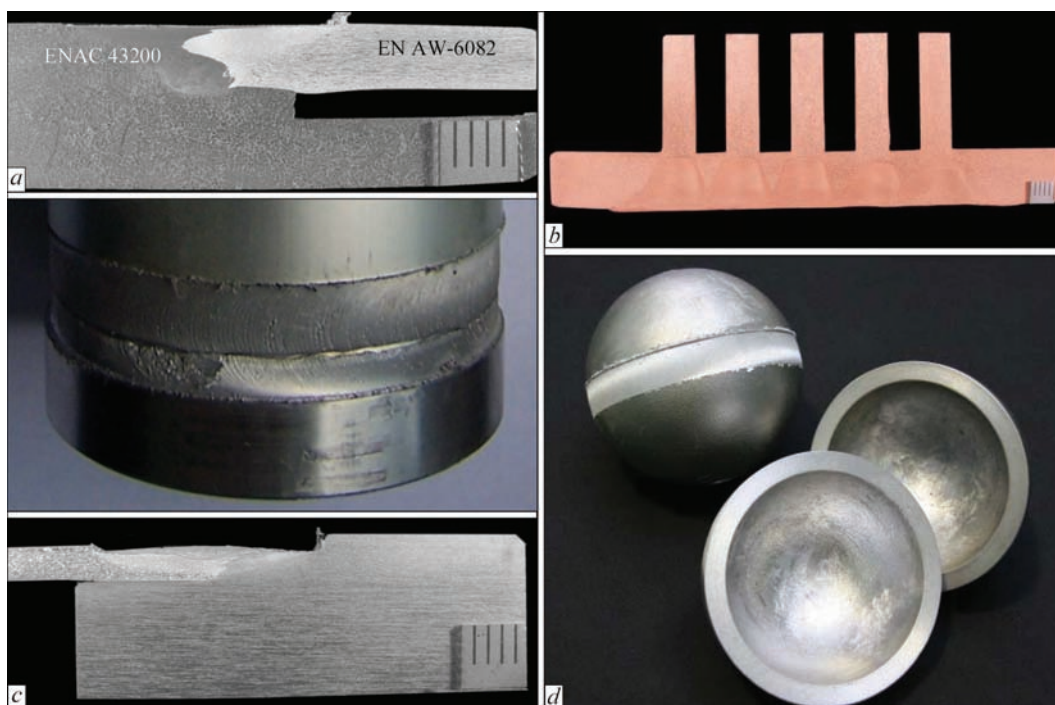
**Summary.** While using FSW process it is possible to join various materials, including materials of significantly different physical properties. During testing, application of two alloys being able to be joined but differing in chemical composition and properties, like EN AC 43200 casting alloy and wrought alloy EN AW 6082, proved useful. Placing materials from the retreating or advancing side enables observation of the process of heating and creation of the weld structures. Casting alloy used as a marker made it possible to observe the process of metal movement around the tool and the structure of the FSW joint.

As it was revealed [6] during the FSW process the largest amount of heat is produced as the result of tool shoulder action, however the proper structure of a weld in the whole thickness of the components being joined, in case of elements thicker that approximate-

ly 2.0 mm, depends on the shapes and dimensions of the tool probe and its movement. For thin elements the probe is not playing the crucial role in the process of the weld formation. The tool moving and plunging into the material starts to heat and plasticise various material zones. Heat in the welding process, as a result of good conduction is heating also material before a tool, what facilitates plunging a tool into the material preheated to the certain temperature.

The research revealed that with increasing the friction speed the friction factor  $\mu$  is reduced during working of a tool on each tested material and in all temperature conditions.

At temperature higher than 400 °C, i.e. in the temperature range observed in FSW process, for higher frictional speed the change of friction factor value along with changing temperature does not practically occur. This results in the fact that at higher frictional speeds such a friction conditions are stabilised in the friction interface, that the temperature of the plate (base) does not



**Figure 16.** Examples of the application of FSW process [12]: *a* — heat exchanger cross-section; *b* — cross-section of an electrical connector made of M1 copper; *c* — components and cross-section of a weld in pneumatic cylinder of EN AW-2017A alloy; *d* — components of balls for check valves of EN AC 43200 alloy



influence significantly the friction process and associated friction forces. At high temperature of the plates, friction forces are relatively low. For low frictional speeds, temperature has an impact on friction force value.

The above presented research revealed that during conducting typical FSW process the temperature of plates being welded has little influence on the friction torque. In turn, rotational speed of a tool influences it significantly. It can be however noticed, while analysing the research results, that tool rotational speed has an impact on the down force. During testing, it was not assumed that the process would be conducted at the same, constant down force. Down force value in this case is a resulting value and is associated with a tool leading in such a way, that the weld face is formed correctly.

As can be noticed, for growing frictional speeds of a tool, down force is being reduced. It is associated, as can be concluded, with heating of the material in the friction zone, which for higher frictional speeds is being heated more intensively, causing the reduction of mechanical properties of metal and consequently, the reduction of down force recorded by measuring head.

Thus, frictional speed has an impact on friction processes, it is associated with temperature of metal in friction zone and this metal temperature, in turn, influences in a certain way the down force of a tool (in a tool axis). However, temperature of plates fails to influence clearly the value of friction force (friction torque).

Beside temperature, which undoubtedly influences friction processes, the second factor which should be taken into consideration in the analysis of the processes occurring while forming of the FSW joint, is a layer of metal being modified using friction processes and undergoing plastic distortion.

By the action of a tool in the conditions of friction heating and upsetting, the metal layer in the direct vicinity of a tool undergoes thorough modification. Research revealed that it is a region of very high refinement of grains having a shape factor 0.4–0.7 (Figure 15) and undergoing dynamic recrystallisation and/or healing.

The analysis of friction force courses (friction coefficient), structures of material layers being modified and temperature in the friction area has revealed that overall friction forces, recorded during testing (e.g. friction torque), more depend on the thickness of a layer undergoing modification and distortion, (i.e. internal friction) and in lower extend on external friction, that is on conditions in the friction interface: tool — welded metal. In turn, the thickness of a layer undergoing plastic deformation in which internal friction occurs, depends on friction speed. The higher friction speed the thinner layer [10].

The research into friction welding quality in a straight majority of cases shows, that metals coming from retreating and advancing side, modified with friction process and upset against each other on the retreat-

ing side, while movement backwards are joined correctly. Depending on the welding process parameters as well as applied tool and thickness of the plates being welded, the area of limited metal coherence can be located behind the tool on the advancing side [10, 12, 14].

The manner of the metal transfer around the tool significantly influences the structure of FSW joint. As can be seen, at the specimens with included casting alloy, strongly heated and deformed material during extruding around the tool effectively recreated its previous localisation. Dissimilar physical properties of materials on both sides of a tool (advancing and retreating sides) proved not to prevent such a systematic placement of material after the process of extruding backwards.

Research into average size of the particles and the shape factor of the material subjected to the strains and deformations shown that FSW process caused very high refinement of particles and changed their shape towards particles being more equiaxial.

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