Mirosław Nowak, Paweł Szostek, Marcin Nowak

Extended Friction Stir Welding Applications and the Use of an Innovative FSW Head

Abstract: The article presents general information about friction stir welding process (FSW) as a welding method involving the stirring of the weld material, discusses the course of the welding process itself, describes the structure of the FSW joint, presents advantages and disadvantages of the method as well as discusses factors affecting the quality of FSW joints. In addition, the article describes an innovative FSW head (designed by Stirweld (France) and installed on CNC machines) as well as illustrates the operation of the head and enumerates the advantages resulting from the use of the head in comparison with those characteristic of "conventional" friction stir welding machines.

Keywords: friction stir welding (FSW), process parameters, aluminium, tools, FSW head

DOI: 10.17729/ebis.2022.5/7

Introduction

The years 1991–1995 saw the development of the friction stir welding method (FSW) at the Welding Institute (TWI) in Cambridge, the UK. The method, combining friction welding and the stirring of the weld material, was patented in 1995. The FSW patent was bought by the ESAB company, which has used the method on special gantry-type machines. The FSW method is applied primarily to join elements made of aluminium and its alloys, yet it also enables the joining of other material configurations such as aluminium and copper or aluminium and steel. In the friction stir welding process, the joining takes place through the zonal stirring of two elements in the solid plasticised state. The FSW process usually occurs at temperature by approximately 30% higher than the melting point of aluminium or its alloys, thus generating significantly smaller deformations than those characteristic of the TIG or MIG welding processes. The significant plastic deformation, resulting from the tool operation, enables the obtainment of joints characterised by the fine-grained and recrystallized structure.

The mechanical properties of FSW joints are usually higher than those obtainable using the TIG and MIG methods. In addition, FSW joints are characterised by even higher mechanical properties when compared with those obtained using the laser beam welding technique [1].

The variants of friction stir welding include friction stir spot welding (FSSW) and refilled friction stir spot welding (RFSSW) (Fig. 1).

Terminology used in FSW [1]

Figure 2 presents basic names and terms used in the FSW process.

inż. Mirosław Nowak (IWE), mgr inż. Paweł Szostek (IWE), Marcin Nowak – Technika Spawalnicza, Poznań

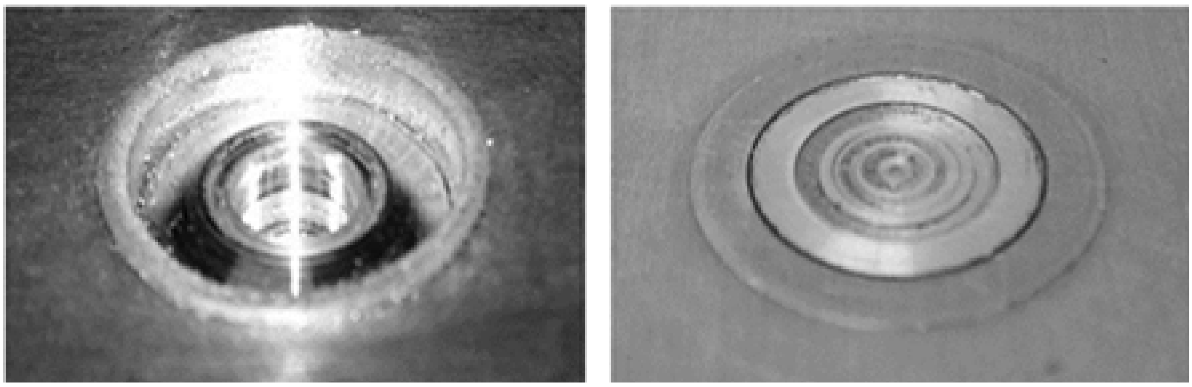

Fig. 1. Variants of the FSW process: FSSW (left) and RFSSW (right)

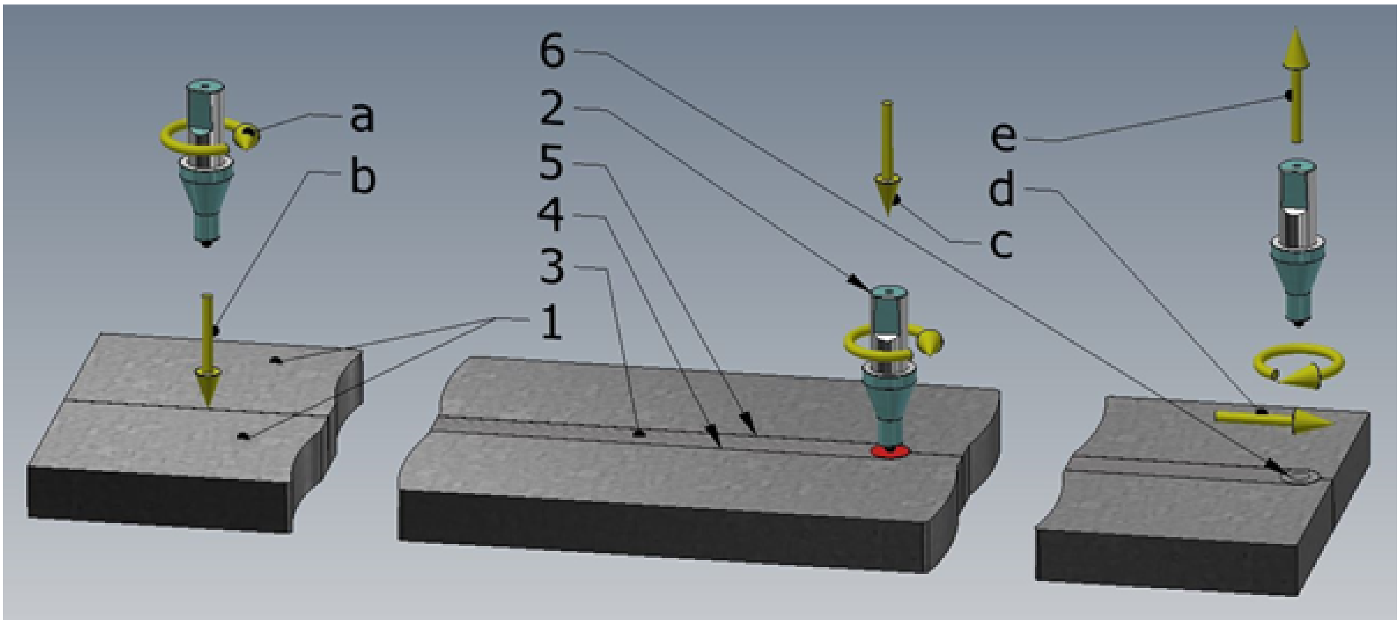

Fig. 2. Basic names and terms used in relation to the FSW process [own elaboration];
Position: 1 – elements being joined, 2 – tool, 3 – weld surface, 4 – weld retreating side, 5 – weld advancing side, 6 – outlet: a – direction of tool rotation, b – direction of tool penetration, c – axial force, d – welding direction, e – direction of tool exit

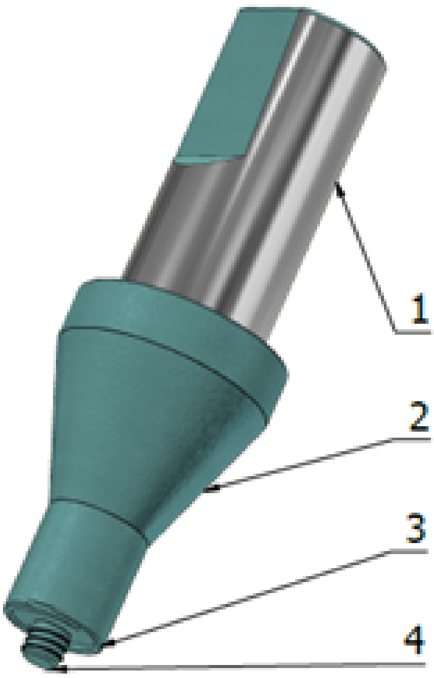

Fig. 3. View of the FSW tool [own elaboration]

FSW tool

Figure 3 presents elements of the FSW tool. The FSW tool consists of the following elements:

- grip (1),
- housing (2),
- shoulder (3),
- pin (4).

Tools used in linear friction stir welding (FSW) and friction stir spot welding (FSSW) must be adapted for operation in solid metallic environments, where forces of pressure and friction are used to overcome the form resistance of materials subjected to joining. The extremely difficult operating conditions of FSW tools necessitate the latter to be made of special materials, characterised by the following features: [2]

- small changes of properties (hardness, structure, abrasibility, etc.) and shapes at high temperature,
- low linear and volume thermal expansion,
- invariable friction coefficient within the wide range of welding rates and that of temperature,
- crack resistance,
- resistance to local surface pressure,
- low sensitivity to the presence of variable (tensile and compressive) stresses originating from rotation bending,
- material formability and surface processing,
- long failure-free service life and price-related availability.

The selection of tool material groups for FSW/FSSW tools is limited and based primarily on alloys of high-strength and high-melting metals such as tungsten, rhenium, cobalt, titanium, iridium, nickel or on ceramic materials such as PCBN, WC and composites [2].

FSW process

The FSW process consists of four separate stages presented in Figure 4 [4].

- Stage 1 – firm fixing of elements to be joined and the correlation of positions of the elements with the vertical axis of the FSW tool in the position initiating the process.
- Stage 2 – vertical insertion of the FSW tool pin (at a tool rotation rate of up to 5000 rpm) deep inside the elements being joined. The highest quality of FSW joints is obtained where the length of the pin is smaller (by between 0.15 mm and 0.4 mm) than the thickness of elements to be joined.
- Stage 3 – heating of elements (being joined) in the zone of the penetration of the tool as a result of friction exerted by the pin and the shoulder against the material of the elements. After the stabilisation of temperature, the tool moves in a linear manner at a preset travel rate along the elements being joined. During the linear movement of the FSW tool, (pressure) force is controlled within the range of 3 kN to18 kN [4]. Heat generated by friction plasticises the materials being joined and the tool stirs them. The welding of the materials takes place in the solid (plasticised) state, without melting.
- Stage 4 – tool exits the joint at the end of the fusion line, leaving a technological process hole. The joint should be designed so that the aforesaid hole is located at a specific point. Afterwards, the hole can be "closed" using the TIG method or by applying a more advanced technology with the so-called extendable pin, eliminating the above-named imperfection. The application of the FSW process leads to the formation of small weld collar, which is best removed by milling. The

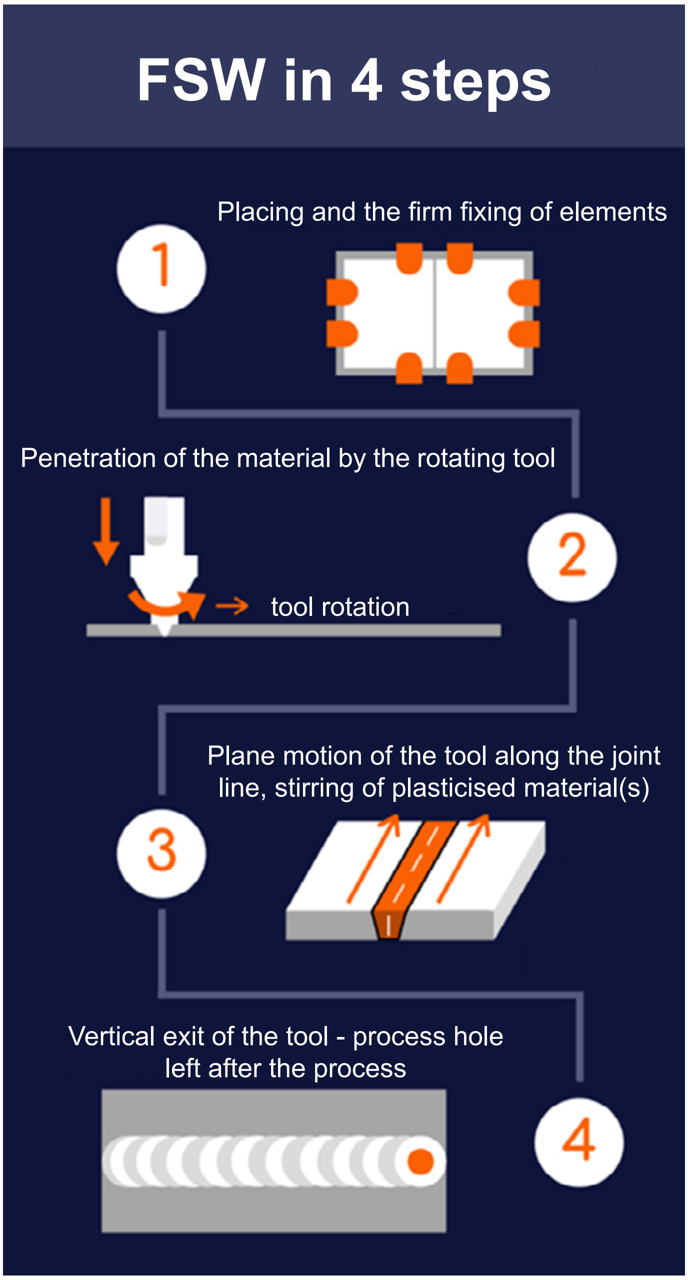

Fig. 4. Stages of the FSW process [4]

procedure consists in the manual removal of the tool and the fixing of a special milling cutter. The tool can also be removed automatically using a dedicated station.

FSW joint characteristics [1]

The structure of the FSW joint contains the following zones (Fig. 5):
- parent material (PM, also known as the base material) is the material located away from the weld, which was not deformed during the FSW process. The parent material could be affected by the thermal cycle during the welding process, yet without triggering changes of the microstructure and mechanical properties,
- heat affected zone (HAZ) is the area where heat emitted during the process led to changes of the microstructure and mechanical properties, yet without the generation of plastic strains,
- thermomechanically affected zone (TMAZ) is the area where the material is deformed plastically by the rotating and moving tool and affected by heat generated during the process. The thermomechanically affected zone contains a clearly visible boundary between the recrystallised zone (weld nugget) and deformed thermoplastic zones.
- weld nugget (WN) is the recrystallised area (also known as the dynamically recrystallised zone) directly affected by the pin during the welding process and characterised by fine equiaxial recrystallised grains [1].

In the FSW joint it is possible to distinguish two characterised sides, i.e.
- advancing side, where the direction of FSW tool rotation is compatible with the direction of welding,
- retreating side, where the direction of FSW tool rotation is opposite to the direction of welding.

Figure 6 presents the distribution of temperature during the friction stir welding of aluminium alloys.

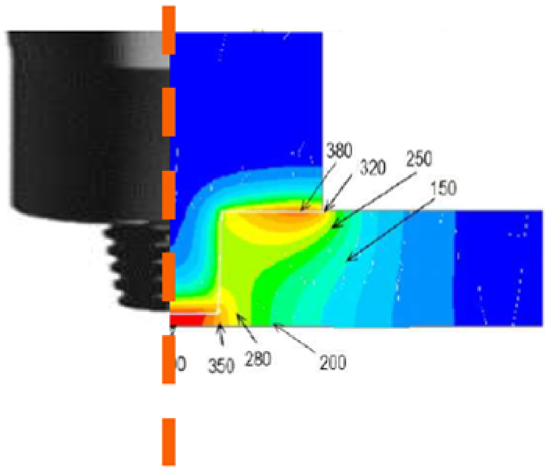

Fig. 6. Distribution of temperature in the FSW process [4]

Obtainment of high-quality joints

Presented below are the four primary criteria related to the obtainment of high-quality welds [4].

1. Clamping system and fixtures (Fig. 7)

During the FSW process, the key roles are played by the clamping system and fixtures,

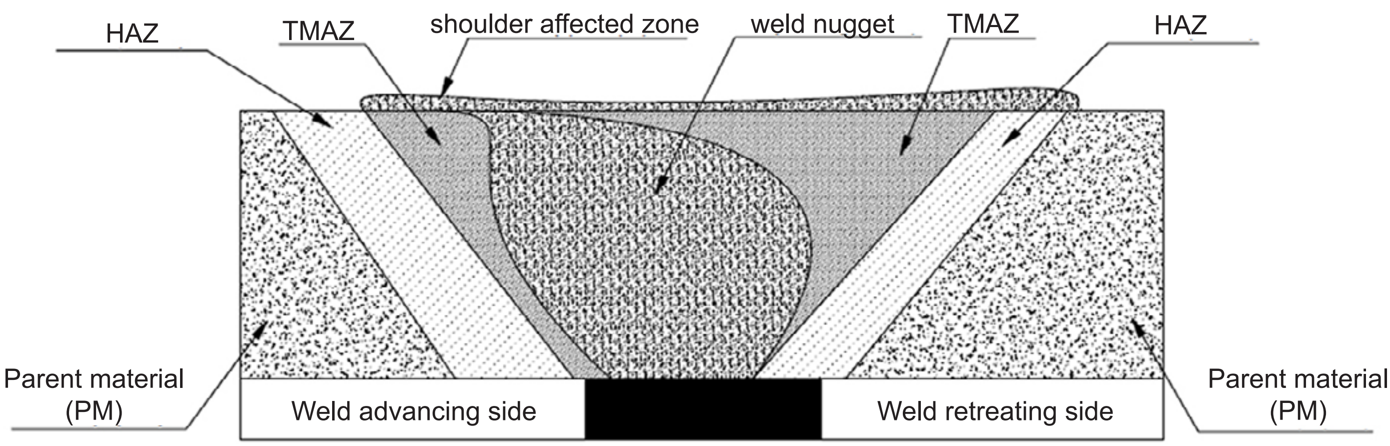

Fig. 5. Characteristics of the FSW joint [1]

responsible for providing appropriate rigidity and preventing the uncontrolled displacement of elements during the process. The clamping system along with fixtures must be designed in a manner ensuring the collision-free linear movement of the tool.

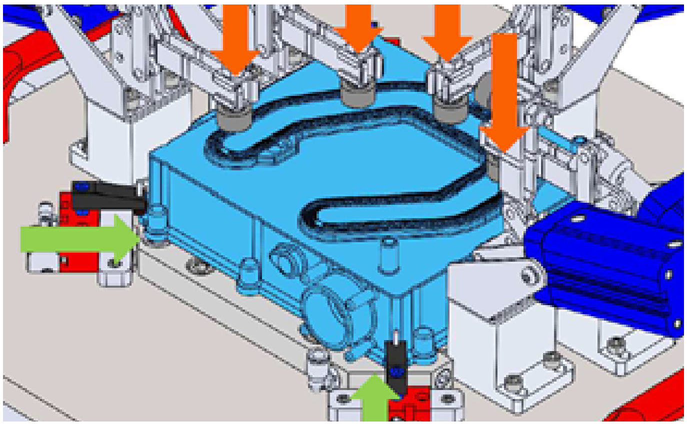

Fig. 7. Exemplary clamping system used in the FSW method [4]

2. *Tool geometry (Fig. 8)*

The FSW tool geometry is responsible for the proper distribution of the temperature field in the joint area as well as for the proper axial (and also radial) transport of the material plasticised around the tool. There are many pin geometry-related solutions, yet the most common one involves a truncated cone with a line incised around its circumference (in a manner resembling a thread line) as well as incisions made on the element of the cone. The geometry of the pin can also be based on the shape of pyramids or truncated prisms. More complicated tools enable the obtainment of joints without the so-called dead welding zones, characterised by high operational quality. The geometry of the shoulder translates into the obtainment of process temperature and prevents the outflow of the plasticised material from the joint zone. The smooth surface of the shoulder leaves the smallest relief on the weld face after the run of the tool. However, the significant outflow of the material from under the shoulder in the retreating side may also take place. The application of grooves on the shoulder surface provides additional space for the material and slightly increases the intensity of the plastic strain near the weld surface [2, 5]. The analysis and the geometry of FSW tools are discussed in detail in publications [3, 5]. Exemplary pin and shoulder-related geometry solutions are presented in Figure 8.

3. *Tool force control*

Semi-finished products made of aluminium are supplied with a workmanship tolerance of approximately 0.5 mm. Heat generated during the process is responsible for additional material deformation of between 0.5 mm and 2 mm.

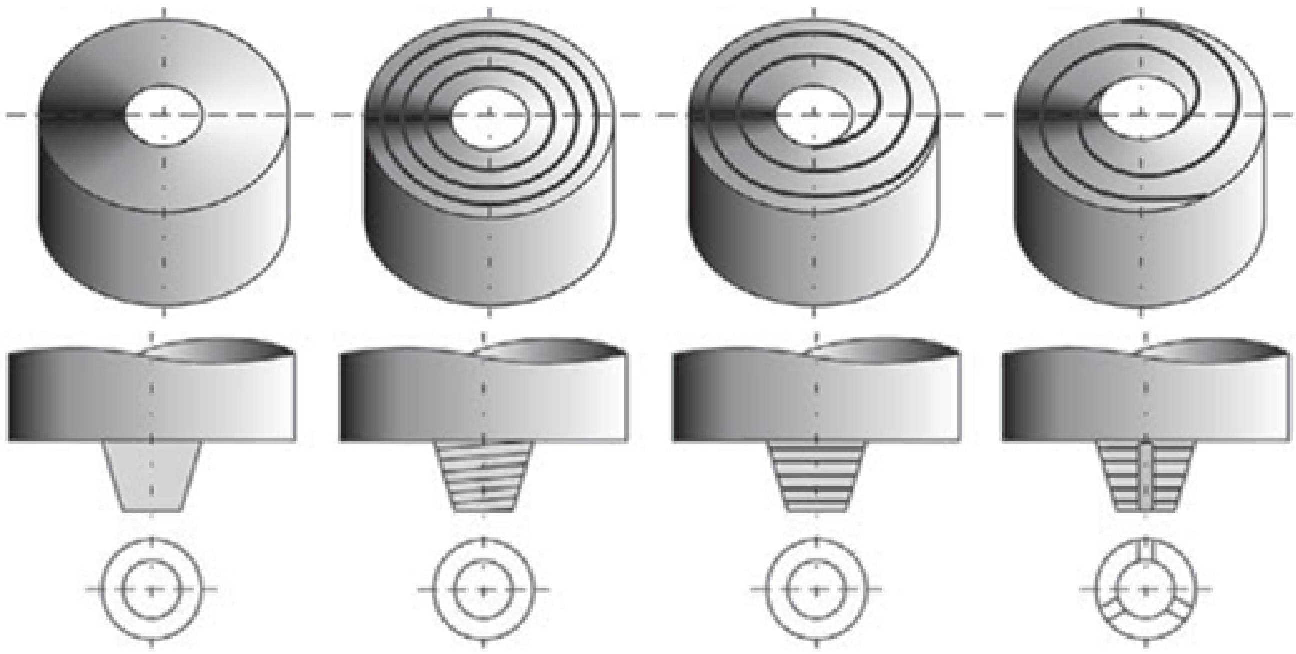

Fig. 8. Structural solutions of FSW tools used in industry [5]

However, the FSW process requires a z-axis positioning accuracy of ± 50 μm. Failure to prevent the aforesaid dimensional changes affecting the joint area leads to the formation of welding imperfections such as weld collar (if the penetration of the tool is excessively deep) or a groove on the weld face surface (if the penetration of the tool is overly shallow). The formation of the above-named imperfections can be prevented by using a system enabling the measurement and control of tool (pressure) force in the z-axis (see Figure 9).

4. Welding parameters

The most important FSW parameters include the tool rotation rate, the linear welding (travel) rate, the tool (pressure) force in the z-axis as well as the angle of tool inclination. All of the parameters depend on grades of materials subjected to joining, thicknesses of sheets/plates and the structure of the joint. In each case, the aforesaid parameters should be adjusted by performing pre-manufacturing tests and welding procedure qualification in accordance with the EN ISO 25239 standard.

4.1. The tool rotation rate (up to 5000 rpm) affects the temperature of the welding process and, consequently, the quality of the weld itself. The tool rotation rate should be adjusted depending on the type of a material to be welded as well as its thickness. For instance, an increase in the amount of heat resulting from the increased tool rotation rate and, consequently, of the temperature of the tool itself, leads to the situation where the material subjected to welding tends to stick to the shoulder surface, thus leading to the increased roughness of the weld face surface and the formation of surface imperfections [1]. The tool rotation rate affects directly the stirring of elements being joined around the tool pin. An increase in the tool rotation rate is accompanied by an increase in temperature (as a result of intensified friction) [4]. The tool rotation rate should be correlated with the linear travel rate. The maladjustment of the tool travel rate and the tool rotation rate leads to the formation of imperfections inside the joint [5].

4.2. Similar to the tool rotation rate, the linear welding rate (up to 2 m/min) is adjusted in relation to types of materials to be joined and their thickness. An increase in the tool travel rate (in relation to the constant tool rotation rate) changes mechanical properties of joints by decreasing temperature in the joint area. In extreme cases the forgoing could preclude the stirring of the material and the formation of the so-called worm holes (welding imperfection) [1].

4.3. Tool (pressure) force (of approximately1 kN per 1 mm of sheet/plate thickness). The adjustment of tool force depends on types and thicknesses of elements to be joined as well as on tool geometry (particularly the tool shoulder diameter). The aim is to ensure the appropriate contact of the tool (shoulder) with the surface of elements being joined and prevent the outflow of the plasticised material outside the weld [1].

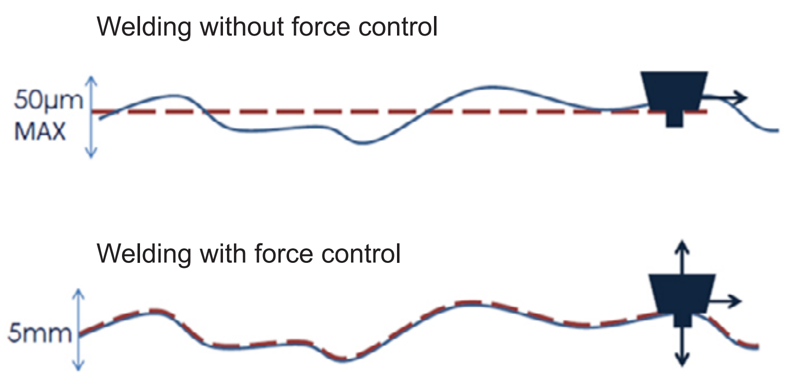

Fig. 9. Comparison of the FSW process performed with and without tool force control [4]

4.4. Tool inclination angle. The appropriate inclination of the tool in the direction of rotating tool movement makes the tool shoulder stop ("arrest") the stirred material. The tool inclination angle also translates into the uniform stirring and the movement of the material. The lack of tool inclination may lead to the formation of welding imperfections (particularly to excessive weld collar).

4.5. Tool penetration depth. The above-named parameter is strictly connected with the geometry of the tool pin (i.e. its height) in relation to the thickness of elements being joined. Excessively deep penetration may damage the surface of a device fixing the elements or even damage the pin itself (as a result of its contact with the surface). Overly shallow penetration may result in the insufficient penetration of the tool in the joint area and, consequently, could preclude the stirring of the material across the entire thickness of the elements being joined. In terms of butt welding, the length of the pin should be by between 0.15 mm and 0.4 mm smaller than the thickness of the elements.

Advantages and disadvantages of the FSW method

In the 20th century, the FSW technology constituted one of the most important achievements as regards the joining of metals. Today, in the 21st century, particularly because of the development of electromobility, friction stir welding is enjoying its spectacular comeback, being, in some cases, the only applicable joining method. The advantages of the FSW technology are both of metallurgical and environmental nature.

The most important metallurgical advantages of the FSW technology are the following:

- formation of the joint in the solid state,
- lack of shrinkage during solidification,
- very small deformations,
- very high static and dynamic mechanical properties (higher than those obtainable using the MAG and MIG methods),
- lack of hot cracks, characteristic of welding processes [3],
- significantly lower segregation of alloying elements and intermetallic phases in the joint (particularly in comparison with fusion welded joints) [3].

The most important environmental advantages of the FSW technology are the following:

- unnecessity of using welding consumables (filler metals and shielding gases) during the process,
- no emission of welding fumes, ultraviolet radiation and infrared radiation,
- significantly lower power consumption in comparison with the TIG, MAG and laser beam welding processes.

The disadvantages of the FSW technology are the following:

- limited scope of applicability – strictly dedicated solution,
- necessity of using special fixtures,
- formation of the process hole (at the final stage of the process), which must be closed using, e.g. TIG welding or a technology involving the use of the extendable pin or, alternatively, run-on and run-off plates,
- limited applicability in steel-steel types of joints.

Plug-in FSW head (Stirweld) – extended applicability of the FSW process

The Stirweld company (France) has developed a special FSW (plug-in) head (Fig. 10), mounted on CNC machines and significantly extending the applicability of the FSW method. The special FSW head is delivered with a dedicated software system, enabling the monitoring and the control of the welding process on a real-time basis.

The special FSW head can be used with nearly any machine tool satisfying the following conditions:

- fixing size: ISO 40, BT 40 or HSK 63 (or another equivalent one),
- continuous spindle power – minimum 10 kW,
- minimum torque – 50 Nm at 1000 RPM,
- height (distance between the table and the spindle) – minimum 350 mm (head height: 315 mm),
- force transferred in the z-axis – minimum 7 kN.

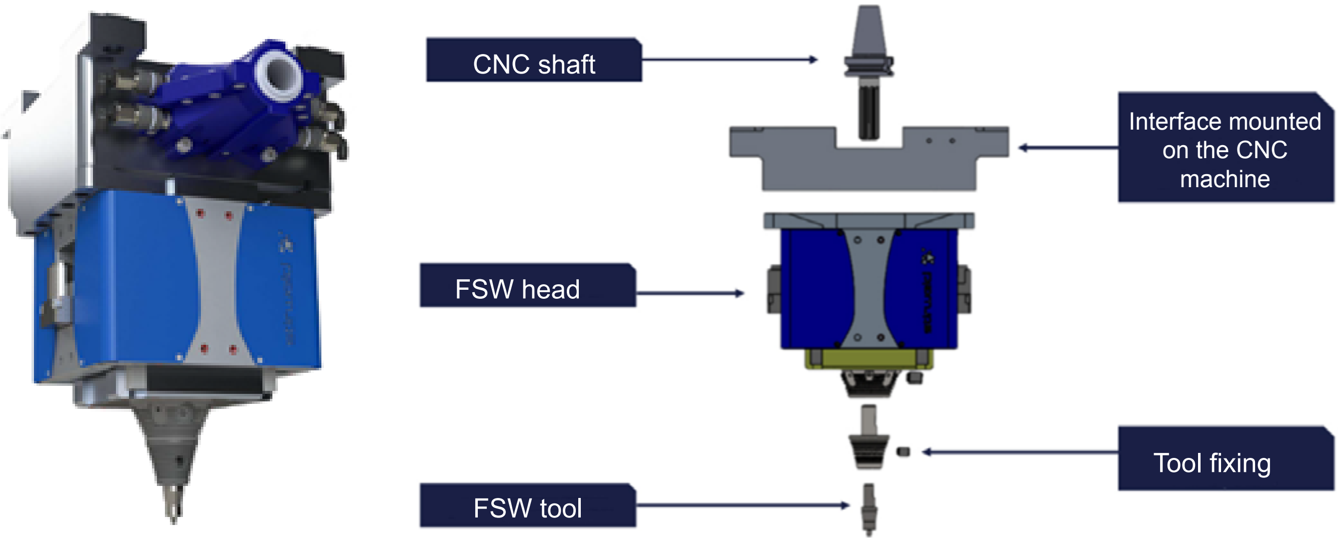

Fig. 10. FSW head by the STIRWELD company [4]

Figure 11 presents the CNC machine (left) integrated with the special FSW head (STIRWELD) (right).

1. **Special FSW head design**

Drive shaft is tasked with the transfer of drive from the CNC machine spindle to the drive system of the active part of the head. The monolithic shaft is composed of a fixing element (enabling fixing to the CNC machine) and splines, transferring the torque from the CNC machine (SK, MK, HSK). **Adapter (interface)** is fixed to the frame of the CNC machine spindle so that forces generated during the welding process are not transferred to the bearings of the CNC machine spindle. The adapter enables the positioning of the tool in the x and y-axes and is dedicated to a specific CNC machine. **FSW head (active part of the head)** is connected to electric leads as well as to control and measurement devices. The housing is provided with cooling medium and compressed air connections. The drive system inside the housing consists of barrel bearings and the drive shaft, transferring torque to the tool. To extend its service life, the system transferring torque is overmotored. The FSW head is equipped with a jaw clutch, insulating vibration (in torque – radial vibration or translational – axial). Inside the active part there is also a system measuring the force exerted by the tool.

Fig. 11. Plug-in FSW head (STIRWELD) integrated with the CNC machine: machine (left) and FSW head (STIRWELD) (right)

2. System for special FSW force control

The special FSW head features a tool positon correction functionality (± 1 mm (Fig. 8)). The force sensor also warns the operator when force exerted by the device nears the ultimate force of the CNC machine. As a result, the maximum force transferrable by the CNC machine is never obtained or exceeded. Another measurement element is a thermocouple, located near the tool and enabling the control of process temperature as well as the identification of optimum welding process parameters. The base of the active part is provided with the tool fixing system composed of a grip and the FSW tool.

3. Cooling system of the special FSW head

3.1. Air cooling system (Fig. 12 - above)

Compressed air is supplied to the special head through ducts in the working part. The outlet is located near the tool (in order to reduce operating temperature). Compressed air usually comes from the CNC machine system.

3.2. Water cooling system (Fig. 12 - below)

Cold cooling liquid from the external radiator flows through the active part and returns to the radiator container in the closed circuit. The FSW head-related requirements concerning cooling systems are the following:

- compressed air:
  - compressed air pressure: 2 bars,
- cooling liquid:
  - cooling unit power: restricted within the range of 3 kW to 3.5 kW,
  - minimum flow rate of the cooling liquid: 20 l/min,
  - cooling liquid temperature: restricted within the range of 10° to 30°C,
  - minimum container capacity: 35 l.

The special FSW head is delivered with a dedicated software programme (STIRWELD) installed on a PC (Fig. 13). The software enables the following activities:

- setting the maximum load of the CNC machine in the z-axis,
- real-time control of force exerted by the tool,

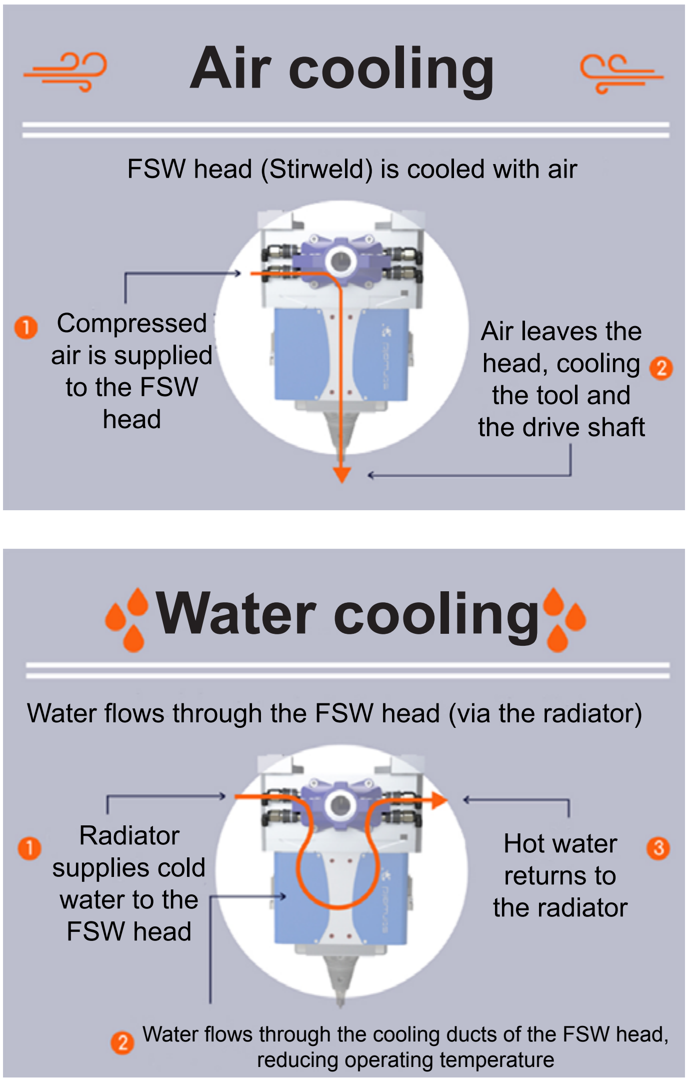

Fig. 12. Cooling systems of the FSW head (STIRWELD): air cooling (above) and water cooling (below) [4]

- setting of optimum (pressure) force,
- control of process temperature.

4. Fixing the special FSW head

The fixing of the special head on the CNC machine takes no longer than 15 minutes. Such quick fixing is possible as a result of using a special device (Fig. 14) placed on the CNC machine table during the fixing process (the device is provided with rubber feet); the CNC machine spindle does not take part in the fixing process. The tightening of bolt fasteners is followed by connecting the head to water, air and electric conduits. The stages of connecting the head to the CNC machine are presented in Figure 15.

5. Advantages of the special FSW head (Stirweld)

The special FSW head protects the CNC machine drive system from vibration and overload.

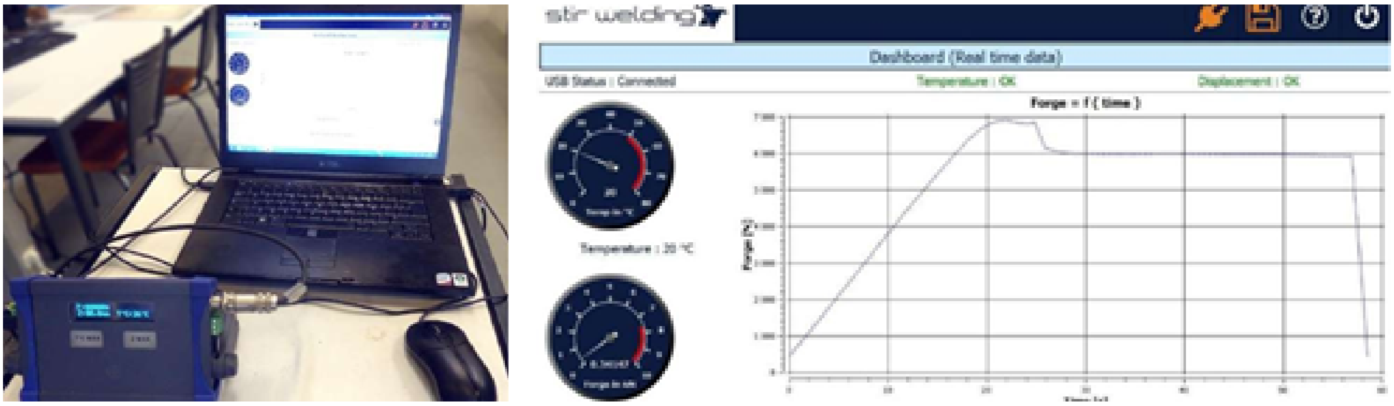

Fig. 13. Software of the FSW head (STIRWELD) [4]

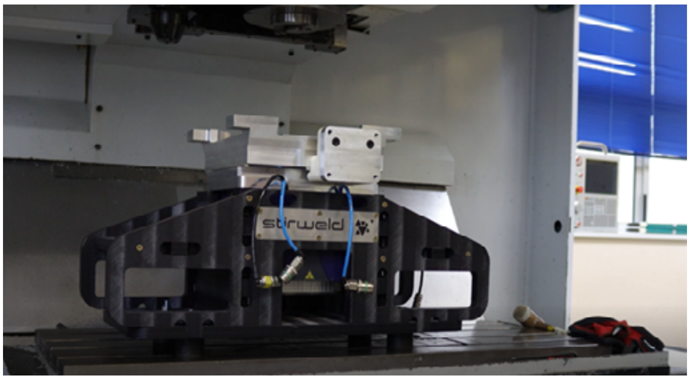

Fig. 14. Housing of the FSW head [4]

The application of built-in sensors (along with the software programme) does not necessitate any structural or programme-related changes of the CNC machine. The special FSW head enables the finishing treatment (milling) of the workpiece surface. The milling cutter can be mounted manually or automatically (Fig. 16).

The special FSW head can feature an extendable (retractable) pin (Fig. 17), eliminating the necessity of performing the spot welding of materials (to get rid of the process hole).

Another solution involves the development

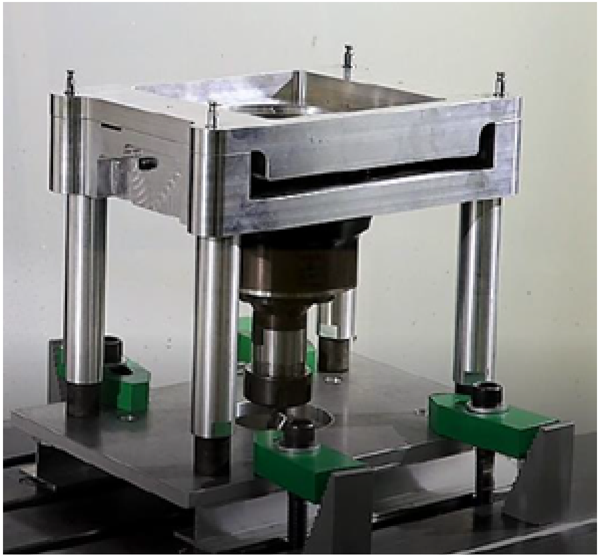

Fig. 16. Station for exchanging the tool (STIRWELD) [4]

of a special FSW head installable on industrial robots (Fig. 18), which must be characterised by high rigidity and high power of drives (possibility of 3D welding).

In addition to the sale of a selected head, the STIRWELD company helps users implement the technology by offering the following services:

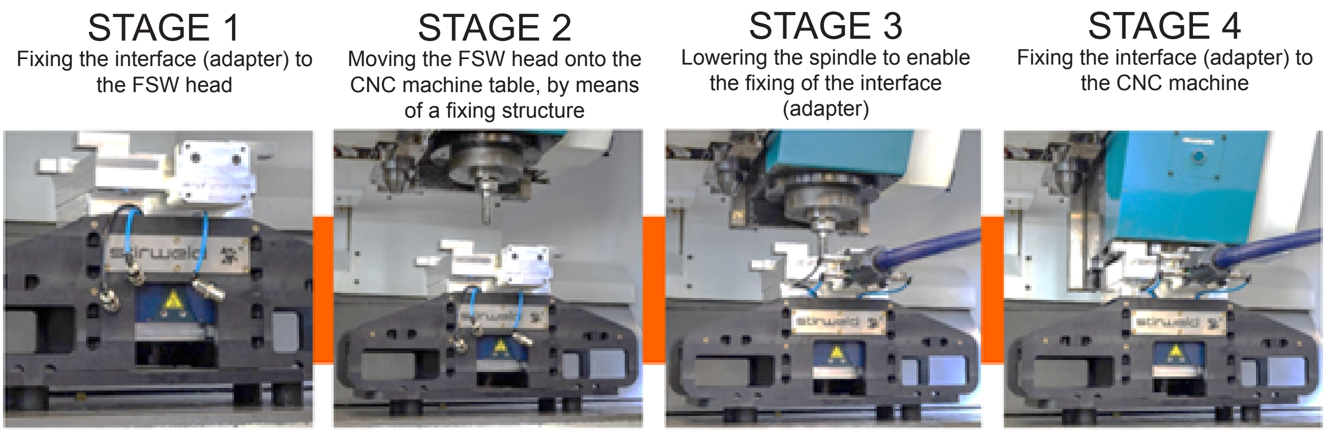

Fig. 15. Stages of the fixing of the FSW head on the CNC machine [4]

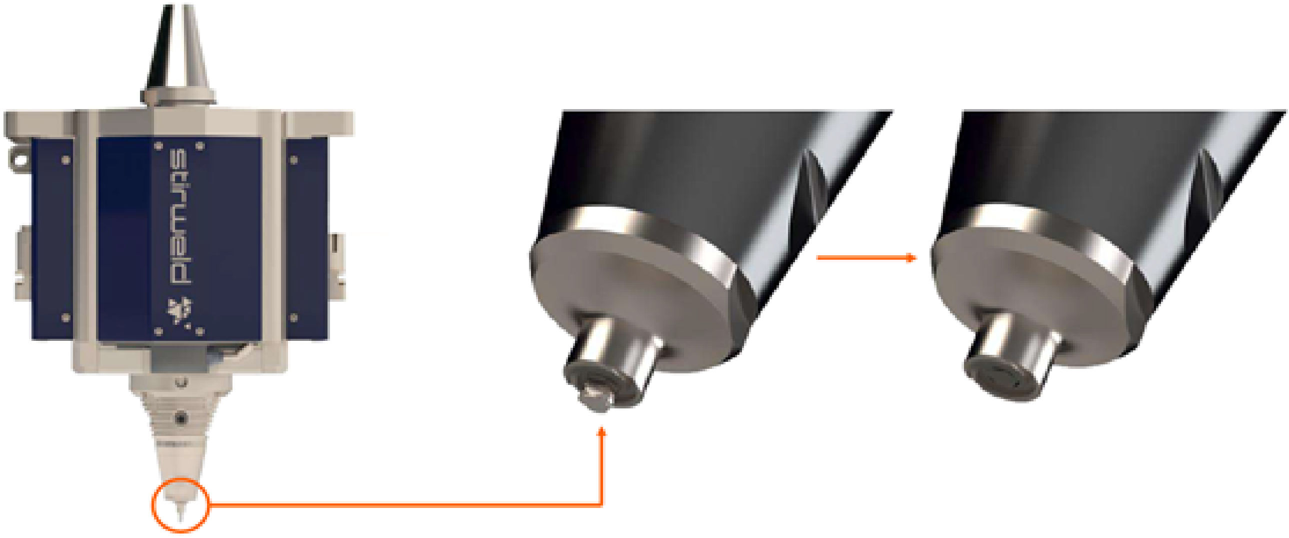

Fig. 17. Special FSW head with the extendable (retractable) pin [4]

- adjustment of proper welding parameters,
- training of personnel in issues related to process metallurgy, designs of FSW tools and imperfections formed during the process,
- design of elements used in the FSW process,
- FSW procedure qualification in accordance with the EN ISO 25239 standard,
- qualification of operators in accordance with the EN ISO 25239 standard.

An exemplary implementation is presented in Figure 19.

The general advantages resulting from the application of the FSW technology are discussed at the beginning of the article. In addition to technological advantages, significant upsides of the method include lower investment costs and short delivery times (significantly shorter than those resulting from the use of the GANTRY-type machine). The use of the

Fig. 18. Special FSW head (STIRWELD) for installation on the robot [4]

Fig. 19. Implementation by STIRWELD [4]

CNC machine and the FSW head enables the joining of materials having a thickness of up to 20 mm, which is sufficient in most applications. Because of the fact that many applications allow two-sided welding, weldable thicknesses increase by further 20 mm. The FSW head manufactured by the STIRWELD company is the only presently available device offering such high process control without intervening in the machine design.

Conclusions

1. The implementability of the special FSW head on any CNC machines will contribute to the popularisation of the FSW method.
2. The integration of the special FSW head with the CNC machine offers severalfold lower costs if compared with investing in a special FSW machine; the use of the GANTRY-type device provides notable economic advantages.
3. The disadvantages of the FSW method include the limited scope of applicability and the necessity of using special fixtures.

References

[1] Gałczyński T., Luty G.: Technologie łączenia struktur lotniczych, cz. 2, Zgrzewanie tarciowo liniowe z przemieszaniem (FSW – Friction Stir Welding). Konstrukcje Inżynierskie, 2018, vol. 11, no. 134.

[2] Wojsyk K., Kudła K.: Analiza konstrukcji i opracowanie geometrii narzędzi do zgrzewania złączy ze stopów metali metodą FSW. Przegląd Spawalnictwa, 2015, no. 10.

[3] Kuderczyk Z., Kudła K., Wojsyk K.: Właściwości zakładkowych złączy spajanych metody zgrzewania tarciowego z przemieszaniem (FSW – Friction Stir Welding). Obróbka Plastyczna Metali XXIV, 2013, no. 3.

[4] Materials of the STIRWELD company

[5] Mroczka K.: Charakterystyka mikrostruktury i właściwości zgrzein FSW wybranych stopów aluminium. Wydawnictwo Naukowe Uniwersytetu Pedagogicznego w Krakowie, Kraków 2014.