Friction Stir Soldering (FSS)

R. Cojocaru, V. Verbițchi, H.F. Daşcău, L.N. Boțilă, C. Ciucă

National Research & Development Institute for Welding and Material Testing - ISIM Timisoara, Romania

E-mail: vverbitchi@isim.ro

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1. Introduction

A new process for joining certain base metals is addressed. The process utilizes metal-metal friction for the purpose of melting the filler metal, for the soft bonding of base metal sheets, similar or dissimilar. The principle of the process consists in the thrust, rotation and travel of an active rotating element on the surface of overlapped base metal sheets, between which a filler metal is located that has a melting temperature in the range of 230-350°C, so that the friction-released heat causes the filler metal to melt and penetrate by the capillary effect into the gap between the base metal sheets, where it solidifies, making the joint of the sheets.

The authors propose the name "friction stir soldering", abbreviated FSS, for this joining process.

2. Present soldering processes

In the present technique, some processes are known for joining by soldering [1] of metals, using filler alloys, by the temperature 230 to 350°C: soldering iron-based process using fossil fuel or electric heating; electric heater gun soldering; thermostatic-controlled gun soldering; soldering in a wave alloy bath; gas flame soldering; vacuum oven soldering or bonding; controlled atmosphere oven soldering; ultrasonic - processed soldering; laser soldering; and so on.

In soldering processes a very high temperature of the base metals should not be achieved, but only the melting temperature of the filler or addition metal [2-4]. If the temperature is too high, there is even the risk of volatilising certain components of the filler alloy, resulting in non-compliance in meeting the technical requirements of the joint.

For certain soldering applications of relatively large parts, it is not necessary to concentrate the energy, but it is more appropriate to distribute the energy on a particular area, where the filler metal is added and the joining has to be made. In this case it is important to achieve a certain value of the energy density on the surface.

The use of a concentrated energy source or a too high temperature source leads to an increase in the temperature of the base metal and to some rapid temperature variations during the brazing process, which result in structural changes in the base metal that are not completely under the control of the operator. Also, the amount of heat accumulated in the base metal causes deformations of the base metal. They bring difficult technology problems, because it is necessary to straighten the base metal sheets or pieces, which requires special machinery and devices, as well as additional work time and reduced productivity that increase the cost of the work for the joining operations.

High energy processes [1] (flame, electric arc, etc.) have the disadvantage that they do not allow sufficient control over the joining process, but may cause local overheating, with the volatilisation of some components, the formation of fragile constituents because of rapid temperature variations, internal stresses and deformations of the base metals.

3. Main features of the process

A soldering process has been developed, which allows to make joints, according to certain technical requirements, using low temperature filler alloy (solder) and decanting flux, as filler materials, with low energy consumption and minimal deformation, for sheets or parts of base metal, having the thickness in the range of a few millimetres. The process is also ecologic [5-6], as it does not use or produce toxic substances or greenhouse gases, as long as the materials are environmentally friendly.

Friction stir soldering, as performed by an active rotating element, is primarily characterized by the distribution of the thermal energy generated by the metal-metal friction process onto a certain surface around the place where the active rotating element acts [5-9], depending on the process parameters, by which melting of the filler metal and its flow occurs between the sheets to be bonded, followed by the solidification of the filler metal, as the active rotating element is removed from the said area and then the metal cools, resulting a soft bonded joint without melting the base metals, under the effect of a temperature gradient between the area subjected to friction and the adjacent area. In this way, joints can be practically performed at a low temperature, with low heating of the base metal parts, relative to their entire mass, which allows deformations to be minimal.

Friction stir soldering (FSS), as a process, has a relatively high energy efficiency, because the heat generated by friction is located in the friction area and some of the heat flow can be oriented through the filler metal, before passing to the adjacent areas of the base metals and to the fastener jig, where the heat dissipation occurs. The remaining extent of the heat produced dissipates directly into the surrounding environment from the active rotating element. Compared to other processes, the FSS process directly uses a friction heat source without the need for complex transformations from other energy kinds that reduce overall yield.

The soldering process requires the base metal to be heated to a temperature below its melting temperature, but sufficient to melt the filler metal, so that it flows into the joint gap, where solidification of the filler metal occurs and the joint is made. The friction process proposed for bonding fulfils these requirements.

In view of the above aspects, the friction process [5-9], controlled by some parameters, proves to be an adequate energy source with an appropriate extent of the surface energy density, which ensures an adequate distribution of the thermal energy in the low temperature joining area.

4. Advantages of the FSS process

The advantages of the new process result from the fact that the friction stir soldering process (with the active rotating element) uses the metal-metal friction [7-9] as a non-polluting heat source with the corresponding technological effect for the distribution of thermal energy to the working area, where melting of the filler metal and its flow into the bonding gap take place, followed by the solidification of the filler metal and bonding of the similar or dissimilar base metals.

The typical linear energy of the process is relatively high, in the range of 1.6 ... 4.8 kJ/mm, achieved with less installed power of the friction joining equipment compared to other friction processes for similar applications. This allows for a suitable thermal effect and adequate energy efficiency for joining parts of certain materials (copper, brass, steel and other alloys, etc.), having thickness extents (s_1 and s_2) of 1.0... 3.5 mm, respectively, with a joint gap of at least $\delta = 0.05 ... 0.15$ mm (as a form of joint preparation), which permits the molten filler metal to penetrate by capillary effect, having the goal to execute the joint by filler metal-based soldering.

The friction stir soldering process (with active rotating element) has a direct heat input with adequate spatial distribution, according to the specific requirements of a soldering process for the purpose of melting the filler metal and its flowing into the joint gap, to achieve the joint.

The soldering process described does not produce a higher temperature than the melting temperature of the filler metal, which would cause energy losses and would reduce the energy efficiency of the process.

By the proper design and execution of the active rotating element [9] (the specific tool of the process) and of the fastener jig for the coupling parts on the working table of the friction equipment, as well as by the corresponding configuration of the coupling parts, a favourable path of the thermal energy flow can be achieved, so that it passes through the filler metal to be melted, in order to perform a suitable bonding [10-12] on the entire cross section of the gap or groove prepared for the joint, so as the energy losses by dissipation into the environment to be reduced.

The friction stir soldering (FSS) process has the following advantages:

- The FSS process produces suitable joints [10-12] using low-temperature filler metal (230 to 350 °C), located in an area of the joining gap, by means of the heat input of the metal-metal friction phenomenon, as a source of energy appropriate to the technical requirements of a soldering process that uses alloys having a relatively low melting temperature.
- The process makes adequate joints [10-12] by soldering with filler metal, without overheating the base metal parts to be joined and the filler metal. If overheating would occur, it could reduce the quality of the joint and the energy efficiency of the soldering process.
- The control over the shape, dimensions, appearance, technical characteristics and properties of the soldering joint is ensured by the following factors:

a. The parameters of the technology process of friction stir soldering: thrust force, rotational speed and travel speed of the active rotating element [5-9];

b. Shape and dimensions of the parts or sheets to be joined;

c. Shape and sizes of the fastener jig for the joining parts;

d. Design, shape, dimensions and technical characteristics of the friction joining equipment [7-9];

e. Other secondary or unnamed factors involved in the friction stir soldering process.

By properly combining all these parameters and factors, appropriate results of the friction stir soldering process, respectively adequate joints can be obtained.

- The deformation of the base metal parts that are joined by the friction stir soldering process is negligible, because the thermal energy is appropriately distributed for melting, without excessive concentration; in addition, the fastening jig for the sheets or parts to be joined prevents their deformation.
- Individual adjustments of each parameter can be performed, with its specific weight on the cumulative effects of the process.

5. Principle of the friction stir soldering (FSS)

Figure 1 shows the principle of the friction stir soldering process, using an active rotating element.

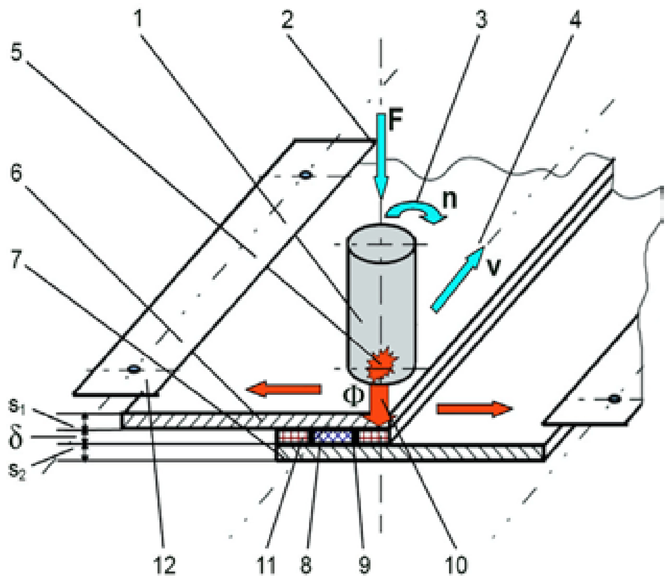

Figure 1. Principle of the friction stir soldering process.

The friction stir soldering (FSS) process is executed by means of an active rotating element (1), which exerts a thrust force F (2) of 4 … 20 kN, has a rotational speed n (3) of 600 ... 1500 rpm and moves at a travel speed v (4) of 50 ... 200 mm / min. The thrust force (2), the rotational speed (3) and the travel speed (4) are the mechanical technology parameters [1, 5-9] of the soldering process, which produce a metal-metal friction phenomenon as a local heat source (5) on a top sheet (6) of base metal of 1.0 ... 3.0 mm thickness, superimposed on a bottom sheet (7) of base metal of 1.0 ... 3.0 mm thickness. The said base metals may be similar or dissimilar. Between the two sheets there is a

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low melting temperature (230 ... 350 °C) strip, sheet or foil of filler metal [2-4] (8), placed inside a gap (9).

The filler metal melts under the effect of the heat flow Φ (10), produced by the local heat source (5), which is caused by the friction phenomenon, and then the molten filler metal flows and penetrates by the capillary effect onto the entire section of the gap (9), after which the solidification of the filler metal and making of the soldering joint (11) take place, while the heat source (5) determined by the local friction phenomenon moves away from the considered area and the soldering process continues in the next zone on the direction of the travel speed. Finally, a soldering joint is achieved, with appropriate mechanical characteristics, verified by [10-12], compliant with the requirements, without defects of the categories: lack of fusion, lack of wetting, lack of material, voids, solidification flaws, cracks, inclusions, etc., respectively without deformations of base metal parts, which is possible due to the appropriate distribution of the heat flow produced by the friction phenomenon. This favourable distribution is due to the design and execution of the following components: the active rotating element (1) as a specific tool of the process, the base metal fastening jig (12), as well as the parts of the sheets (6, 7) to be joined.

6. Results and discussions

a) FSS experiments on S235 steel

The purpose of the experiments was to obtain information regarding the possibility of applying the friction stir soldering process to joining S235 steel sheets.

Experimental conditions:

- S235 steel sheet with 3 mm thickness;
- Filler material S-Sn97Cu3, flattened wire, placed between the sheets;
- Flux type ROSOL 3, placed between the sheets;
- Soldering tool without tip and with Ø20 mm diameter shoulder made of P20S sintered tungsten carbide;
- Tool rotational speed n = 1000 rot/min;
- Tool travel speed v = 50 mm/min.

Figure 2. Friction stir soldering (FSS) process of S235 steel.

In the figure 3, the appearance of the zone processed by the FSS tool is presented.

Figure 3. Appearance of the zone processed by the FSS tool.

In the area processed by the soldering tool a clean surface resulted with roughness values close to the ones obtained after classic lathe processing (Rp = 1.2 – 2.8 μm).

Alternative samples were extracted for metallographic analysis and tensile strength tests.

Both the macroscopic and magnified (30 X) appearance of the cross section of the joint are presented in the figure 4.

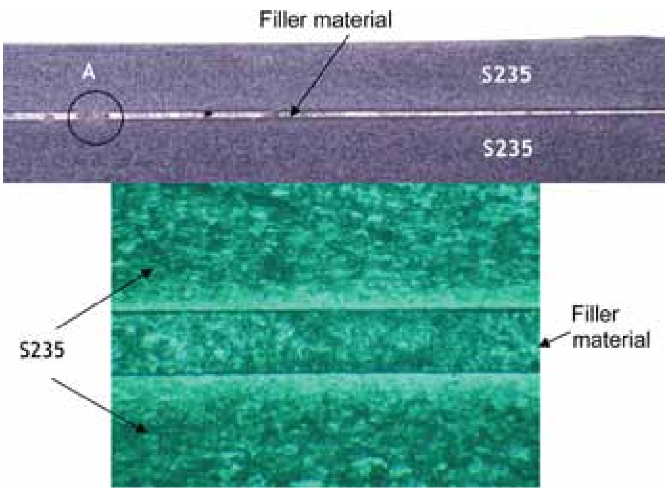

Figure 4. Macroscopic appearance of the samples extracted at 15 mm away from the start of the soldering process.

In the case of this soldering experiment on S235 steel sheets, the following items were noticed after the tensile strength tests:

- The sample processed at 30 mm from the start point of the process failed at a force value F_{max} = 2800 N, related to the process temperature of 580 – 600˚C; there is a lack of solidified filler material, marked by A, having an influence on the maximal tensile force;
- The other two samples extracted at 75 mm and 80 mm from the process start point failed at the highest force value of 5100 N, related to the process temperature of 650 – 700˚C, respectively 4850 N, when the temperature was 850˚C.

Taking into consideration these results, it can be stated that the optimum process temperature for soldering 3 mm thick sheets of S235 steel is 650-700˚C (based on the criterion of the results obtained by the tensile strength tests).

b) FSS experiments on the dissimilar combination of Cu99 copper and S235 steel

In these experiments the possibilities of joining by FSS of Cu99 and S235 were analysed.

Experiment conditions:

- Cu99 sheet with 1.5 mm thickness, placed on top.
- S235 sheet with 3 mm thickness;
- Filler material S-Sn97Cu3, flattened wire, placed between the sheets;
- Flux type ROSOL 3, placed between the sheets;
- Tool without tip and with shoulder diameter Ø20mm made of sintered tungsten carbide P20S;
- Tool rotational speed n = 1000 rot/min;
- Tool travel speed, v = 50 mm/min.

The macroscopic, respectively the magnified (30x) appearance are presented in the figure 5.

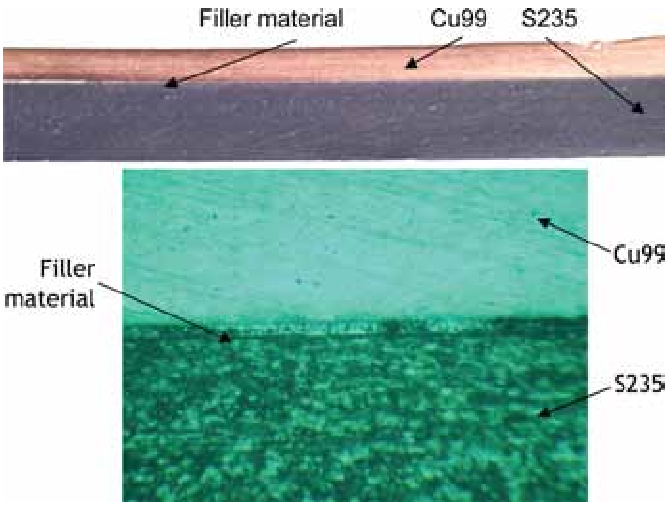

Figure 5. Macroscopic appearance of the samples extracted at 75 mm from the start of the soldering process.

It is observed that during progressive pressing of the tool shoulder onto the copper sheet (tool rotates with 1000 rot/min, but standing still) the temperature increases to a maximum value of 680˚C. When the soldering tool starts the travel by the soldering speed (50 mm/min), the temperature begins to drop, oscillating between 460 – 480˚C.

Even if the temperature had very different values during the soldering process, the samples subjected to tensile strength test behaved in a similar manner:

- Sample 1 had the top force extent: F_{max} = 3500 N
- Sample 2 had the top force extent: F_{max} = 3400 N
- Sample 3 had the top force extent: F_{max} = 3400 N

These values indicate the fact that large variations in temperature do not influence the tensile strength of the soldered joint (if the temperature does not drop below the minimum required for melting and distributing equally the filler material).

7. Industrial applications

The process can be applied industrially to friction stir soldering, using an active rotating element, providing a technology variant for making joints by soldering with a low melting temperature alloy (230-350 °C), allowing for improved quality of joints in certain applications, depending on the shape and dimensions of the joining parts and the assembly to be executed.

Experimental selection of the optimal values of the parameters of the friction stir soldering process is an elaboration stage of the manufacturing technology, depending on the type and thickness of the base metals, the type and use form of the filler alloy, as well as other technical requirements.

Possible applications are mainly in the fields of the electro-technical and the electronics industries, by the manufacture of contact parts, assembly elements, cases, screens, etc. made of copper, brass, steel and other alloys with thickness of 1.0 ... 3.0 mm, respectively the minimum length and width of about 10 ... 50 mm. The maximum length and width values are limited only by the required fastener jig. The process is suitable for mechanization and automation on specialized equipment. Certain applications are possible for the execution of elements of heating, water, sanitary, gas, refrigeration or air conditioning installations, as well as for the manufacture of decorative and ornamental objects.

8. Conclusions

The FSS friction stir soldering process is executed by means of an active rotating element, which exerts a thrust force F of 4 … 20 kN, has a rotational speed n of 600 ... 1500 rpm and moves at a travel speed v of 50 to 200 mm / min, as the technology parameters of the soldering process, which produce metal-metal friction as a local heat source on a top metal base sheet superimposed on a lower base metal sheet.

Between the two sheets there is a tape, sheet or foil of filler metal, having a relatively low melting temperature of 230 ... 350 °C, placed within a gap.

The filler metal melts under the effect of the thermal flow Φ, produced by the local heat source, created by the friction phenomenon, and then the molten filler metal flows and penetrates by the capillary effect across the entire gap, after which solidification of the filler metal and making the joint by soldering occurs. In this way, a soldering joint is achieved, having appropriate mechanical characteristics, without defects, or without deformations of the base metal parts.

Achieving the joint is possible due to the appropriate distribution of the heat flow produced by the friction phenomenon, as a result of the manufacturing solutions of the active rotating element, the fastener jig, as well as the base metal sheet parts.

Possible applications are mainly in the fields of the electro-technical and the electronics industries, by the manufacture of contact parts, assembly elements, cases, screens, etc. made of copper, brass, steel and other alloys within the thickness range of 1.0 ... 3.0 mm, respectively the minimum length and width extents of about 10 ... 50 mm. The process is applied on specialized, mechanized and automated equipment.

Specific applications are possible for the execution of components of water, sanitary, gas, refrigeration or air conditioning installation, as well as for decorative and ornamental objects.

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