Contributions to the development of friction stir welding process (FSW)

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1. Introduction

The problem of the developing of new joining processes for advanced material is present at horizontal level in the priority scientific and technological fields of research at the European level, as for example, in those that aim the future fabrication processes, new materials, transports, aeronautic, inclusively, but also those related to the restructuring some of traditional industrial sectors such as the steel industry and constructions.

The development of these fields impose special requirements to the joining processes from the technical point of view (materials, shapes, sizes, structures, loading), economical (productivity, consumption, cost) and environment (pollution, toxic fumes). The respective requirements, in continuous growth, cannot be entirely met by the welding processes used at present industrial level.

The innovative FSW welding process answers to these high requirements by its extraordinary potential for development.

The process developed rapidly, having a good grip on some prestigious research centers in the world, as well as on leading industrial companies in top sectors such as aerospace or land transport [1], [2]. Having these considerations as a basis, after the year 2000 the research of welding by the FSW process is included in the scientific program of the institute.

2. Performances/results obtained in FSW field

The evolution for researches and achievements in the FSW field can be structured according to the diagram presented in Figure 1.

Preliminary experimental programs were conducted on a system with specific adjustments done for welding on a classic milling machine. The obtained results were considered as the base for the expansion and further research in this area.

Execution and commissioning of the specialized FSW machine in 2008, designing and execution some of specific welding tools, allowed the start of a wide and complex long term research program.

The entire research program in FSW field is based on the use of advanced materials such as aluminum, titanium and magnesium alloys, metallic matrix composite materials, copper alloys, steels, material combinations.

For FSW joining of these similar or dissimilar materials, optimum process parameters were determined and very good results were obtained.

Using the friction stir processing (FSP), the mechanism and effective conditions to modify the materials characteristics, at the micro scale, were studied. The investigation was made (with adapting of the process parameters) for the case of cast aluminum alloys and copper, of hard aluminum alloys and steel, and aimed aspects such as grains, eutectics distribution, hardness and porosity.

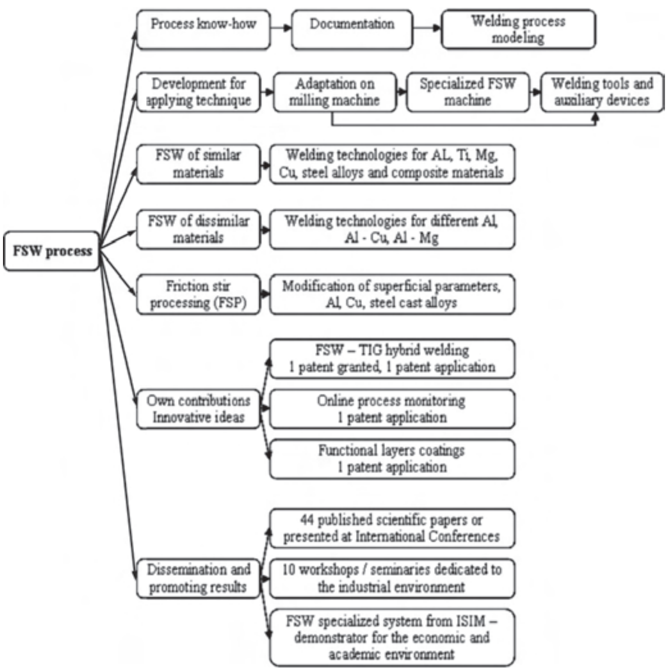


Figure 1. Scheme of achievements in FSW field.

Also, experimentally, it was investigated the possibility of repair some of superficial defects such as cracks or pores in composite and cast materials.

Activities to disseminate and promote the results of researches were a very important objective and were focused mainly on the following directions:

- knowledge, promotion and identifying the opportunities for application of FSW process in the Romanian industry;
- use of complex technological FSW system, from ISIM Timisoara, as demonstrator for specific industrial applications.
- international visibility increase by publication or presentation at international conferences of a number of 44 scientific papers in the FSW field;
- knowledge and promotion of the process in university environment by participating in conferences organized by the technical universities, but also through practical demonstrations, for students and masters.
- protection of innovative ideas/original achievements at worldwide level in FSW field.

3. Innovative contributions to FSW development

The innovative character of ideas as own contributions have materialized in the granting of a patent and request for 3 more patent applications filled at OSIM.

3.1. FSW-TIG hybrid welding

TIG assisted friction stir welding method is a new FSW technique proposed by team of authors. TIG assisted friction stir welding, represent a development of FSW technique and create an hybrid welding process, in solid state, that integrates the preheating of plates through TIG welding process (Figures 2 and 3).

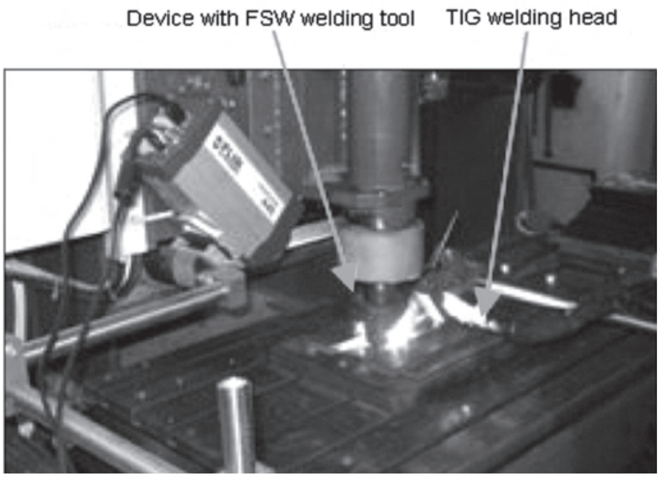


Figure 2. FSW-TIG assembly.

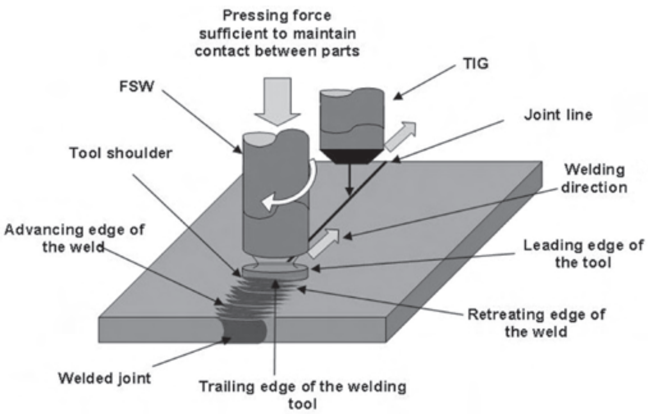


Figure 3. FSW-TIG scheme.

Experiments were developed for materials that have difficulties at classic friction stir welding: aluminum alloy EN AW 7075-T651 (s_1 = 5mm), copper Cu 99 (s_2 = 5mm) and steel S235JR+N (s_3 = 3mm).

For welding of EN AW 7075-T651 were used welding tools having threaded cylindrical pin and smooth shoulder, made from X38CrMoV5 (AISI H11), heat treated at 52-54 HRC. For welding of copper and S235 steel were used welding tools having smooth conical pin and smooth shoulder, made from tungsten sintered carbides (P20S).

Table 1 shows the technological parameters used in experimental program / each material.

Using optimized parameters for both methods, classical FSW and FSW-TIG, welded joints without imperfections/defects were obtained. Figure 4 shows the macroscopic images of welded joints, in transverse direction on movement direction of welding tool.

Table 1. Technological parameters.

Welding materials	Procedure	Welding tools		Welding process parameters		
		Characteristics of pin	Caracteristics of shoulder	Rotation speed rot/min	Welding speed m/min	Sense of rotation
EN AW 7075	FSW	threaded cylindrical, M6 l_{pin}= 4,85 mm	smooth, $Ø_{shoulder}$=22 mm	1200	120	anti clockwise
	FSW-TIG			1000	200	
S 235 JR+N	FSW	smooth conical l_{pin}= 2,75 mm	smooth, $Ø_{shoulder}$=20 mm	800	20	
	FSW-TIG			800	100	
Cu 99	FSW	smooth conical l_{pin}= 4,80 mm	smooth, $Ø_{shoulder}$=20 mm	1000	100	clockwise
	FSW-TIG	smooth conical l_{pin}= 4,80 mm	smooth, $Ø_{shoulder}$=25 mm	1200	200	

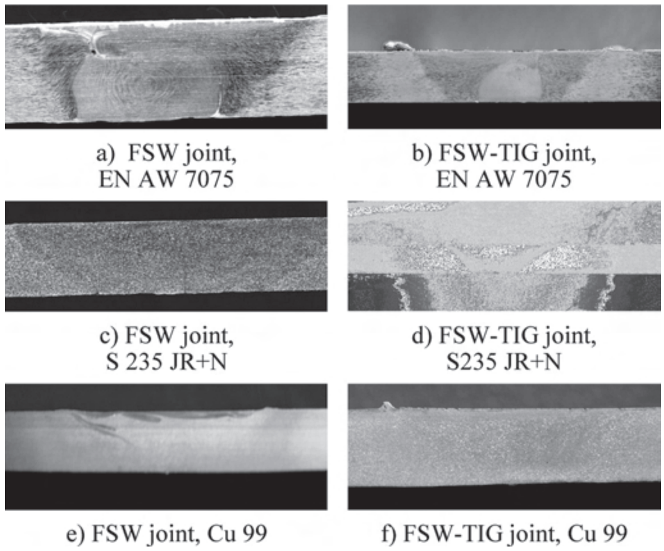


Figure 4. Macroscopic aspects of welded joints.

The mechanical characteristics of welded joints, for both procedures, are presented in table 2.

Table 2. Mechanical characteristics of welded joint.

Material	Procedure	Strength resistance		Degree of deformation	HV5 (HV3) Hardness			
		Rm_{weld} / Rm_{MB}	Breaking place		BM	HAZ	TMAZ	N
EN AW 7075	FSW	0,77	TMAZ	maximum	160	~120	~160	~185
	FSW-TIG	0,75	TMAZ		160	~105	~120	~130
S 235 JR+N	FSW	-	BM		125	~115	~135	~120
	FSW-TIG	-	BM		125	~140	~150	~170
Cu 99	FSW	0,97	N		88	91	91	90
	FSW-TIG	0,98	N		88	90	90	88

At a comparative analyze of mechanical characteristics of FSW welded joints, respectively FSW-TIG, it can be observed that those are similarly, the small differences are negligible.

From point of view of proposed objectives through FSW-TIG welding procedure, comparatively with classical FSW, were obtained:

- increase of productivity through increasing of welding speed (at EN AW 7075 alloy with ~67 %, at S 235 steel with ~500% and copper Cu 99 with ~200%);
- more stable welding process (without vibrations) that ensure a better protection for machine and welding tools;
- welding tools wear has a significant decrease at FSW-TIG hybrid welding, compared with classical FSW.

3.2. Deposition of functional layers (aluminum alloys) on steel substrate, using FSW principle

Deposition of functional layers that is a result of consuming of tool, is achieved by combination of three specific movement of welding tools: rotation, vertical translatory motion for ensuring of necessary fluxe of material that will be deposited and translatory movement along the substrate surface, effective formation of functional layer.

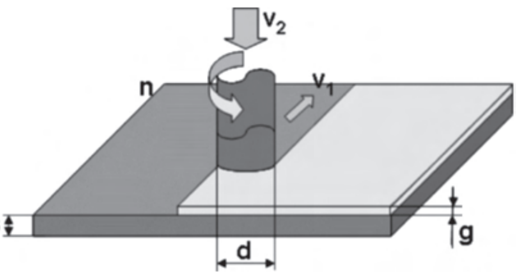


Figure 5. Scheme of deposition procedures.

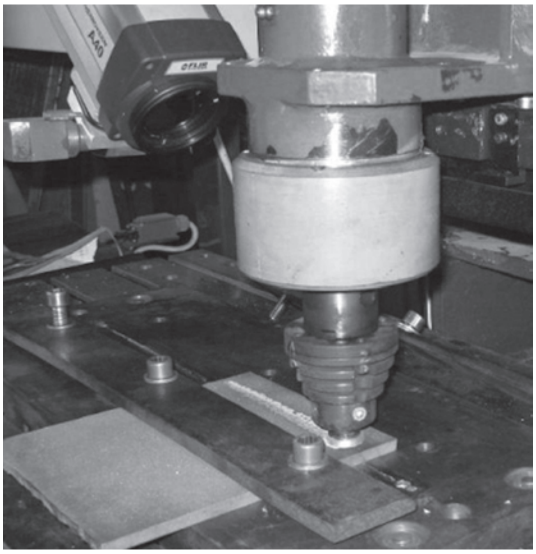


Figure 6. Deposition of functional layers.

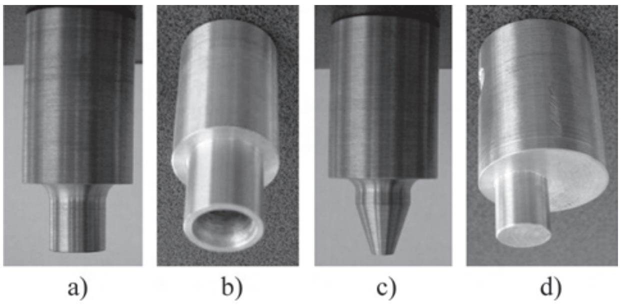


Figure 7. Consumable FSW tools.

One of important problem that had to be solved was designing of optimum geometries for consumable welding tools made from aluminum, that using the friction stir welding principle, to allow the generation of aluminum alloys layers on steel substrate:

- cylindrical tools having different diameters – Figure 7a.
- tubular tools having different outside/inside diameters – Figure 7b.
- conical tools – Figure 7c.
- tools with eccentric having different diameters and different value of eccentricity – Figure 7d.

Tools having different physical and mechanical properties were made from aluminum alloys: EN AW 5086, EN AW 5083, EN AW 6061 and EN AW 7075.

In all experiments, to ensure fast heating of aluminum alloy and achieve the plasticizing temperature, high rotation speed of welding tools, between 1200-1300 rot/min, were used.

Speed of movement on vertical direction for consumable tool, that ensure quantity of deposited material, was in range 20-30mm/min, and speed of movement of tool on substrate surface was in range 60-200 mm/min.

Aspect of deposition in one or two layers, using EN AW 7050 material and tool having diameter Φ12 mm, is shown in Figure 8.

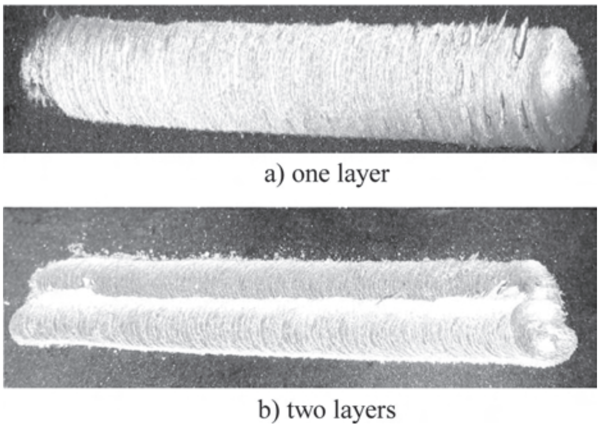


Figure 8. Deposition of EN AW 7050, using tool having diameter Φ12mm.

Best results were obtained to functional layers deposition using cylindrical tool having Φ20 mm diameter, made from EN AW 5086.

From all experiments, this was most stable, fact demonstrated by temperature evolution diagrams during process (Figure 9).

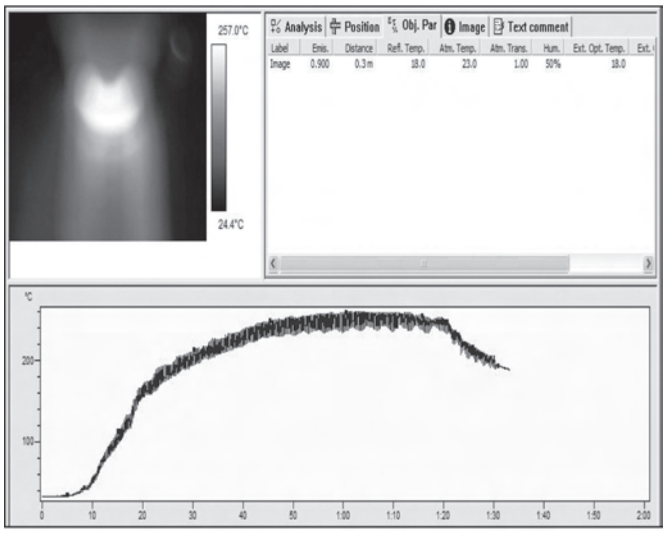


Figure 9.Temperature evolution during FSW deposition process, using tools having Φ20mm, made from EN AW 5086 (v=200 mm/min).

Deposition of layers with thickness between s = 1,1 - 1,5mm were obtained. Macroscopic aspect of deposition is shown in Figure 10.

Microscopic structure of characteristic zones is presented in Table 3 and Figure 11.

Microstructures of welded joints were evaluated through Vickers hardness measurements in a perpendicular plane on direction of movement for consumable tool (perpendicularly on Ox direction).

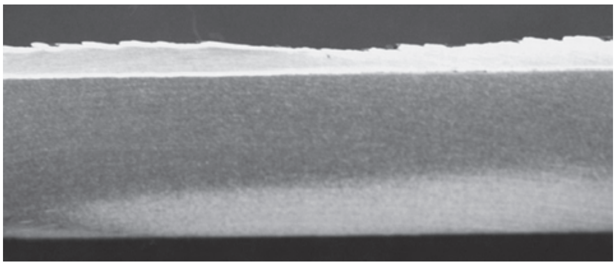
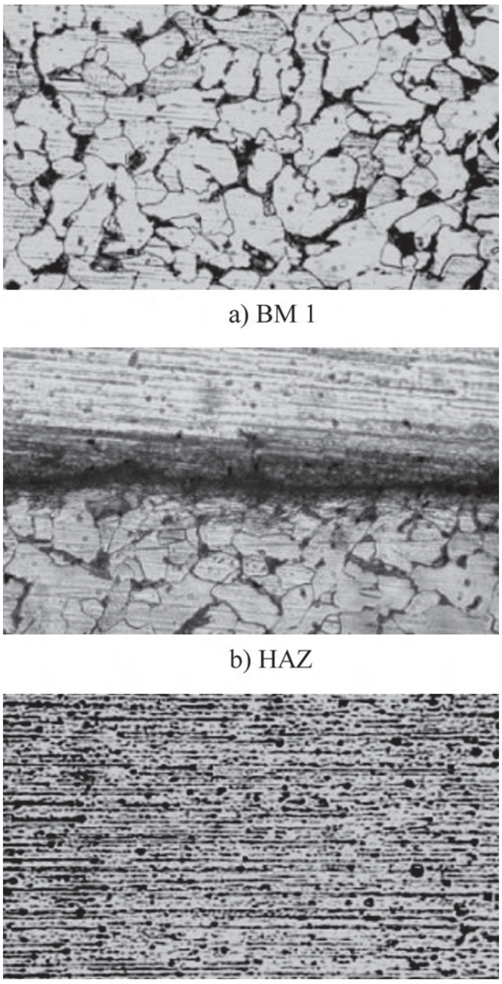


Figure 10. Macroscopic aspect of deposition.

Table 3. Microscopic Structure of Deposited Zone.

Examinated zone	Structure [100×]	Etching
BM 1	Ferrite, pearlite	Nital 2%
HAZ	Ferrite, pearlite	Nital 2%
BM 2	Solide sollution Alα +$CuAl_2$ and fine non metallic inclusions	NaOH 5%



a) BM 1

b) HAZ

c) BM 2

Figure 11. Microscopical aspect of deposition.

Due to strong strain hardness of substrate material, and also of material of consumable tool, in heat affected zone, significant changes of hardness were recorded:

- higher hardness value with approx. 24%, to steel;
- higher hardness value with approx. 33%, to aluminum.

The obtained results demonstrated that innovative proposed procedure can be developed through further research and applied if will be followed some basic rules:

- deposited material and substrate are compatible;
- optimized geometry of welding tools are used;
- substrate surface is properly prepared;
- optimal process parameters are used.

4. Monitoring in real time of FSW process

The field of components and materials for which friction stir welding procedure can be used is constantly expanding, process quickly became an important industrial technology and environmentally efficient.

There are numerous applications especially in naval field, aeronautics and transportation, that requires welded joints on large length (2 ÷ 15 m). From this reason, monitoring in real time of welding process has became a priority.

The worldwide achievements for FSW process monitoring are well known. Excellent results were achieved in particular by using complex systems that ensure monitoring of the forces developed during the process and acting on the welding tools [3], [4].

4.1. Monitoring of FSW process using infrared thermography technique

Recent research conducted at ISIM Timisoara, have demonstrated that infrared thermographic technique can be a viable method for monitoring of the automatic and semi-automatic processes, aplicable inclusive to the friction stir welding process (FSW) [5].

The following research methods were used:

- simulation method of defects type holes, slots and implants having different sizes [6];
- real time tracing method of welding process - welded joints for different materials were made using welding parameters optimized in previous research programs, the diagrams of temperature evolution were analyzed;
- samples were taken from welded joints, which were non-destructive and destructive analyzed and controlled, etc.;
- comparing the results of the analysis diagrams of the evolution temperatures measured during the welding process, with the results obtained during the non-destructive and destructive control and evaluation of welded joints, for a wide range of types and thickness of metallic materials.

The temperature recording was realized in real time, using a Thermo – Vision A 40 M camera, at an aquisition rate of 20 images/s. This camera was placed on the welding equipment, (Figure 12) in order to trace the intersection zone between the tool shoulder and the weld surface, on the back semi-circle zone (π/2).

The measurements were made on the joint line at a distance of 1 mm behind the welding tool shoulder (Figure 12).

Based on the recorded values from the temperature measurements, done with the infrared thermographic camera, the temperature evolution diagram during friction stir welding process could be obtained.

The monitoring system can provide information on process stability, constancy of welding parameters, inducing some imperfections and/or defects, and also quality analysis of welds through the thermal image, as well as adjustment and optimization of welding parameters by feedback connections.

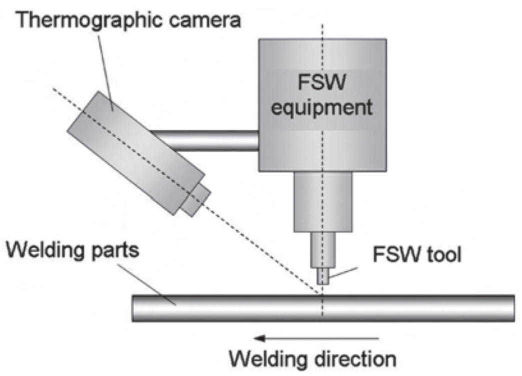


Figure 12. Scheme of positioning for thermographic camera on FSW machine.

To check-up of the operating principle in terms of identifying imperfections during the welding process, revealed that they can be evidenced through thermographic method because they represent a thermal barrier which are preventing the heat propagation inside of the object examined in accordance with its thermal characteristics, by having a different thermal conductivity of imperfections compared with the homogeneous material.

The experiments demonstrated the viability of infrared thermography in detection of the defect during the welding process [7].

The experiments were based on different forms and dimensions for the artificial defects made in the welded sheets. The sketch with the positions and the dimensions, for the case of simulated artificial defects having elliptical slits with variable width 2 - 6 mm and constant depth h = 4 mm, are presented in Figure 13.

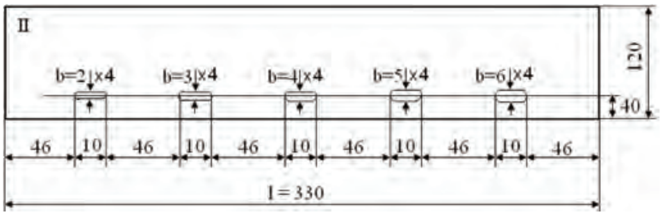


Figure 13. Sketch of samples with simulated defects [6].

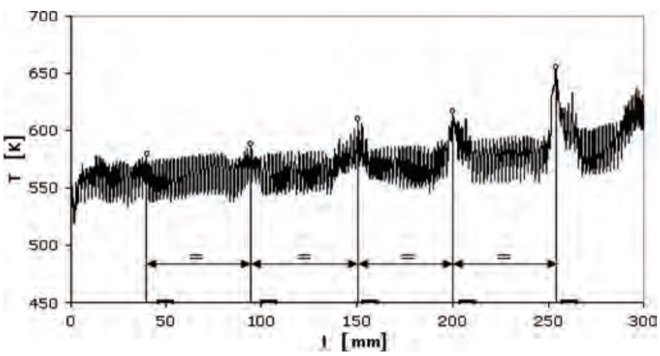


Figure 14. MIT recording of the process [6].

In respect to the temperature evolution, recorded by thermographic camera, for welds done over the open slots, the recording T = f(l), presented in the oscillogram from Figure 14 was obtained. Significant for the experiments are the "jumps" that appear on the temperature graphic, in front of the slits, due to the local overheating.

The appearance of the peaks of temperature on the length of the welded joint and their sysyematic localizations in the defects zone, and in the working area of the welding tool respectively, was determined by the suddenly modification of the temperature gradient, caused by the thermal conductivity variation.

Also, it was concluded that, no matter the shape of the artificial defect, the minimum necessary volume to obtain a good evaluation of the thermographic recording can be determined [6].

In a concrete application, for AISI 304L stainless steel, after the 80 - 100 mm from the beginning of the effective welding process, the temperature was constantly evolving around 980 - 1000^{o}C (stable welding process), Figure 15.

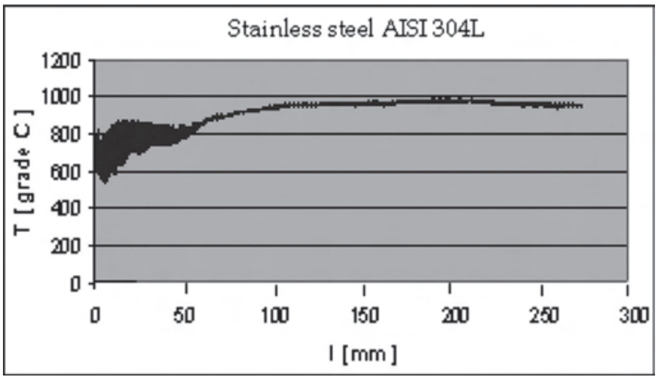


Figure 15. Evolution of temperature – AISI 304L, monitoring by infrared thermographic camera [5].

Through X-Rays analyze and macroscopic analyze it has demonstrated that welded joint without defects was obtained and also formation of nuggets well consolidated in center of the weld.

A particular case was observed to another experiment for welding of AISI 304L stainless steel.

Analyzing the evolution of temperature diagram from Figure 16 is noted that approximately 150 mm welding there was a disturbance (area A).

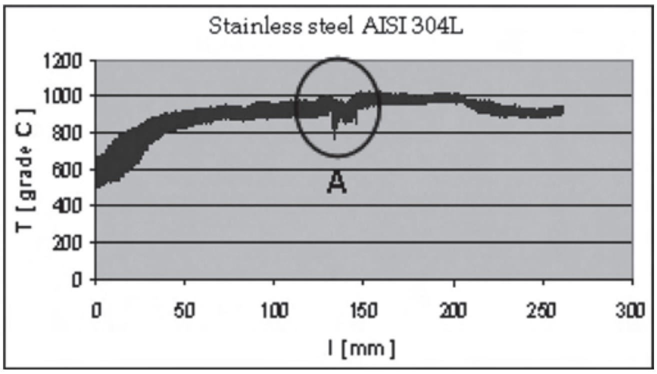


Figure 16. Detection of defect by thermography [5].

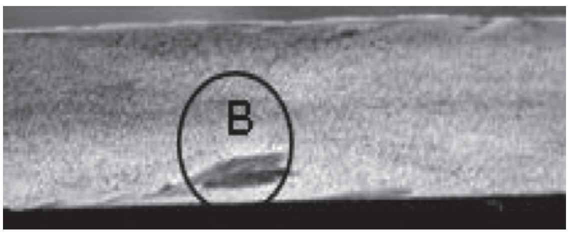


Figure 17. Detection of defect in welded joint [5].

Subsequent verifications of welded sample showed that there in that area was damage in 20% of the pin (broke a volume of approx. 20% of pine, which remained „implanted" in the welded material, Figure 17, the area marked B.

This incident supports the theory that the infrared thermography technique can be used for monitoring in real time of FSW welding process.

4.2. Monitoring of FSW process by real time control of energy consumption

The welding process is pure mechanic and requires mainly three motion of FSW welding tool, provided by three engines (Figure 18):

- M1 provides vertical movements of the welding tool, penetration of pin in welding materials and pressure of tool shoulder with Fz force (on welding materials);
- M2 provides rotation of the welding tool with prescribed rotation speed;
- M3 provides movement with prescribed speed of the welding tool toward the welding material.

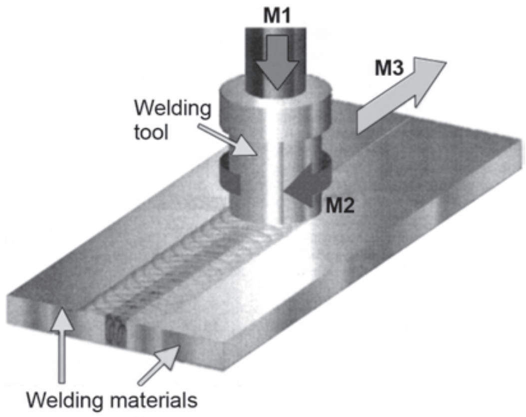


Figure 18. Friction Stir Welding process.

Completion the FSW machine (Figure 19) with monitoring in real time and control system of the FSW process through control of energy consumption can provide information on process stability, constancy of welding parameters, inducing some imperfections and/or defects, and also quality analysis of welds through the thermal image, as well as adjustment and optimization of welding parameters by feedback connections.

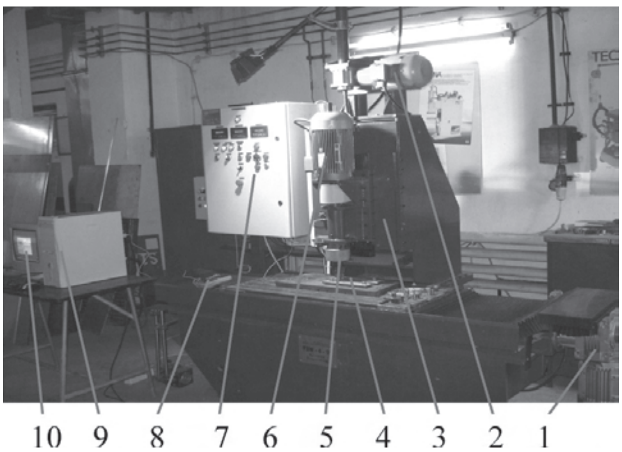


Figure 19. Monitoring system to determine the energetic consumption.

The experimental stand was used to measure of current consumed by FSW equipment or some of its components (engines), as well as for computerized data aquisition.

This is consist of (figure 19): FSW welding machine (position 3), welding tool (position 5), type UT 70B multimeter (position 8), computer for data aquisition, respectively for recording of measurement (position 9), computer monitor (position 10).

Measurements to M1 (pos.2), M2 (pos.6) and M3 (pos.1) were done.

In the experimental program were used welding materials and FSW tools with different characteristics for which, in the previous experiments, optimization of the welding parameters was achieved.

Rotational speed has an very important role regarding to quantity of heat developed during welding process in welding materials, as well as on plasticization grade of their and forming mechanism of welded joint.

In the analysed case, M2 is the engine that provides the rotational motion of the welding tool. M2 is the most loaded engine because of:

- continuous functioning in entire time of cycle (Figure 20);
- transmit the movement to welding tool, is directly connected to the main spindle of the FSW machine. This is necessary because of high rotational speed which are used for welding tools (400 ÷ 2000 rot/min). This fact allows to introduce some of specific modules (eg. worm gear) in cinematic chain, which could reduce the high impact of welding process on the engine (M2).

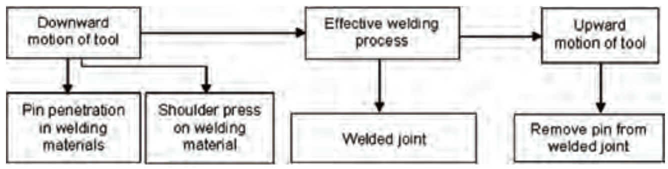


Figure 20. Secquences and stages of FSW process.

The values recorded in principal sequences of process were tracked, namely:

- control start engine M2;
- contact between welding pin tool – welding material;
- contact between welding tool shoulder – welding materials and start effective welding process;
- welding process;
- complete the welding process ;
- remove the pin tool from welding materials

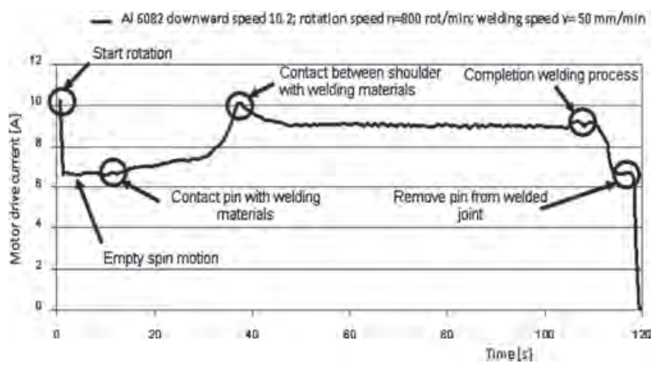


Figure 21. Evolution of measured consumption at M2 engine.

For example, when welding sheets from EN AW 6082-T651 aluminum alloy, having g = 6 mm thick, there quite large variations of measured values were recorded, especially in the analysed sequences (except during effective welding process).

In figure 21, these variations are within the range 6,3÷10A.

The highest values (≈10 A) were recorded at transmission of command for rotation (start rotating tool), respectively in moment of the optimal contact (necessary and sufficient) between tool shoulder and welding materials.

Also, zones corresponding to other sequences of process are clearly distinguished: contact between pin and welding materials, completion of welding process (stop M3 engine which execute the motion with prescribed welding speed for welding materials in relation with tool), remove of the pin tool from welding materials.

The stable evolution of values of current (≈9A) during effective welding process is noticeable.

If the disturbance factors appeared accidently during the welding process (eg. pin broken, change of optimal position between the welding tool shoulder and the welding materials, modification of welding speed, etc.), certainly they would be influenced the stable evolution of diagram corresponding to effective welding process.

The results obtained demonstrate that through analyse of functioning behaviour of engine M2, to join the EN AW 6082 - aluminum alloy, can be monitorized the FSW process using optimized welding parameters (tool geometry, rotational speed and welding speed), as follows:

- shoulder of the welding tool is pushed in the welding materials until a optimal value of current, that is experimentally established, is recorded (in the analyzed previous case - 10A);
- it follows that during effective welding process, optimal value of current, that is experimentally determined, to be stable (in the analyzed case ≈ 9A).

These values can be experimentally determined for different type and thickness of material. The method is used at worldwide to determine the downforce optimal values of welding tool on welding materials. These values are used to monitoring in real time of FSW process (through downforce).

5. Conclusions

- Since year 2000, the researches for friction stir welding process were included in scientifical program of ISIM Timisoara.
- Applying the innovative FSW-TIG hybrid welding, relative to classical FSW assure: productivity increase, through considerable increase of welding speed; machine protection and FSW welding tools, through reducing of forces that are developed during FSW process (obtaining a stable welding process), significantly reducing of wear for welding tools.
- The feasability of depositing the functional layer of aluminum alloy on steel substrate, using friction stir welding principle was demonstrated. The rotating active element is a consumable tool.
- Monitoring in real time of the welding process is important owing to use FSW process in many industrial applications (especially those requiring long lengths of welded joints). Two innovative methods, based on experiments, were developed for this. These evidenced that:
  - there are the real possibilities, qualitative and quantitative for detection of defects from FSW welded joints through infrared thermography. On one side, a good reproducibility of results relative to defects localization, was evidenced, and on the other side a dependence of temperature variations of the volume displaced by defects.
  - good results can be achieved by monitoring of functioning behaviour for engine that assure rotation speed of welding tool, obtaining of information about current consumption in the main sequences of FSW process: start rotation - contact between pin tool and welding materials - contact between tool shoulder and welding materials - effective welding process - completion of process and remove of welding tool from welded joint.

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