Monitoring and control methods of friction stir welding process

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1. Introduction

In this paper are presented results of FSW research team from National Research and Development Institute for Welding and Material Testing - ISIM Timisoara, regarding to the possibilities for monitoring of the friction stir welding process (FSW).

One direction of research was based on research of the possibility to monitoring the FSW process by using infrared thermography method.

Infrared thermography is a modern imagistic method that, without contact, allows temperature determination of an object, from distances till of hundred meters.

Welding imperfections can be highlighted through thermography method, because these imperfections are a thermal barrier that block heat propagations inside the examined object in accordance with its thermal characteristics, imperfections have a different thermal conductivity than the homogeneous material.

Some of the worldwide achievements for FSW process monitoring are known. Good 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.

At ISIM Timisoara was developed a technical solution for measurement and online monitoring of vertical forces which actuate on welding tools. Knowledge and control of this force can be useful for monitoring of welding process and is important for stage of welding technologies optimization.

2. Monitoring of friction stir welding process using infrared thermography

For welded joints, thermographic inspection is very useful for detecting defects and through this for evaluating the welding process and welded structures [1].

The main researches objective was to demonstrate that the infrared thermographic technique can be used to monitoring the FSW process and also limits its application.

The following research methods were used:

- simulation method of defects type holes, slots and implants having different sizes
- tracing method in real time 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 thicknesses of metallic materials.

Samples from areas where on the temperature diagrams were reported disturbance, discontinuities, etc. were analyzed in particular.

It is important to note that the welded joints without defects/imperfections can be obtained on certain materials, for a wide enough field of welding parameters (tool geometry, welding speed, rotational speed of welding tool, etc.), but the characteristics (mechanical properties) obtained may be different.

Therefore it is important to be known and also monitored the temperature for that welded joints with characteristics/desired mechanical properties, specific for a concrete application are obtained.

2.1. Experimental program

The experimental program was conducted on the specialized FSW machine (Figure 1), from ISIM Timisoara, with the following main technical characteristics:

- adjustable welding speed range: 60 - 480 mm/min;
- adjustable speed of the welding tool in range: 300 - 1450 rot/min;
- usable stroke (welding): 1000 mm.

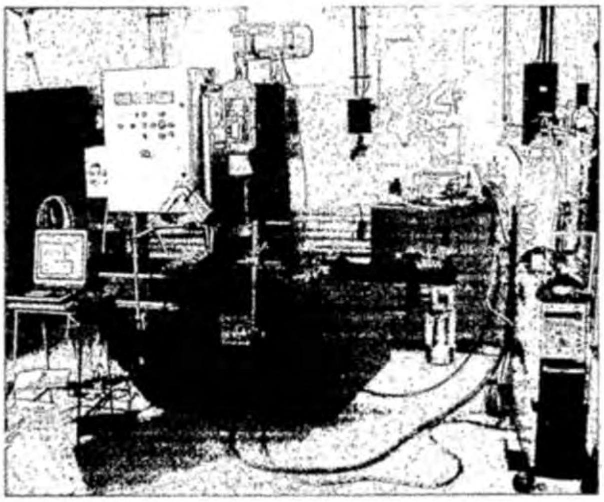

Figure 1. FSW machine (with monitoring of process) from ISIM Timişoara

Welding parts were butt positioned and rigidly fixed on a steel backing plate.

Completion the machine with a monitoring and control system of the FSW process using infrared thermography can provide information on process stability, constancy of

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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.

Checking the operating principle in terms of identifying imperfections in welding, found that they can be evidenced through thermographic method because reprezent a thermal barrier which preventing the heat propagation inside of the object examined in accordance with its thermal characteristics, having a different thermal conductivity of imperfections compared with homogeneous material.

Temperature recording was realized on-line, using a camera Thermo - Vision A 40 M, having a frequency of 20 images/s. This camera was placed on the welding equipment, (Figure 1) in order to follow the intersection zone of the tool shoulder with the weld surface, on the back semi-circle zone of the tool, Figure 2. The temperature recording was made using the Therma Cam Researcher Pro software.

Figure 2. Thermal field at FSW, seen on the infrared image

In Figure 3 is presented the positioning scheme for the thermographic camera on the installation respectively the FSW tool.

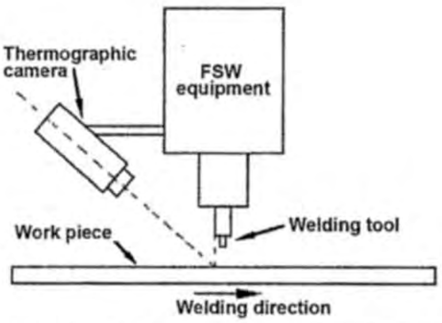

Figure 3. Scheme of positioning for thermographic camera regarding to FSW machine

Based on the values of temperature measurements, made with an infrared thermographic camera, could be achieved the evolution diagram of temperature during FSW welding process.

To see how temperature varies in the two materials during welding, measurements of its were made perpendicular to joint line at different distances from the weld start and have drawn the afferent graphs of variation.

In order to make a practical test of the possibilities to apply the infrared thermography for monitoring on-line the welded joints defects, it was developed an experimental program, according to scheme from Figure 4 [2].

Also real defects in correlation with diagrams of temperature evolution were analyzed and correspondence between these were established.

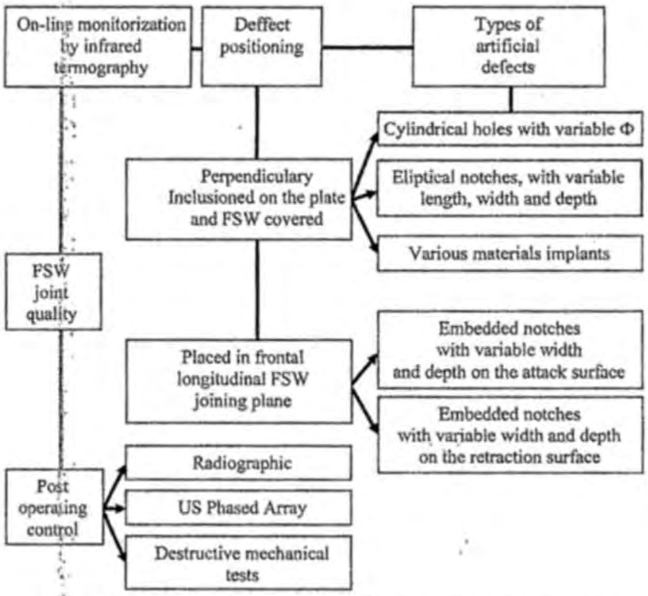

Figure 4. Scheme of experimental program for testing of infrared termography monitoring system to FSW joints [2]

Infrared thermographic technique was recently used also to promoting some of own contributions which include innovative development of FSW principle:

- FSW-TIG hybride welding,
- deposition of functional layers from aluminm alloys on steel base, using consumable friction stir tool.

2.2. Results. Discussion

The experiments have shown that in order to achieve quality welds with a well consolidated nugget covering the entire thickness of the welded materials it is necessary to obtain the optimum plasticizing temperature for these materials. This level varies from material to material and is determined by the welding parameters used (welding speed, rotating speed, tool geometry and dimensions of welding tool). Achieving and maintaining its plasticizing temperature at the optimum level can be tracked on-line on trend charts obtained by using infrared thermography system.

For example, Figure 5, presents the FSW temperature evolution of Cu99 plates with a thickness of 5mm.

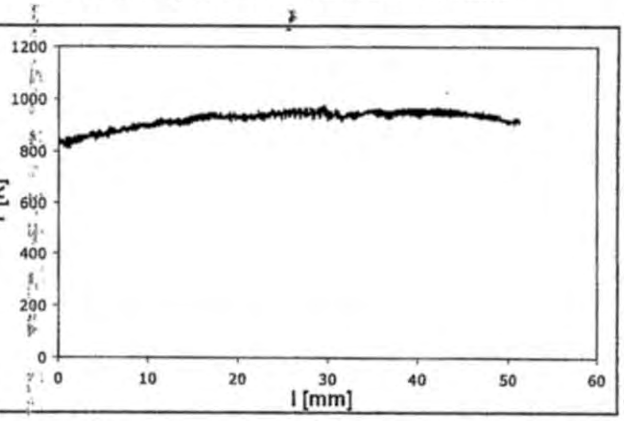

Figure 5. Temperature chart for Cu 99, 5mm thickness

Control of welded joints showed that the optimum temperature at which the welding material must reach in the action zone of the welding tool should be about 640-660°C, in order to achieve flawless joints, in the case of Cu99.

Any amount of recorded temperatures outside this range may indicate imperfection of welds (at lower temperatures - lack of penetration in the root, nugget unconsolidated; at higher temperatures - structural changes, especially in the thermomechanically affected zone, which can have negative effects on static and dynamic characteristics for tensile and bending testing).

When welding dissimilar materials is important to analyze the evolution of temperatures in the two materials in the perpendicular plane over the seam line.

Comparing the evolution of temperature charts on a perpendicular direction to the seam line during the 3 times of measurement (Figure 6), for welding dissimilar aluminum alloys EN AW 1200 - EN AW 6082, several conclusions can be issued, which may have an important role in assessing welded joints and general research results:

- After 50 mm of weld the process is not yet stabilized and optimum plasticizing temperature for the materials has not been reached (75 - 80% of the melting temperature).
- After the welding process was stabilized, the highest temperatures recorded were along the seam line ≈465°C.
- In the area of interference between the welding tool shoulder and welding materials, at ± 11mm from the joint line the following temperatures were recorded: EN AW 6082 ~ 250-330 °C, respectively EN AW 1200 ~ 205-230 °C [3].

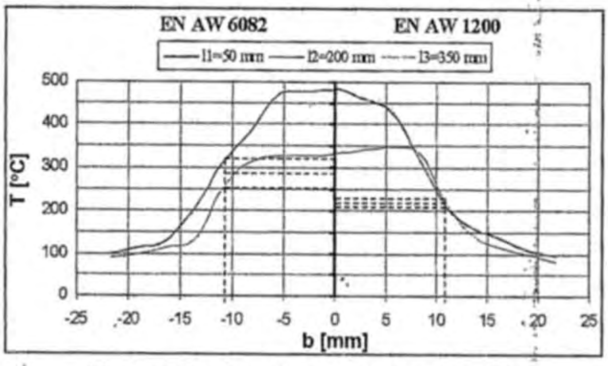

Figure 6. Comparative temperature chart [3].

Several experiments [4] have demonstrated the viability of using infrared thermography for detecting defects that occur during the welding process. For example, an experiment was based on the practice of artificial defects of different shapes and sizes in welded plates. Scheme shown in Figure 7 presents the location and dimensions for the case of simulated failures of elliptic type with variable width slots, 2-6 mm and constant depth h = 4mm.

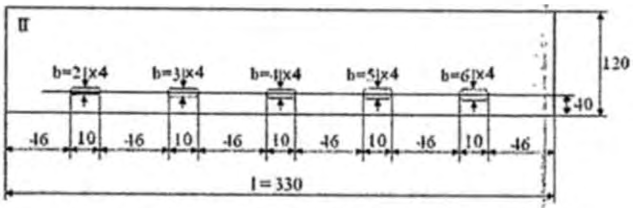

Figure 7. Sample scheme with simulated defects [4]

Temperature evolution recorded by the thermographic camera is shown in Figure 8. Significant for the experiment are the temperature differences near the slots as a result of local overheating.

Researches have revealed real qualitative and quantitative possibilities for detection of major defects in FSW joints, using the infrared thermography method.

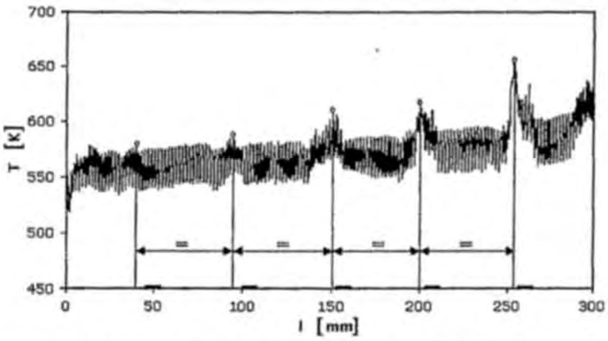

Figure 8. MIT recording of the experiment [4]

On one hand a good reproducibility of the results referring to defects location was observed and on the other hand a dependence of variations in temperature of the volume displaced by defects was also observed.

In the case of simulated defects in the form of slits the temperature peaks are systematically located before the defect, in the position where the welding tool shoulder begins to cover the defect.

It was also observed that regardless of the simulated defect shape the minimum necessary volume can be defined, therefore keeping into the precision limits of determination, a corresponding value for thermographic recordings will be obtained. [4].

Figure 9 is an example of the emergence of a welding defect in the AZ31B magnesium alloy while welding. The existence of the defect (detected by X-ray control) gave rise to some disturbance of the temperature chart.

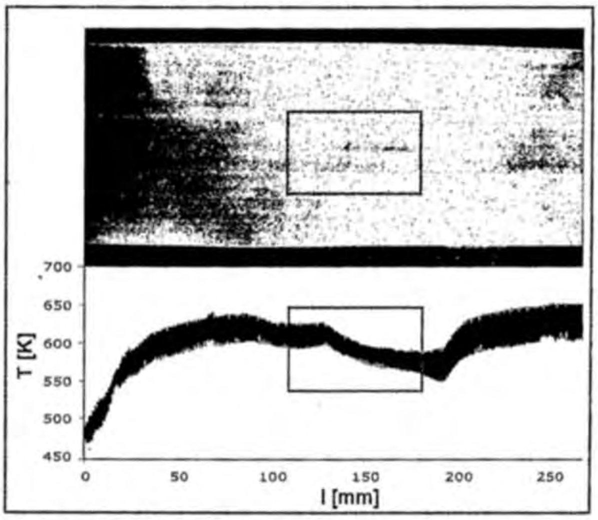

Figure 9. Detecting a defect by radiographic control and correlating the results with the temperature diagram [5]

A decrease of approximately 80°C in the temperature was found in the area where the defect occurred (lack of penetration), followed by a return to normal values after passing it [5].

This was due to a malfunction / failure of FSW machine, which was characterized by a reduction of ~ 40% welding tool speed. Welding speed was maintained at the prescribed values. Because temperature developed during the process is directly proportional to speed, it dropped 80°C, reaching values below the optimal plasticizing temperature of the welding material. As a result there was an insufficient mixing of materials and a consolidated core was not obtained having a tunnel like defect (Figure 9).

After remedying the malfunction and having the tools speed at the initial setpoint, the welding was carried out under optimal conditions which was confirmed by the evolution of the temperature chart.

This fact demonstrates the possibilities of using infrared thermography for real time monitoring of FSW process.

Also when it comes to steels, infrared thermography is used for obtaining information regarding the temperature during FSW and for monitoring the process.

It was observed that for S235 JR+N, S420MC and AISI 304L steels, after 80-100 mm from the beginning of the welding process, the temperature had a constant evolution in the range of 980-1000 °C (stable welding process) Figure 10a.

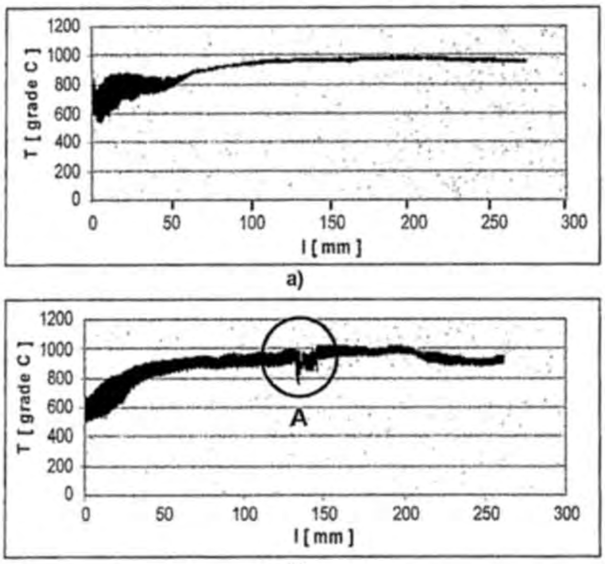

Figure 10. Temperature evolution monitored with thermographic camera

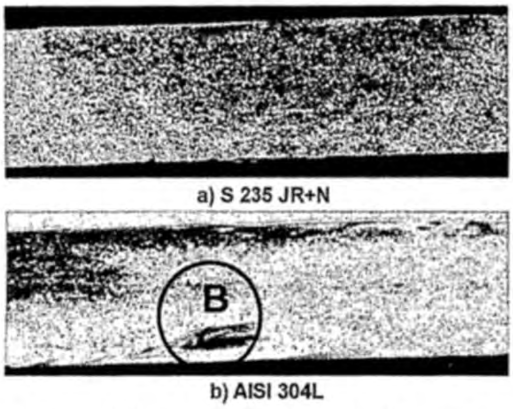

Figure 11. Macroscopic aspects of welded joints

If the process was stabilized and the temperature was maintained at this value, welded joints without defects/ imperfections were obtained. For example, the macroscopic aspects presented in Figure 11a, for FSW of S235 steel shows the lack of defects and also the forming of well consolidated cores in the center of the weld.

A particular case was observed in an experiment in welding AISI 304L stainless steel. Looking at the diagram in figure 10b the temperature evolution after about 150mm of joining a disturbance occurred (zone A). Subsequent checks of the welded sample showed that in that area damage occurred in 20% of the pin (broke a volume of approx. 20% of pin, which remained "implanted" in the welding material, Figure 11b, area marked as B). This incident supports the theory that the infrared thermography technique can be used for online monitoring of FSW process.

3. Vertical force measuring system for monitoring operating parameters

The control system by monitoring forces / moments is intended to measure pressure forces (vertical component) in the operation of FSW process.

In terms of operation this system has two distinct parts, namely:

- Mechanical device that has a fixed force transducer, the device is mounted on main spindle the FSW machine.
- Display unit mounted on a support on the FSW machine chassis.

The actual process of welding starts when the welding tool shoulder comes into contact with the welding plates, while the tool rotates and the displacement is done by moving the machine table.

The tool interaction, which performs two movements, rotation and displacement (linear translation), generates a reaction force from the material, which has three main components on the three axes Ox, Oy and Oz.

The reaction force component, on Oz axis is the main force of reaction and the most important component that ocurrs in the FSW.

The pressure force of the tool necessary for achieving effective welding is measured by the value generated in the main axis of the machine during work.

Vertical downforce is an operating parameter of FSW machine. It represents the force of penetration of a FSW tool in basic metals, in the joint line.

A scheme was developed for measuring vertical force pressing onto the FSW tool, namely the rotating active element, on the basis of the kinematic diagram and FSW machine structure. This scheme is shown in Figure 12.

Component elements of the measuring scheme were presented: force transducer for the range 0 - 20 KN, transmission line, signal amplifier, signal adaptation interface, data acquisition system with sampling frequency of at least 10 kS/s, laptop for running the process, monitoring and recording parameters, data acquisition and processing software. The force measurement scheme is important for the development phase of FSW technologies and to exploit the current FSW equipment as required by the integrated management system for quality assurance, environmental protection and occupational health.

The force transducer presented in this scheme is the mini force transducer type AM [6], shown in Figure 13. It is intended to measure static and dynamic compression forces. It is especially suitable for monitoring the operations of impact shock compression, which requires a robust transducer, insensitive to high resonance frequencies caused by inhomogeneous links in dynamic sequences. Accuracy and stability are not affected by cyclic continuous operation in harsh conditions, even with dynamic loads.

The size of the force transducers are type MA making them ideal for use in the existing equipment.

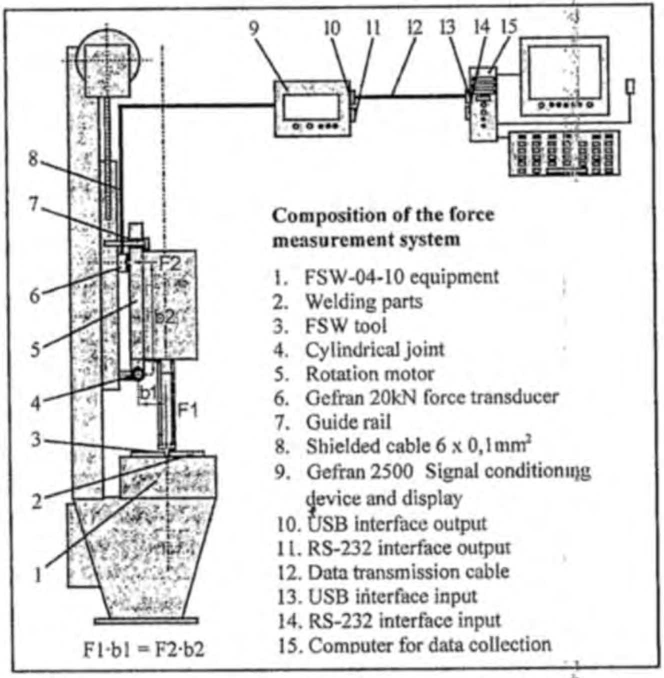

Figure 12. Measuring system for FSW equipment vertical downforce

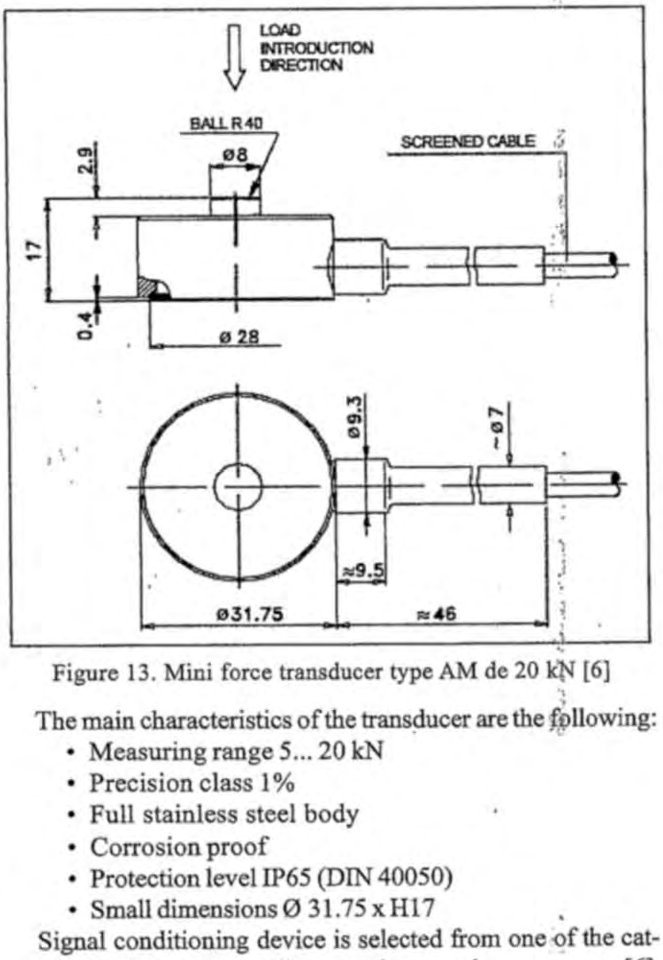

Figure 13. Mini force transducer type AM de 20 kN [6]

The main characteristics of the transducer are the following:

- Measuring range 5... 20 kN
- Precision class 1%
- Full stainless steel body
- Corrosion proof
- Protection level IP65 (DIN 40050)
- Small dimensions Ø 31.75 x H17

Signal conditioning device is selected from one of the categories: indicators, controllers, regulators and programmers [6].

The controller type 2500 has a microprocessor with a single control loop, the format of 96 x 96 (¼DIN), suitable for processes with high variation speed. Due to its extensive functions, configurable hardware and software, it provides high flexibility in practical systems that control and configure the pressure, force, temperature and differential pressure.

There are available extended configurations with the following options:

- serial communication interface:RS485/RS 232 with MODBUS RTU protocol (optional);
- profibus DP communication interface (slave);
- analogical isolated output for resending the process, peak value, remote mounting, deviation, alarm reference, differential values;
- frontal panel with three displays of 5 digits and two bargraphs.

The vertical force measuring system for monitoring the FSW process is developed at an experimental model level and it will be tested on the FSW machine provided within ISIM.

4. Conclusions

Online monitoring of FSW process, can detect defects early in real time, which brings considerable benefits.

Infrared thermography makes it possible to measure temperature from a distance (centimeters to hundreds of meters) and without direct contact, which is extremely useful in welded joints.

Researches carried out have revealed the real possibilities, qualitative and quantitative, for detection of major defects in FSW joints by using the infrared thermography method.

It was also found that irrespective of the defect simulation, the minimum volume necessary for obtaining a proper assessment of thermographic records can be determined within the accuracy limits.

Monitoring and control system for the force provides information on the evolution of axial force pressure of the welding tool onto the welding materials.

Determination of optimal force depending on the type and thickness of the welding materials makes the axial force become an important parameter of FSW process.

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