Infrared thermographic technique – viable alternative for monitoring of friction processing processes

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1. Introduction

ISIM Timisoara had and has concerns for the development and implementation of modern, respectively ecological unconventional processing processes:

- processes based on the use of ultrasonic waves (US) to join of metallic, polymeric and composite materials [1,2];
- thermal spraying processes HVOF - High Velocity Oxygen Fuel [3];
- friction processes – friction stir welding, friction stir processing, friction riveting .

In the field of friction processing, remarkable results were obtained regarding the research and development of the FSW welding process, respectively of the methods/processes derived from it.

Besides the aspects related to the knowledge of the process, the elaboration of own solutions proposed for the development of the experimentation and application techniques, the elaboration of FSW welding technologies for specific couples of similar and dissimilar materials, extensive researches were carried out regarding the possibilities of monitoring and control of the welding process (FSW).

Worldwide, the real-time monitoring of the FSW welding process is already known by using the control of the vertical force Fz, a force with which the welding tool acts on the welding materials, during the welding process.

As an alternative to this variant, ISIM Timisoara has proposed for research and development a new innovative technical possibility, namely monitoring of the FSW process by a method based on the infrared thermographic technique.

Infrared thermography allows the measurement of temperatures at a distance (centimeters to hundreds of meters) and without direct contact, which is extremely useful, for example, in the case of electrical equipments that are under voltage or in the case of parts or materials at high temperatures (e.g.: online temperature measurement during the welding process).

This is a method of non-destructive investigation because it does not intervene and does not influence in any way the material, object or process investigated.

It is an ultra-sensitive measurement technique, being able to highlight temperature variations of tenths of a degree, both spatially (from one point to another in the image) and in time (transient regimes that take place in time intervals of the order of seconds to hours and even days).

The difference between thermographic inspection and other control methods, such as ultrasound, magnetic powder or eddy currents, is the ability to detect defects in a wide range of metallic or non-metallic materials.

From the point of view of the detectability of welding defects, they are thermographically detected because they represent a thermal barrier that blocks the heat propagation inside the examined object, in accordance with its thermal particularities. A defect has a different thermal conductivity than the rest of the material.

The paper presents the own achievements of ISIM, which are based on results obtained regarding the possibilities of using infrared thermographic technique to monitoring of the friction processing processes.

For example, fig. 1 shows a specific thermogram for monitoring of the FSW welding process, with the highlighting of the heat affected zone [4].

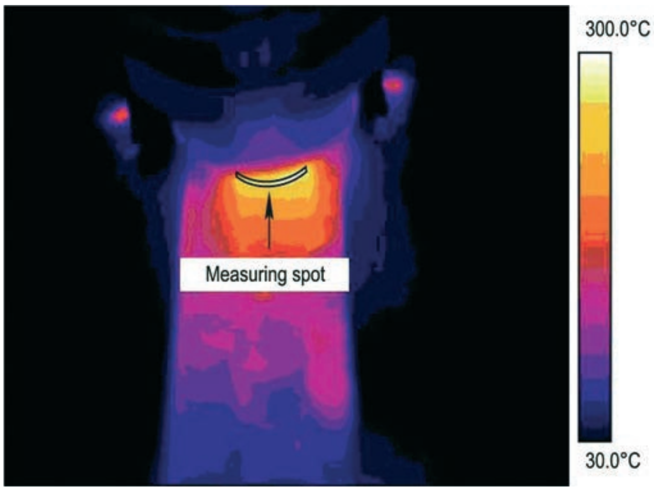

Figure 1. Thermal field during friction stir welding process (FSW) [4].

In general, welding processes monitoring by using infrared thermography can assure verification and correction of two categories of characteristics, which in the end, determine the weld quality:

- geometrical characteristics: weld width, depth of penetration, position of weld in relation with the symmetry axis, increased height of weld, the relative position of components involved in the weld formation, etc.;
- macro- and microstructural characteristics, depending on: the type of the materials, the thermal regime established and practically achieved, as well as on the uniformity in time of the thermal regime parameters.

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2. General considerations

In the field of friction processing, in recent years, ISIM Timisoara has developed extensive research programs, mainly in three directions:

A. Friction Stir Welding (FSW) is an innovative, environmentally friendly process with excellent qualities of the welded joint (when is correctly applied).

The research and activities carried out had as main results: knowledge of the process, conditions necessary for application, techniques required for application, as results worldwide obtained; conception and design of equipments, welding tools and related devices required for application with relevant results; specific friction stir welding technologies for couples of similar and dissimilar materials, in different welding variants – by overlapping, as well as butt welding.

A wide range of light metallic materials (aluminum alloys, magnesium and titanium), copper, carbon steel and stainless steel, respectively polymeric materials, have been addressed.

Figure 2 presents the sketch of the FSW process principle.

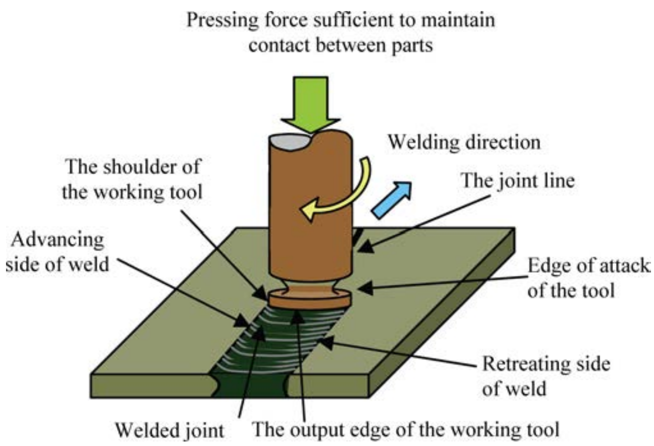


Figure 2. Sketch of principle for the friction stir welding process FSW.

B. Friction Stir Processing (FSP) is an innovative process developed from the friction stir welding process FSW, with the possibility of application for a wide range of metallic materials, in order to obtain local modifications on well-defined areas of the microstructure and of the mechanical properties / characteristics. These transformations in the processed materials may be useful, as appropriate, in some industrial applications.

In FSP processing, the tool moves on the surface of a single piece, on an established trajectory (on the processing direction). Figure 3 shows the principle of applying FSP processing in multiple passes, in order to obtain the desired properties / characteristics on a larger surface of processed material.

Friction stir processing (FSP) represents a topical field of research at ISIM, carrying out experimental research for a series of aluminum alloys (cast and laminated respectively), copper alloys (brass, bronze) and stainless steel respectively.

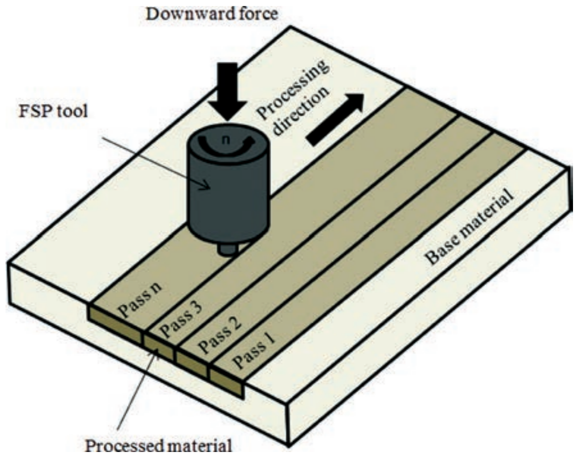


Figure 3 Sketch of principle - friction stir processing FSP.

C. Friction riveting (in the classic version), respectively riveting with hybrid effect

At ISIM Timisoara, two new innovative techniques were developed, for joining by riveting of some metallic materials: classical friction riveting, respectively riveting with hybrid effect (mechanical grip – friction welding), for which two patents applications were submitted to OSIM Bucharest (No. A/00049/05.02.2020, respectively No. A/00127/05.03.2020).

In principle, the friction riveting process has the following working sequences: rotating the rivet with a certain rotational speed → lowering the rivet through BM_1 (provided with a through hole) → lowering the rivet to reach BM_2 → lowering the rivet with a prescribed speed on a set distance →stopping the rotation movement of the rivet → release the rivet from the positioning and fixing device (fig. 4).

In the riveting process with hybrid effect (mechanical grip and friction welding) the working sequences are: → rivet rotation with the prescribed rotational speed → downward vertical movement of the rivet to BM_1 and BM_2 → rivet penetration through BM_1 with prescribed speed → rivet penetration through BM_2 at the prescribed speed → continue lowering the rivet until the rivet shoulder penetrates approx. 0.1 mm in BM_1 → stop rotation movement of the rivet → release rivet from the positioning and fixing device (fig. 5)

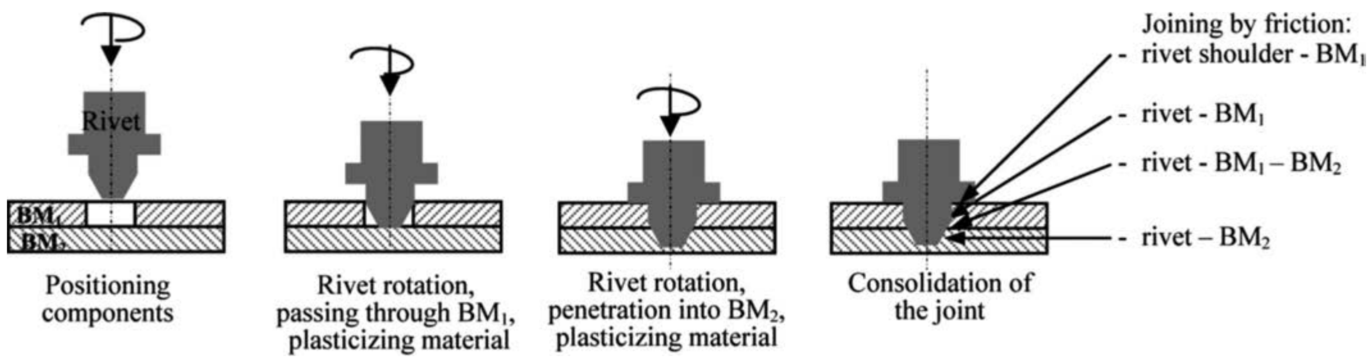


Figure 4. Sketch of principle - friction riveting process.

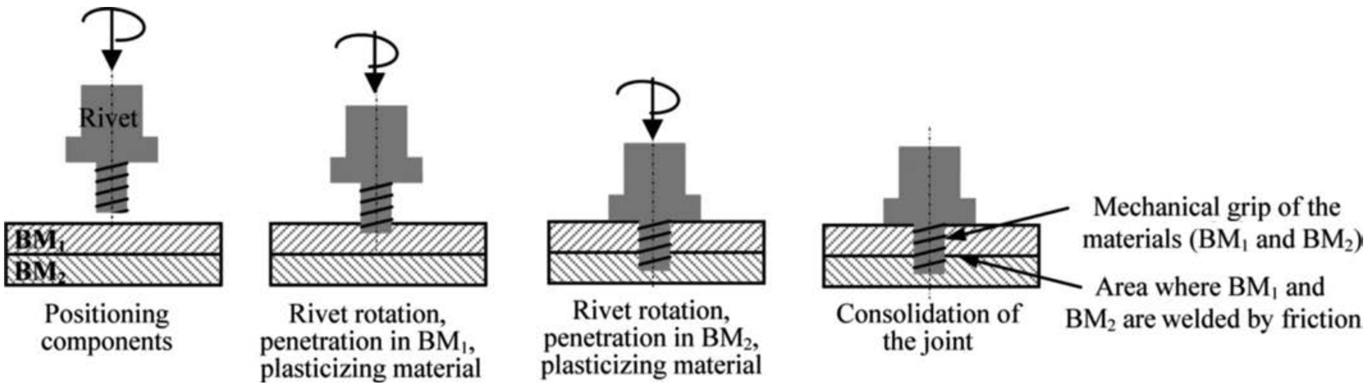


Figure 5. Principle sketch - riveting process with hybrid effect (mechanical grip - friction welding).

In all the processes mentioned above, the process temperature was monitored using the infrared thermographic technique.

3. Monitoring of the processing processes using the infrared thermography technique

Research conducted at ISIM Timisoara has shown that infrared thermography can be a viable method for monitoring of automatic or semi-automatic processes, applicable also to friction stir welding [4-6].

In the case of the FSW process, infrared thermography could have an important role in several directions:

- in order to obtain quality welds, with a well-consolidated nugget on the entire thickness of the materials to be welded, it is necessary to obtain the optimum plasticization temperature level. This level differs from material to material and is determined by the welding parameters used (welding speed, rotational speed, geometry and dimensions of the welding tool). Reaching the plasticization temperature and maintaining it at optimal values can be tracked online through the evolution diagrams obtained by using the infrared thermography system;
- identification and real-time detection of defects in the welded joint;
- providing information that can be useful in the process of evaluation of FSW welded joints, by correlating the characteristics of the joint, related to the process temperature.

For monitoring of the friction stir welding process it was used a system composed of:

- Thermo – Vision camera type A40M, having a frequency of 25 frames/s, fixed on the head of the welding machine, with specialized software for real time thermographic analysis of image;
- Therma Cam – Researcher Pro software with four hardware configurations, which allows download on the PC or laptop.

The assembly allows the adjustment of direction and distance so that the camera can constantly follow the area of ±1 mm from the intersection of tool's shoulder with the weld surface, on the almost semi-circular side behind the tool, where the temperature is maximum, according to fig. 6.

3.1. Monitoring of friction stir welding process FSW

In order to demonstrate the real, qualitative and quantitative possibilities of detecting defects in FSW welded joints by infrared thermography method, was developed an experimental program of welded joints containing simulated artificial defects by: holes, slots and implants of different sizes and materials in order to establishing the capability of the system and its validation.

The sketch of the samples with defects included in the part, which were covered with welding is shown in fig. 7.

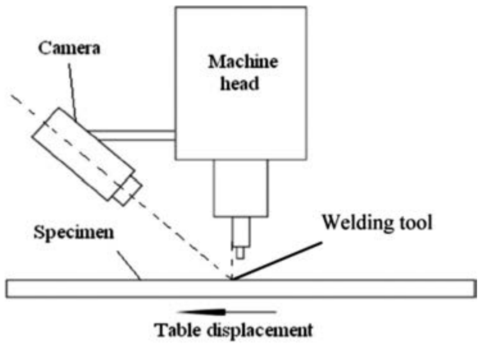


Figure 6. Sketch of the welding machine and infrared thermography.

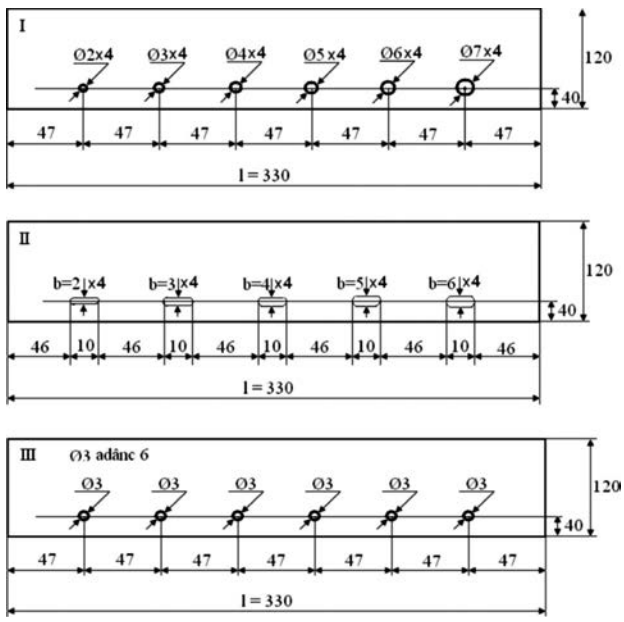


Figure 7. Sketch of specimens with artificial internal defects: a – open holes with variable diameters; b – elliptic slots with variable width; c – implants Ø 3x6 mm of Cu (2), Mg (2), tool steel (1), stainless steel (1) [7].

The types and sizes of defects varied significantly, most exceeding acceptable limits in order to determine the capability of the method in a wide range of situations.

For example, when passing with FSW welding over artificial defects such as elliptical slots with variable width

(2 - 6 mm) and constant depth of h = 4 mm, according to fig. 7b, resulted in the thermographic recording from fig. 8. The positions of the defects are marked in bold on the abscissa. The evolution of the temperature corresponding to the experiment, recorded with the thermographic camera, is shown in the diagram in fig. 8.

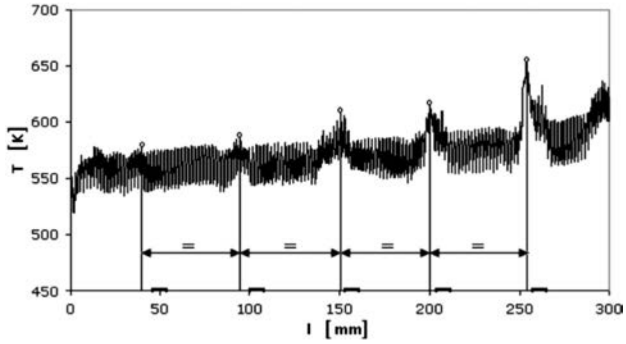


Figure 8. Temperature evolution - experiment with elliptic slots [7].

The diagram reflects a slow increase of the average temperature along the specimen in a range of 20-30 degree. This result may be caused by the general heating of the specimen during the experiment.

Significant for the experiment is the temperature jumps in the area corresponding to the slots due to local overheating. The results of the measurements are presented in Table 1. Considering the shape of the cross section, the volume displaced by the slot was approximated with the relation:

$$V = 0.85b \bullet h \bullet l = 0.85 \bullet 40b \text{ (mm}^3\text{)} \qquad (1)$$

where; b – thickness of materials to be joined, h and l – the width and the length of the slot

Table 1. The results of the measurements [7].

Slot width b (mm)	2	3	4	5	6
Slot volume 0,85 ·40b (mm^3)	68.0	102.0	136.0	170.0	204.0
Surface ~8,5b (mm^2)	17.0	25.5	34.0	42.5	51.0
ΔT (˚K)	20.7	27.5	34.5	50.0	76.0

The experiment marks out the following important aspects:

- presence of ΔT consistent temperature variations at almost all slots widths 2–6 mm;
- equidistant location of the peaks of temperature variation, proving a good degree of reproducibility in identifying the defect's position;
- peaks creation in a position where the tool's shoulder partially covers the defect [7].

Figure 9 show the temperature evolution for a specific application – friction stir butt welding of steel S420MC (EN 10149-2), having 2mm thickness.

After the stabilization of the FSW welding process, a constant evolution of the temperature diagram is observed. The fact that no large temperature variations are detected, can be an indication that the welding is performed at optimal quality parameters.

The research for the further development of the FSW procedure at ISIM Timisoara continues at present. There are ongoing activities for the research of the FSW welding process in shielding gas environment (FSW-IG).

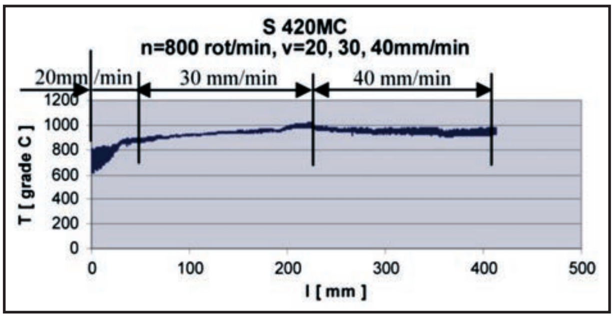


Figure 9. Temperature evolution – FSW welding - steel S420MC.

Monitoring the FSW process using infrared thermography in this case, involves finding solutions adapted to this new situation.

Figure 10 shows the assembly used if the shielding gas is supplied to the welding area through a piping system that does not block the area of action of the thermographic camera on the materials to be welded.

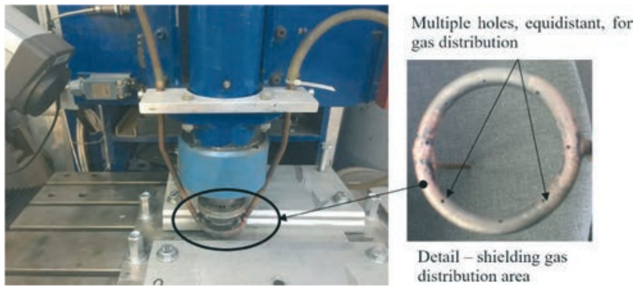


Figure 10. Shielding gas supply assembly for FSW-IG.

In this case, when welding FSW in a shielding gas environment of titanium TiGr2 (thickness 4mm), the temperature evolution diagram (fig.11) is similar to the classical situation, in which shielding gas is not used.

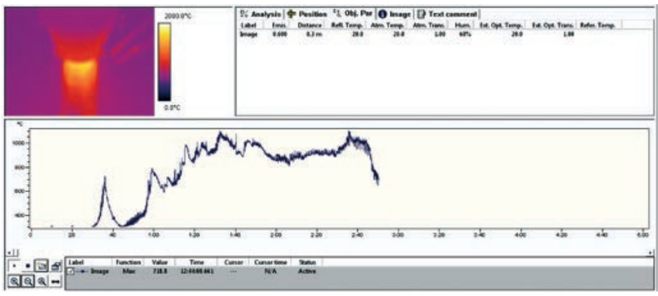


Figure11. Temperature evolution diagram for FSW-IG of titanium Ti Gr2, 4mm thick.

For the variant in which a closed enclosure was used to ensure the shielding gas (fig.12), much lower temperature values were recorded T_{max} ~ 500˚C (fig.13), compared to the temperatures recorded if no such enclosure was used T_{max} ~ 1.180˚C (fig.14), due to the fact that between thermographic camera and temperature investigation place, the wall of gas enclosure (made of Plexiglas 10mm thick) was interposed.

Figure 12. Enclosure for shielding gas supply (FSW-IG).

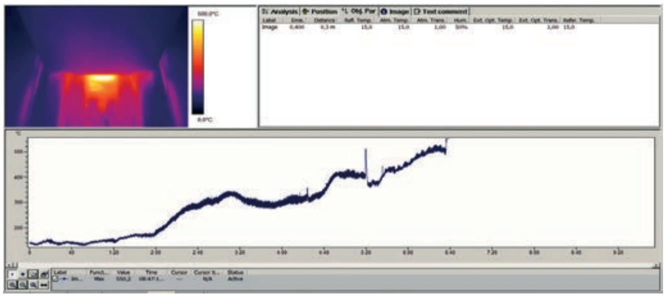


Figure 13. Temperature evolution diagram for FSW-IG (using enclosure for shielding gas supply).

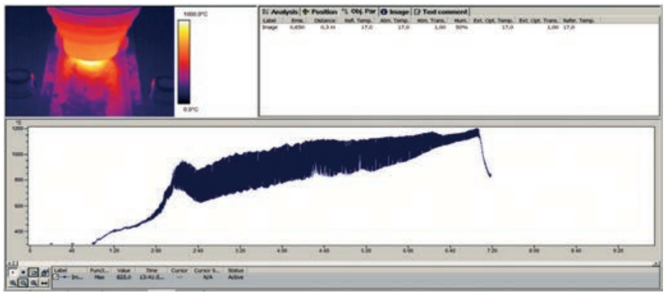


Figure 14. Temperature evolution diagram – DD13 steel welding.

In view of this, a technical solution is being developed to ensure the correct use of the thermographic camera in case that the shielding gas is provided through a closed enclosure.

3.2. Monitoring of the friction stir processing process FSP

By applying the friction stir processing FSP process, the local modification of some properties of materials for specific applications, it is desired.

For this reason, in the case of friction stir processing, a very important role is played by the value of the temperatures at which the process takes place.

Temperature being a very important factor in the process of forming of the processed area and in generating of its microstructural and mechanical characteristics, it was proceeded to monitoring and control of the temperature evolution, as a process parameter also for this process.

When using the thermographic camera, all measurements for which the temperature diagrams were taken, were performed on the processed materials in the immediate vicinity of the processing tool, at a distance of ~ 1 mm behind the tool shoulder. The evolution of the temperature for each FSP pass and as a whole was analyzed on each processed material, for successive passes made on the same piece. For example, fig. 15 shows the temperature evolution graphs for processing in 5 successive passes of AlSi12 alloy, using a processing tool with M6 threaded cylindrical pin and smooth shoulder diameter $Ø_{shoulder}$ = 20 mm, rotational tool speed n = 1000 rpm and processing speed v = 150 mm/min.

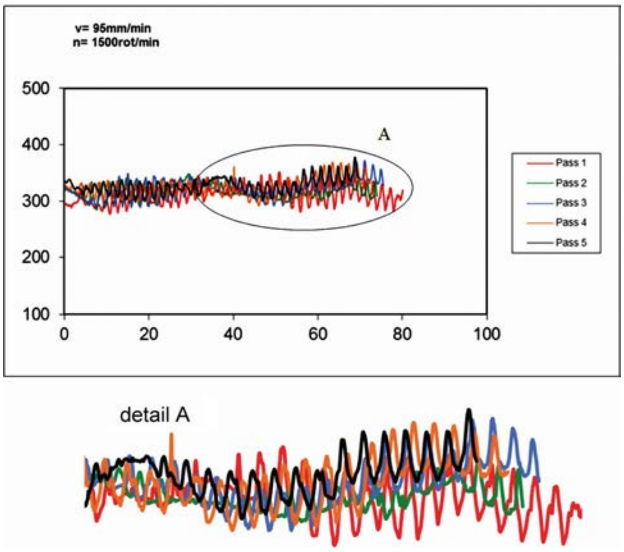


Figure 15. Temperature evolution graphs – friction stir processing in multiple passes.

The first pass was made with the material subjected to FSP processing, at ambient temperature (≈20˚C). The 5 successive passes were made at equal time intervals, ~2 min. The difference between the average temperatures developed at the first pass (≈310˚C) and the last pass (≈330˚C) is ~20˚C.

Temperature monitoring was useful for determining process temperatures in all stages of the process, reported at each pass separately. A comparative study of the evolution of the temperatures from one pass to another could be performed. This fact was the basis of some analysis of the characteristics of the processed areas, related to the areas corresponding to each passing.

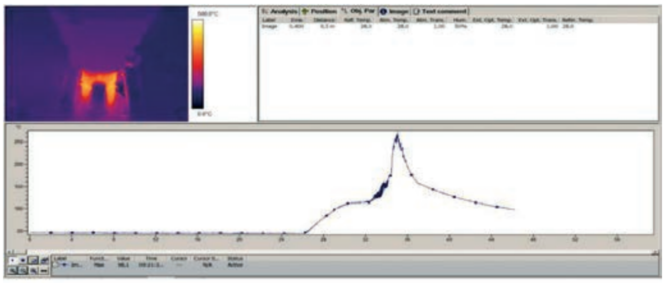
3.3. Monitoring of the friction riveting and hybrid riveting processes

Classic friction riveting is an innovative process, proposed for development by ISIM Timisoara. In this procedure, too, the use of infrared thermography was tested to control and monitoring the process. For example, fig. 16 shows the evolution of the temperature during the classic friction riveting of some EN AW 1200 sheets with EN AW 5083 rivets, EN AW 6082 sheets with EN AW 6082 rivets, respectively EN AW 7075 sheets with EN AW 7075 rivets.

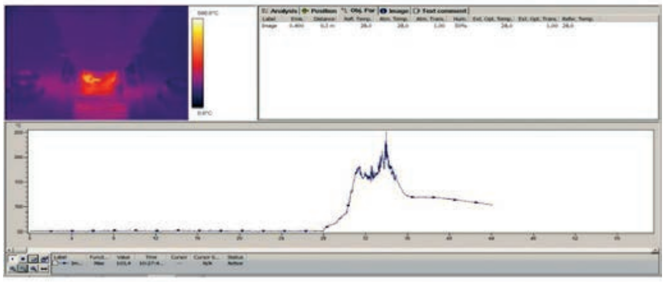
The maximum process temperature is mainly determined by the following factors: sheet materials, respectively rivet material, process parameters (rivet rotational speed), force and time of pressing the rivet shoulder on the base material located above (BM_1). Thus, the maximum process temperature can be used as a process parameter in correlation with the maximum pressing force of the rivet shoulder on the BM_1 surface, as follows:

- the maximum temperature for a certain specific application (for which a joint with good properties was obtained) is determined by experiment;

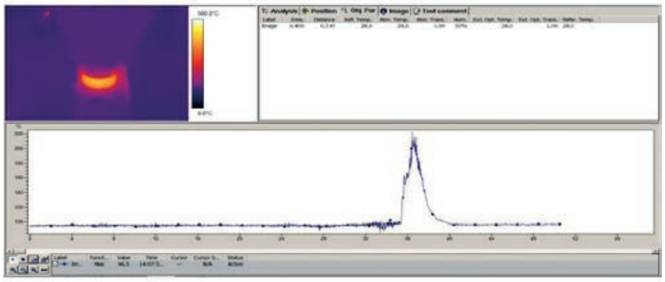
- this temperature will become a process parameter, in addition and in correlation with other factors / parameters of rivet that can influence the joint quality (rotation speed, material, action time on BM_1 and BM_2, etc.)



a. (T_{max}~270°C) ENAW1200/ENAW1200, rivet EN AW5083



b. (T_{max}~250°C) ENAW1200/ENAW6082, rivet ENAW6082



c. (T_{max}~220°C) ENAW1200/ENAW7075, rivet ENAW7075

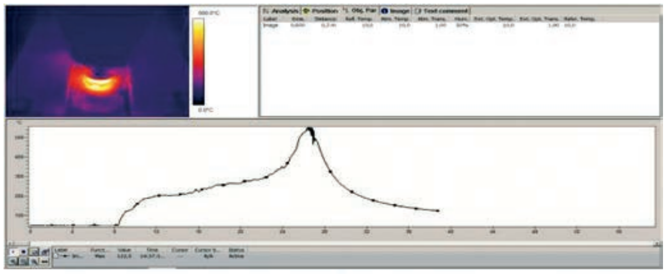
Figure 16. Temperature evolution – friction riveting.

In friction riveting with hybrid effect, the use of infrared thermography in process monitoring is applied according to the general principles presented in conventional friction riveting. The following aspects will be taken into account:

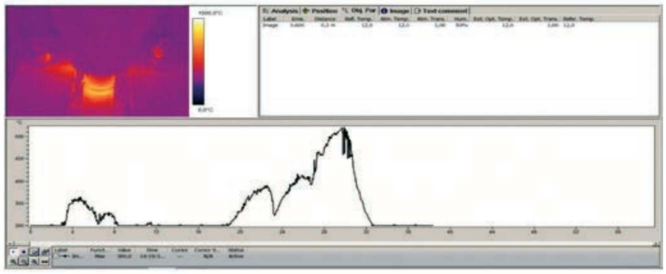
- the rivet acts on both materials (BM_1 and BM_2);
- BM_1 and BM_2 are soft materials (Al, Cu, Mg alloys);
- the rivet is threaded and made of steel resistant to mechanical stress;
- the process temperature is mainly dependent by the type of the materials to be joined, and in the case of dissimilar materials, and how they are placed relative to each other.

Figure 17 a) shows the temperature evolution to the friction riveting with hybrid effect of two sheets from EN AW 1200, using M6 threaded rivets made of C45 steel. The maximum temperature for which quality joints were obtained was 560˚C. Figure 17 b) and c) show the evolution of temperatures at the joint by hybrid riveting of Cu99 with EN AW 6082 sheets, using M6 threaded rivets of C45 steel. There is a very large temperature difference (approx. 320˚C) between the two modes / possibilities of placing the sheets.

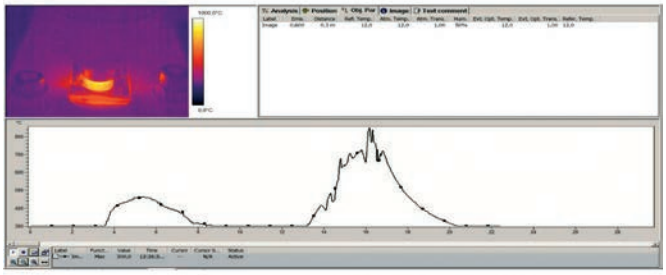
Also for this riveting process, the temperature can be an important parameter, which can be established by experiment for each specific couples of materials to be joined.



a. (T_{max}~ 560°C), EN AW 1200/EN AW 1200, rivet(M6) C45



b. (T_{max}~ 520°C) EN AW 6082/Cu99, rivet (M6) C45



c. (T_{max}~ 840°C) Cu99 /EN AW 6082, rivet (M6) C45

Figure 17. Temperature evolution – riveting with hybrid effect.

Processes monitoring using infrared thermographic technique has been used with good results in the monitoring of other innovative processing processes, promoted by ISIM: deposition (by friction with consumable tool) of functional layers of aluminum alloys on steel substrate, as well as friction stir soldering using ecological bonding materials [8].

4. Conclusions

• Worldwide, the use of infrared thermography is in full development and rise at worldwide level, including in the fields of welding, but also in the control and testing of materials.

• Worldwide, for the real-time monitoring of the FSW welding process, an already established method is used: monitoring the process by controlling the pressing force Fz of the FSW tool on the materials to be joined.

• ISIM Timișoara has proposed, developed and implemented a new method for monitoring of the FSW welding process, based on the use of infrared thermographic technique

• The technique necessary for the application of this type of monitoring was conceived, designed and realized, a technique that allowed the integration of the thermographic camera on the welding machines and its use in optimal conditions.

• It was experimented the use of monitoring in the FSW process but also in friction processing processes, derived from FSW: FSP processing, respectively friction riveting.

• The results of complex experiments have shown that infrared thermography can be used to monitoring the FSW process, as well as FSW derived processes, being able to provide important information on:

- Stability of the welding process; disturbances during the actual welding process and even the detection of welding defects may be reported in real time. Research continues to determine the size of defects that can be detected using the infrared thermographic technique;
- The evolution of the temperature during the welding process, which can be very useful when evaluating and analyzing the welded joints.
- Establishing temperature values by experiment, for specific applications, can be the basis for establishing temperature as a process parameter.

• It has been shown that the system used for online monitoring of the FSW welding process has a good reproducibility compared to a wide range of defects only if they exceed a certain displaced volume (≥25 mm^3).

• The non-destructive control applied post-operatively was able to confirm the presence, volume and location of the defects, thus contributing to the validation of the adopted monitoring system.

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