Contributions to the development of modern riveting processes

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1. Introduction

Currently, there are many dedicated metal joining methods, depending on the field of use, the type of application and the materials used. The riveting operation involves a rigid assembly between two or more plates (or profiles) using rivets as intermediate pieces, these being made of malleable materials (aluminum alloys, copper alloys, brass, soft steels, stainless steels, alloys zinc, etc.). [1], [2], [3]. Classical manual riveting requires preparatory operations (e.g., surface cleaning, hole centring, table drilling, riveting positioning) followed by riveting and deburring. These operations require a great deal of work, time and resources, resulting in low productivity [4]. As a result, manual riveting is only performed on individual production and in maintenance and repair shops [5].

The classic mechanical riveting uses specialized machines (for mechanical riveting, pneumatic, electromechanical or electromagnetic portable mechanical riveting hammers, riveting presses, riveting machines), reducing the working time, lowering costs and thus increasing productivity. Also, at mechanical riveting, the material spill and the filling of the riveting hole are better achieved, thus increasing the joint strength [4].

In the present paper there are presented ISIM Timisoara contributions for the research, development, promotion and application of a hybrid riveting process, which has the effect of combining mechanical grip - friction welding.

The riveting process with a hybrid effect (mechanical grip and friction welding) is an innovative variant of joining metallic materials. Joining techniques using this process have great potential for development and implementation in important industrial areas.

The process has been researched, experimented and developed at ISIM Timisoara for the joining of various aluminum alloys (with different properties) and industrial copper by hybrid riveting.

The tests and evaluations made allowed to obtain important primary technical data on the principle of the process, how to form the joint, data on the technological parameters, the configuration of the rivets and the influence factors.

2. Substantiation the research

Friction Stir Riveting is a joining method patented by specialists from General Motors Corporation [6], developed by the University of Toledo [7], designed to join similar or dissimilar light metal materials. Another variant of the friction riveting process was patented by researchers from GKSS Research Center Geesthacht GmbH Germany [8] as a new solid state joint technique, applicable to the joining of polymeric materials or thermoplastic materials using bolts (rivets) made of various metal alloys. These processes can be ecologically and economically efficient alternatives to spot welding processes [9], [10].

Friction or form drilling (FD) process [11], [12] is a non-conventional process to make holes on metal sheets. It is an alternative process, compared to conventional drilling. It is based on the material flow, by using the heat caused by the friction of a conical-shaped rotary tool without cutting edges. The friction drilling tool has two different sections: a conical surface that penetrates the hole and softens the sheet material and a cylindrical segment that calibrates the final hole diameter. Finally, a high burr appears at the hole outlet, that has the shape of a cup. Burrs are undesirable in common machining operations, because they reduce machined part quality. But here, the cup eliminates the need of using a nut in the joint, since threading is applied on the cup inner surface.

Recently, in the frame of the project J-FAST [12], some experiments have been performed on a dissimilar joint of a square-section tube (50mm x 50mm) of S235 steel, according to EN 10 025, to be surfaced with sheets of aluminium alloy EN AW 5754 (thickness = 1.0 mm).

Carbide tools (90% WC and grain size 1 micron), with Ø = 4.3 mm were employed for friction drilling, as shown in the Figure 1.

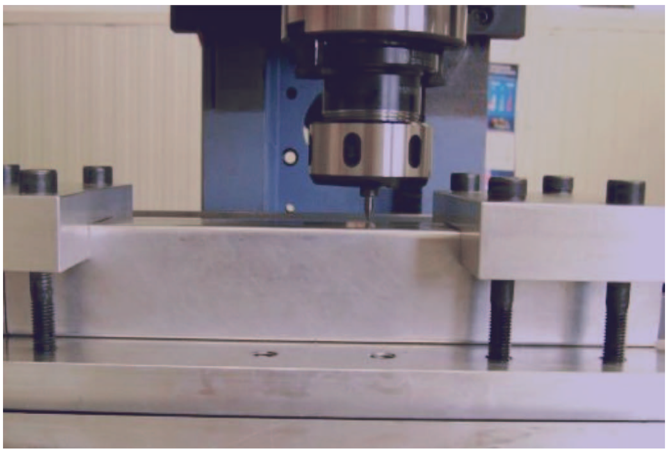

Figure 1. The execution of the holes by the FD process [12].

Form tapping for threading is a process where the holes need to be threaded by form tapping [11], [12]. These taps have polygonal geometry with at least five lobes. They are mainly made of high strength steel coated with titanium nitride (TiN), to provide a core with enough toughness and harder surface. In some cases, anti-friction coatings or internal lubrication

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are advisable. Also, they may have tapered cutting edges with smaller diameter to initiate the material removal. According to the hole machined with the Ø = 4.3mm form tool, a form tap for M5 thread was selected.

In form tapping, the maximum depth of the thread and the maximum thread pitch are the most important parameters.

A form tapping is characterized by the entrance zone, at the tool tip, which has a tapered geometry where the lobes progressively rise to the nominal diameter (according to ISO 8830) and also by the cylindrical part, which acts as a supporting system, guiding the tap during threading operation. The maximum depth of thread is significantly higher than in the case of conventional tools for threading by cutting. It is limited by the quality of the coolant and the tool length. The maximum pitch of the thread depends on the material properties of the workpiece.

A test series of threading operations was carried out with form taps, to select the most suitable process parameters for threading, as presented in the Figure 2.

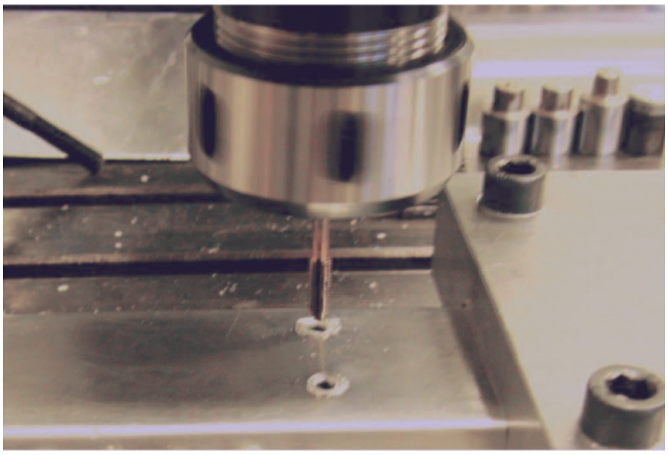

Figure 2. Threading by form tapping of a EN AW 5754 aluminium alloy sheet placed on a 50 mm x 50 mm steel tube [12].

Rotary broaching is an optional process for the final calibration of the holes. The tools for this process consists of a lot of very small chisels on a round part, as a whole.

Alternative friction processing methods are: friction stir riveting, friction drilling, threading by forming, rotary broaching, as well as friction stir welding (FSW). These processes are proposed to increase productivity by the execution of rapid joints in large-scale industrial production technologies.

The target applications of all these processes are dissimilar joints of materials of the categories: carbon steels, low alloy steels, stainless steel, nickel, copper, aluminum alloys, titanium alloys, composites and polymers.

The good results obtained in the world and within ISIM Timisoara in the application of friction processing methods presented have scientifically and technically supported the efficient approach of the new riveting process with hybrid effect.

3. Experimental program

During the experimental program the experimental technique from ISIM was used, research programs were made on couples of similar and dissimilar materials such as: aluminum alloys, respectively industrial copper.

3.1. Experimentation technique

The experimental program was carried out on a complex experimentation technique (Figure 3), consisting mainly of three functionally independent systems:

- FSW machine - pos.1 (main shaft rotation speed - max 1450 rpm, vertical travel speed – 30÷190 mm / min), on which is mounted a positioning and fastening device for materials to be joined (pos. 2) and the rivet together with the rivet holding device (pos. 3).
- A system for tracking and controlling the riveting force of the rivet on the base materials during the riveting process, with a force transducer fixed to a device on the FSW machine (pos. 4a), using a data logger, a modular voltage source and a PC for data acquisition, storage and processing (pos. 4b).
- A monitoring and control system of the temperature that is developed on the rivet shoulder (pos. 5) using an infrared thermography camera attached on a positioning and fastening device, respectively a PC for data acquisition, storage and processing).

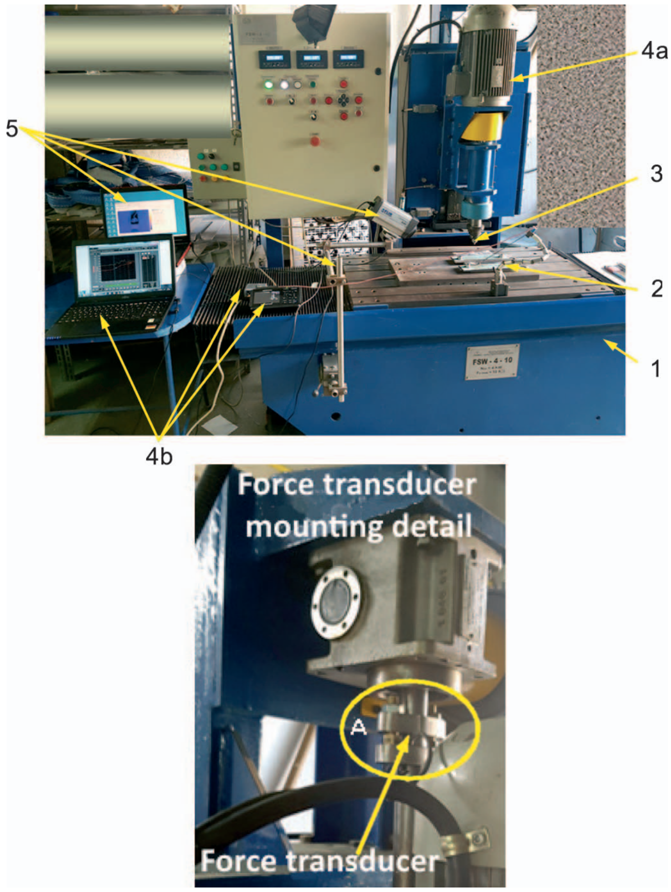

Figure 3. FSW machine interfaced with temperature and force monitoring systems.

3.2. Materials to be joined using hybrid riveting process. Rivets

In the paper there are presented some results obtained at joining of EN AW 1200 as similar materials, respectively at joining of the dissimilar material couple EN AW 6082 - Cu 99. The rivets were made of C45 steel as delivered, or heat treated at 40-42 HRC. The size of the active part of the rivet was M6, with length correlated with the thickness of the materials to be joined. The rivet shoulder was made with a diameter $Ø_{shoulder}$ = 16mm.

Figure 4 shows the constructive solution of the rivets used in the experimental program.

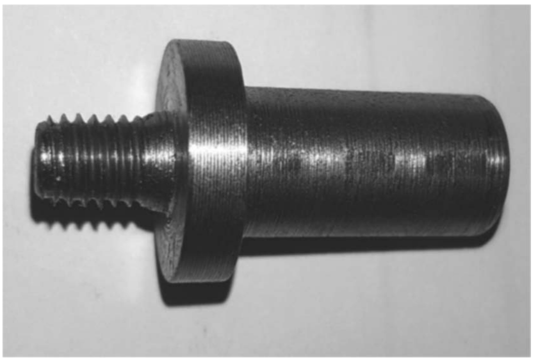

Figure 4. Constructive solution of rivet used in the experimental program.

3.3. Experiments for hybrid riveting joining

In the paper there are presented some results obtained in the experimental programs for joining of similar alloys (EN AW 1200), as well as results obtained by joining dissimilar couples such as aluminum-copper alloy materials.

3.3.1. Joining by hybrid riveting process for Aluminum EN AW 1200 sheets.

The technical data and dimensional characteristics of the base materials, rivets used and process parameters are shown in Table 1.

Figure 5 shows the macroscopic analysis of a hybrid riveting joint for EN AW 1200 (BM_1, BM_2) with C45 steel rivets.

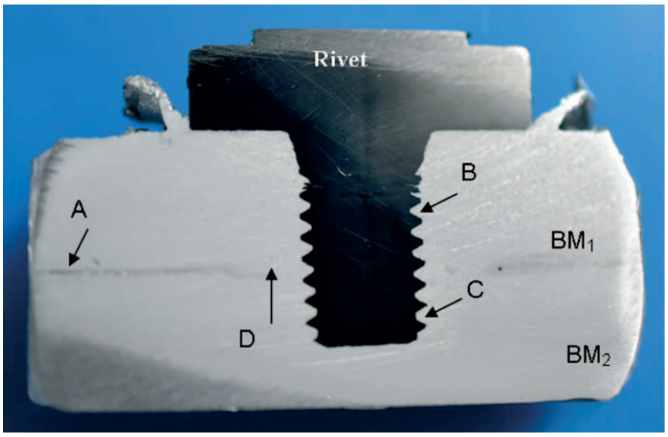

Figure 5. Macroscopic analysis for hybrid riveting experiment with EN AW 1200 (BM_1, BM_2) with C45 steel rivets. Characteristic areas: A - the separation zone between BM_1 and BM_2; B - mechanical joint rivet - BM_1; C - mechanical joint rivet - BM_2; D - friction welding BM1.

In this experiment it was found that the use of high rivet rotational speeds during the process was favourable, in this case the process forces were much lower. For example, at the same geometrical and dimensional characteristics of the rivetsand for a rotational speed of 1450 rpm, compared to 1100 rpm, the force developed in the process had lower values, with approx. 32-33%. The reduction of the forces during the riveting process is favourable from the point of view of the construction of the equipments for the application of the process and especially for the realization of portable/mobile riveting equipment).

Figure 6a shows the evolution of the resisting force values of the materials to be joined on the rivet, during the riveting process. The force has recorded a measured value of 8,300N at the impact between the rivet shoulder and BM_1.

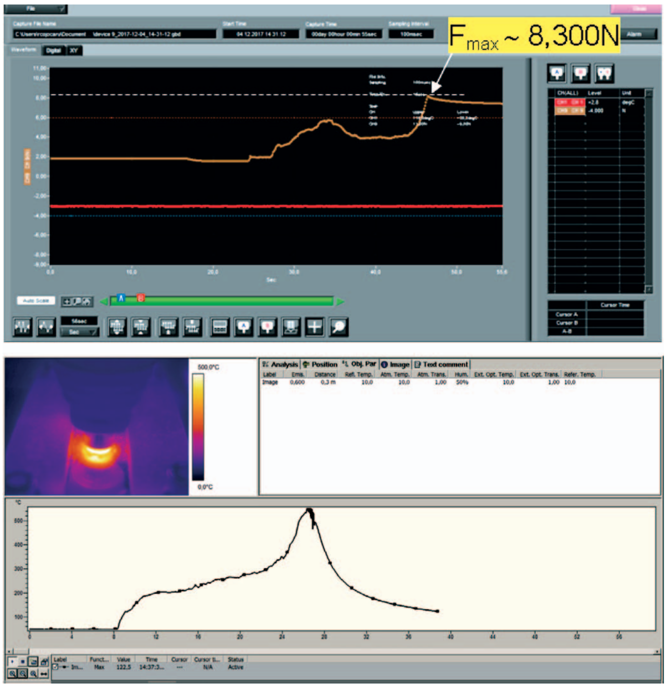

Figure 6. Evolution of values: (a) the resisting force of the materials to be joined on the rivet, during the joining process; (b) the temperature during the joining process (Tmax = 560° C).

The axial movement speed of the rivet (the speed with which the rivet penetrates into the materials to be joined) is important mainly from two points of view:

- Volume of BM_1-BM_2 area joined by friction - This volume decreases as the axial speed of the rivet increases. A larger volume gives a greater mechanical strength of the hybrid joint.
- The productivity of the riveting process - Because of the economic efficiency aspects, high axial speed of the rivet are preferred. Foe example, under the same process

Table 1. Experimental Technical Data - Hybrid Effect Riveted Joining (EN AW 1200).

Base materials		Rivet			Processing parameters		
Thickness BM_1 (mm)	Thickness BM_2 (mm)	Material	Type - cylindrical threaded	Active part length, $L_{pa\ rivet}$ (mm)	Rotational speed, n (rot/min)	Axial speed, v (mm/min)	Rotation direction
EN AW 1200 (6)	EN AW1200 (6)	C45 steel	M6 $Ø_{shoulder}$ = 16,0mm $g_{shoulder}$ = 3.0mm	10,0	1450 1100	10 - 40	counter clockwise

conditions, at the speed of 10mm / min, the maximum diameter of the friction joint is ~31mm and at the speed of 30mm / min, the maximum diameter is ~ 28mm.

Figure 6b shows the temperature evolution during the actual riveting process. Temperature monitoring is important because it provides information on the degree of plasticization of the materials to be joined, an important factor in "mixing" the two BM_1 and BM_2 materials in order to achieve the friction joint. It is noticed that the temperature value increases progressively to a value $T_{max.}$ of 560ºC, which coincides with stopping of the joining process (stopping the rotation and vertical movement of the rivet).

3.3.2. Hybrid-riveted joint on EN AW 6082-Cu99 material couple (s = 3mm), with C45 steel rivets.

The technical data and dimensional characteristics of the base materials, rivets used and process parameters are shown in Table 2.

Figures 7 and 8 show the macroscopic analysis for hybrid riveting samples where EN AW 6082 is located above and Cu99 underneath, respectively Cu 99 is located above and EN AW6082 underneath.

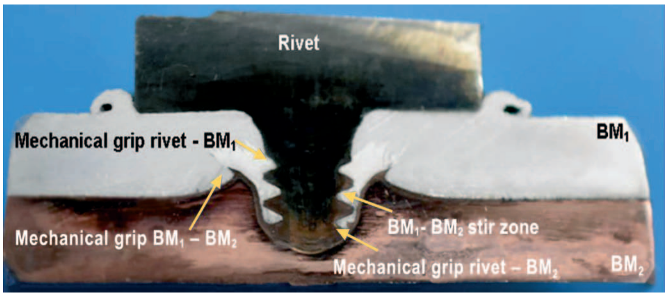

Figure 7. Macroscopic analysis hybrid riveting experiment (EN AW 6082 / Cu99 sheets).

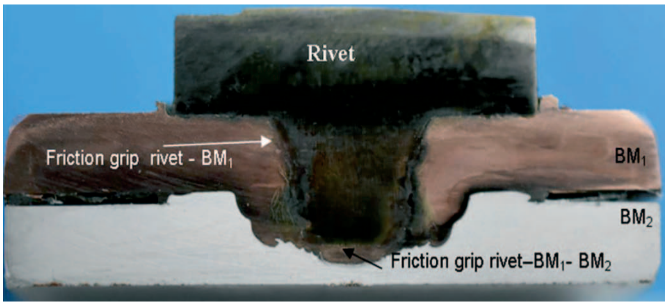

Figure 8. Macroscopic analysis hybrid riveting experiment (Cu99 / EN AW 6082 sheets).

The macroscopic appearance (Figure 7) highlights the three types of joints of the rivet-BM_1-BM_2 assembly: friction joint (mixing zoneBM_1-BM_2); mechanical grip (rivet-BM_1 and rivet-BM_2); mechanical grip BM_2-BM_1 (Cu anchoring in Al). In Figure 8, due to the characteristics and properties of BM_1 (copper) material, it is noted that the thread of the active part of the rivet was mixed with the copper, and it was very possible that it formed a friction joint with it. There is a rather extensive copper area (possibly mixed with aluminum) that formed around the rivet in BM_2 (aluminum). This can give the joint very good mechanical characteristics. The tendency to form the BM_1-BM_2 mechanical grip, if the copper sheet is placed above it, is less obvious / present than if the aluminum sheet is located above.

The shear breaking test was performed for both overlay variants of the base materials. If EN AW 6082 is positioned above, shear occurred at a force F_{max} = 5.532N, and when Cu99 is positioned above, the rupture occurred at a force F_{max} = 10.854N. In order to be able to analyse the effect of hybrid effect riveting, compared with the mechanical grip, screws were also used for both cases.

In the shear test of the screw joint, the maximum breaking force was F_{max} = 9.142N (EN AW 6082 / Cu99) and F_{max} = 9.618N (Cu99 / EN AW 6082). By analysing the two joints (by riveting and by mechanical assembly), it was found that the breaking force of the riveting joint (EN AW 6082 / Cu99) represents about 60.5% of the breaking strength of the screw joint and for the Cu99 / EN AW 6082 sheets experiment the breaking force was higher by approximately 12.85% for the joining of sheets using hybrid effect riveting compared to the mechanical fastening (screw).

4. Discussion

Experiment based research has demonstrated that for the application of the new riveting process with hybrid effect it is necessary to use the correct and validated experimental technologies. Precise conditions for process parameters are required.

At the riveting with hybrid effect, the process technological parameters are:

• Rivet rotational speed - Experiments have shown that high rotational speeds (n > 1300 rpm) are favourable due to the fact that application of these rotational speeds leads to plasticisation, flow and optimal mixing of the materials, the effect being: the formation of an efficient mechanical joint (the flow of BM_1 and BM_2 materials determine the interaction with spirals of threads and "fills" the spaces between spirals), forming a larger volume of BM_1-BM_2 friction joint. In the case of the experimental programs that were developed, the best results (irrespective of the similar or dissimilar material couples BM_1-BM_2) have been

Table 2. Experimental technical data for Hybrid Effect Riveted Joints (EN AW 6082-Cu99).

Base materials		Rivet			Processing parameters		
Thickness BM_1 (mm)	Thickness BM_2 (mm)	Material	Type - cylindrical threaded	Active part length $L_{pa\ rivet}$ (mm)	Rotational speed, n (rot/min)	Axial speed, v (mm/min)	Rotation direction
EN AW 6082 (3)	Cu99 (3)	C45 steel	M6 $Ø_{shoulder}$ = 16,0mm $g_{shoulder}$ = 3.0mm	5,0	1450	15-25	counter clockwise
Cu99 (3)	EN AW 6082 (3)						

obtained using the maximum rotational speed value provided by the FSW equipment (n = 1450 rpm).

• It is possible to improve the process conditions at rotational speeds n > 1450 rpm, and plasticizing of materials to be produced more quickly, thereby reducing the resistance to penetration and advancing of the rivet in the materials, which would allow axial speed increase, contributing to increased productivity (increased economic efficiency of the process).

• The axial penetration speed of the rivet into the materials. Correct correlation of axial speed with the rivet rotational speed is required to achieve optimal plasticisation of BM_1 and BM_2 (as described above). Too high axial penetration speed, correlated with insufficient material plasticization, may cause rupture / shearing or excessive plastic deformation of the rivet. Depending on the nature of the base materials, the speed may be in the range of 10-40 mm / min for the couples of materials used, higher in aluminum alloys than copper alloys. Too high value of the speed penetration of the rivet into the base materials (correlated with insufficient gripping of the rivet) may result in the plates being separated and forming a space between them.

• The pressing force of the rivet on the package of materials to be joining is a very important parameter and relates especially to the moment when the shoulder of the rivet begins to press on the base materials. The value of the force is determined experimentally and depends on the nature and thickness of the base materials in correlation with the geometry and dimensions of the active part of the rivet, respectively the diameter of the rivet shoulder. Examples of forces in concrete applications joined by riveting with a hybrid effect, using C45 steel rivets: ~8,300N, at EN AW1200 (6mm) / EN AW 1200 (6mm) couples of materials; ~11,000N, Cu99 (3mm) / EN AW 6082 (3mm) couples of materials; respectively ~18.000N, EN AW 6082 (3mm) / Cu 99 (3mm) couples of materials .

• Geometry and dimensions of the rivet; sense of rotation of the rivet - in part 3.2 was presented the constructive variant for which the extensive experiments showed very good results. Reference is made to the rivet with the threaded active part. Specific technical assessments are also presented regarding their design and conception. The threaded solution of the active part of the rivet makes the "rotation direction" parameter very important. A counter clockwise rotation is required on a normal metric thread (right). This produces a pronounced friction between the active part of the rivet and the base materials, having as a principal effect plasticisation and a favourable flow in order to form the friction joint. The clockwise direction would favour the appearance of the cutting effect (threaded processing) and thereby reduce friction, with a negative effect on plasticization and mixing of the base materials. The friction joint formation effect in this case is much diminished or does not occur. When using a "left" thread for the active part of the rivet, the rivet must be rotated clockwise.

• Process temperature - The temperature at which the riveting process takes place may become a technological parameter if, depending on the other prescribed parameters, the riveting process is interrupted to a certain temperature value, previously established by the experiments, for each of the couples of base materials approached. In order to use the temperature as a process parameter, riveting equipment needs to be complemented with a real-time temperature control system, which can be quite costly (e.g. if the infrared thermography technique is used). Diagrams with the temperature evolution during the riveting process highlights the maximum process temperature (which coincides with the moment of the process interruption).

5. Conclusions

By implementing the new hybrid-riveting process, a number of advantages over conventional joining procedures are obtained:

- considerable labour saving compared to conventional riveting is achieved, as well as by eliminating some of operations compared to mechanical screw joint. Preliminary holes are removed (making a thru-hole in the sheet above, making a hole in the underlying plate, threading at M6, the hole in the sheet underneath). It can be estimated that the execution time in the case of the joint by the riveting process with a hybrid effect is considerably reduced compared to the conventional riveting, respectively to the mechanical screw joint.
- is a jointing process that can be applied to the joining of materials with different properties and characteristics that cannot be joined with other processes or otherwise very difficult to join.
- no further processing is required which to determine increase the costs.
- the process is environmentally friendly, non-polluting
- the hybrid-riveting process is a promising alternative for joining similar and dissimilar metallic materials as compared to other material jointing processes.
- results obtained may be the basis for improving the methods of application of the approached process, for implementation in industrial activities.

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