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Friction riveting of thermoplastic composite with a CNC machine: experimental work

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Abstract

Friction riveting is studied to reinforce welded aeronautic thermoplastic composite parts. The aim of this research line is to develop a full friction riveting process, from the implantation, to the closing of the assembly, and to include this process in the production line using a robotic arm holding the rivet or the tool. Before it, the two basic processes are studied: the rivet is made of Ti6Al4V while the plates to join are in CF-AE 250. The implantation of the rivet is based on Friction Stir Riveting (FSR) while the closing phase, the rivet head forming, inspired on Friction Forge Riveting (FFR). This article presents experiments performed with a CNC machine to explore the effects of manufacturing parameters on the quality of these two processes. Spindle speed range and feed rates are studied in order to try to process to these riveting methods as the CNC machine is only controllable in speed and position control. The experiments data are composed by the CNC machine data and temperature measurement taken by an IR camera.

Keywords: Smart manufacturing, Thermoplastic composite, Forming process, Friction riveting, Process monitoring

1. Introduction

Aeronautical structures are assembled using several processes. Conventional bolted assemblies require to pre-drill the part as a first step. For composite assemblies, parts are often glued together, then secured by rivets placed to avoid disbond propagation between them. The resulting hole can introduce weakness into the composite parts. It is possible to drill the composite plates separately before the assembly. But this procedure can generate an alignment default in the plate [1]. Friction Riveting processes are considered as a good alternative for reinforcing multi-material assemblies.

Inspired by Friction Stir Welding process, Amancio [2] developed Friction Stir Riveting (FSR) process using aluminum rivet on PEI plate and demonstrated the feasibility of this process on thermoplastic material. The rivet in high-speed rotation is set in contact at the plate upper surface applying a friction force. In a second phase, the force increases to implant the rivet in the plate while the rotation speed decrease. A consolidation phase allows the rivet to cool down. A cartography of thermally affected zone can be initiated in the continuity of study of FSW. Blaga *et al.* [3] studied the tensile pull-out behavior of the joints of glass fiber reinforced polyetherimide and titanium grade 2 and they found that the joints produced a good mechanical performance, achieving an ultimate tensile force of up to 4 kN. Comparing with a bolted joint, the ultimate lap shear force is demonstrated to be up to 20% higher [4].

Since, friction riveting has been updated with the study of Zocoller-Borba [5], introducing a new and simplest way to perform a riveting process by friction. Studies found out that the forging force, and so the forging phase could be eliminated. Based on this statement, Direct Friction Riveting is tested and presented as a more efficient and phase less FSR. These studies [6, 7] are about the feasibility of Direct Friction Riveting process on thermoplastic composite using CF-PEEK plates and a titanium rivet.

Design of experiment allowed to show the importance of process parameters to perform a FSR process on composite. The principal steps of the FSR are illustrated in Figure 1.

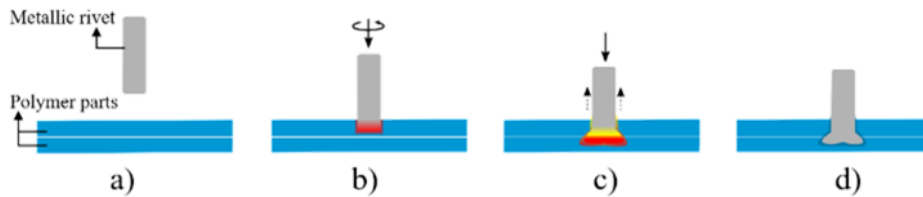


Figure 1 - Principal steps of Friction Stir Riveting process [7]

Altmeyer *et al.* [8] studied the direction taken by the fibers during a process by observing the microstructure obtained with their experiments. The study used PEEK reinforced with 30 wt.% short carbon fibers. It can be observed that fibers take the inverse direction of the rivet.

In all these studies, no information are provided in order to complete the rivet on its external side after these implementing steps. Usually, plastic deformation on the rivet head (external side) is the most employed method to close the assembly after the implantation of the rivet. Special machines, pneumatic or electromagnetic [9, 10] are mainly used. To perform a plastic deformation on the rivet head, a force is applied on the fastener and its amplitude can vary with the different techniques. But they can lead to defects in the assembled plates or/and in the rivet head, which can lead to assembly weakening, and many study mention these types of problem.

The impact of the process parameters on the assembly's quality have been studied by Korbel [11] and Cheraghi [12] using numerical simulation. They worked on the influence of the forming force, the rivet's dimensions and the diameter of the hole to show logically that an increase in the riveting force was given with the increase of the rivet's diameter. Xie *et al.* [13] worked on the effect of ultrasonic vibrations to improve the assembly quality. The vibration can reduce the force needed to form the rivet head. Manes *et al.* [14] studied the stress concentration using Crossland criterion and showed the importance of riveting force to characterize the stress field around the fastener, as this field can impact severely the lifetime of the structure. Lepretre *et al.* [15] worked on a numerical simulation of hot riveting process. Their work aims to improve the stress field around the rivet hole and showed the creation of cracks on the edge beneath the formed rivet head.

An alternative method using friction has been proposed by Ni *et al.* [16], [17]: Friction Forge Riveting (FFR). This technique presents a great alternative regarding the forces applied during the assembly. As the rivet heats, this process enables to reduce the efforts and consequently the risk of damaging the joints. The tool rotates and comes in contact over the rivet head, which heats up, and is subjected to plastic deformation as per the tool load against the rivet. The principal steps of the FFR are illustrated in Figure 2.

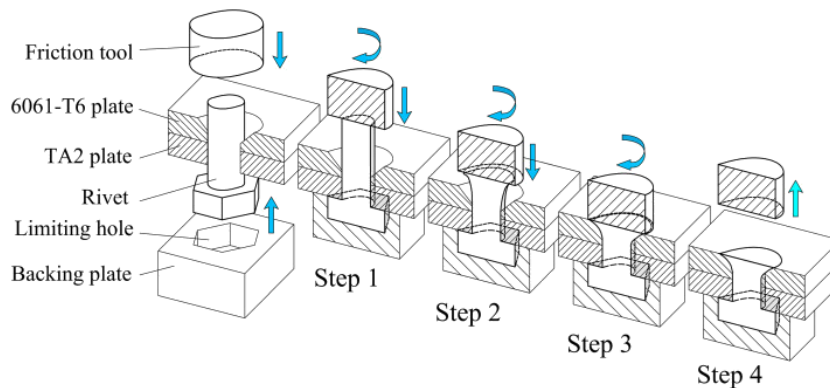


Figure 2 - Principal steps of Friction Forge Riveting process [16]

Inspired by the FSR and FFR processes, the present study proposes to implant and close the rivet by friction in a thermoplastic composite part using a CNC machine as there is no clear publication in the literature about this same purpose. It is an introduction study to combine these independent processes and to control them by speed and position, without the need to purchase specific equipment. Force and temperature are measured during the tests using internal and external sensors on the machine tool. This experimental work presents the implantation phase of the rivet in the thermoplastic composite panel and the rivet head formation separately as a promising assembly process that could be implemented in an automated aerospace or aeronautical assembly line.

2. Methodology

2.1 Composite and rivet materials

The experiments were performed in two separated phases: the implantation of the rivet in the thermoplastic composite and the closing of the rivet head. The rivet is made of Ti-6Al-4V and its diameter and length are 5 mm and 20 mm, respectively. The composite plate used in this study is a Victrex AE 250 (PAEK) plate of dimensions 40x40 mm with a thickness of 7 mm. This PAEK is an innovative material with a lower melting temperature to PEEK while maintaining a similar glass transition and mechanical properties [18].

2.2 Experimental set-up

The experimental set-up for the implantation and the head forming phases is illustrated in Figure 3. A DMG DMU-85 monoBlock machine tool controlled by a SIEMENS 840D SL was used to perform the tests. The spindle speed (1) and its displacement are controlled by the PCL of the CNC machine. The process cannot be controlled by force as described in the literature. A dynamometer Kistler (2) type 9257B clamped on the machine table allows forces measurement. A charge amplifier Kistler type 5070A and an analogic-digital card are connected to the dynamometer. The signal is recorded with an analogic-digital module National Instruments at an acquisition frequency of 250 Hz. During the rivet head forming phase, an Optris PI 08M infrared camera is used to measure the temperature at an acquisition frequency of 10 Hz. The rivet implantation phase requires a higher acquisition rate. A Telops Fast M3K infrared camera (3) is used to measure temperature at 200 Hz. In addition, a high-speed camera (4) captures the closing process. The implantation and the head forming phases are detailed in the following sections.

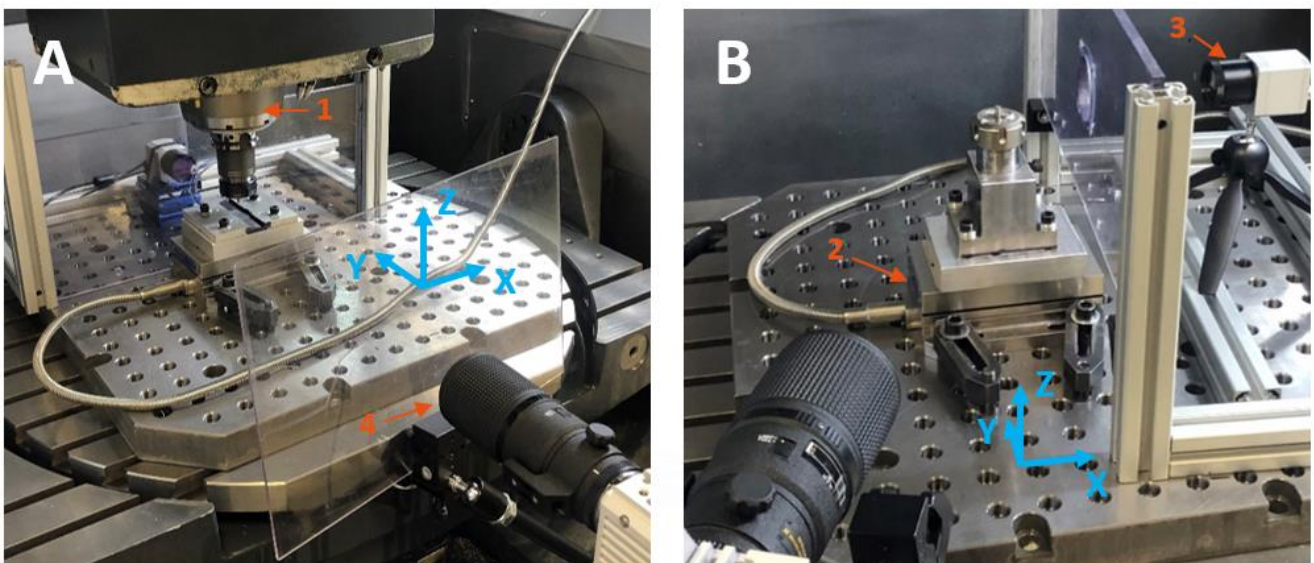


Figure 3 - Photos of experimental set-up for A) Implantation phase, B) Head forming phase

In this article, the implantation and the head forming tests were carried out independently to obtain the correct range of parameters. No specific design of experiment was developed as this study is at an exploratory stage. Then a complete riveting process was carried out, combining both processes.

2.3 Implantation phase

A detailed view of the assembly set-up is presented in Figure 4. The rivet is stored in the machine-tool collector held by an ER32 collet chuck (1). The composite plate (2) is fixed in place using a machined aluminum plate (3) designed specifically for these experiments. This set-up is placed on the dynamometer (4).

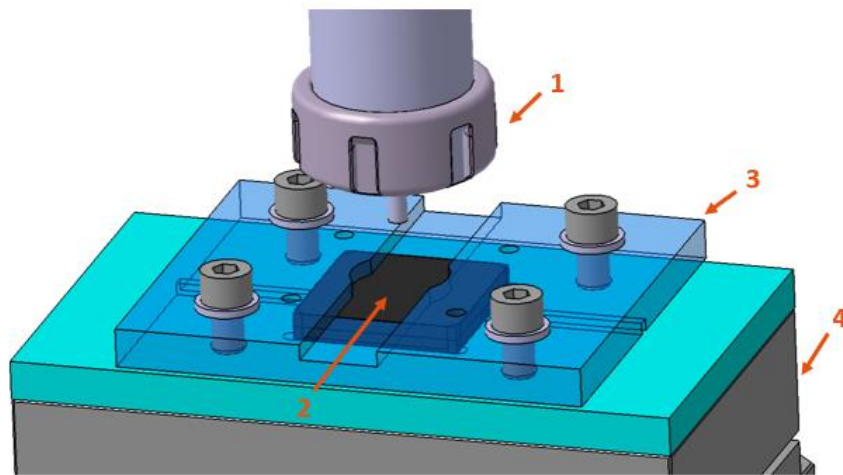


Figure 4 – Experimental set-up for implantation tests

These implantation experiments aim to understand the process forming of the rivet implanted by friction, using force and speed control. Process parameters are measured with the CNC machine and presented in Figure 5.

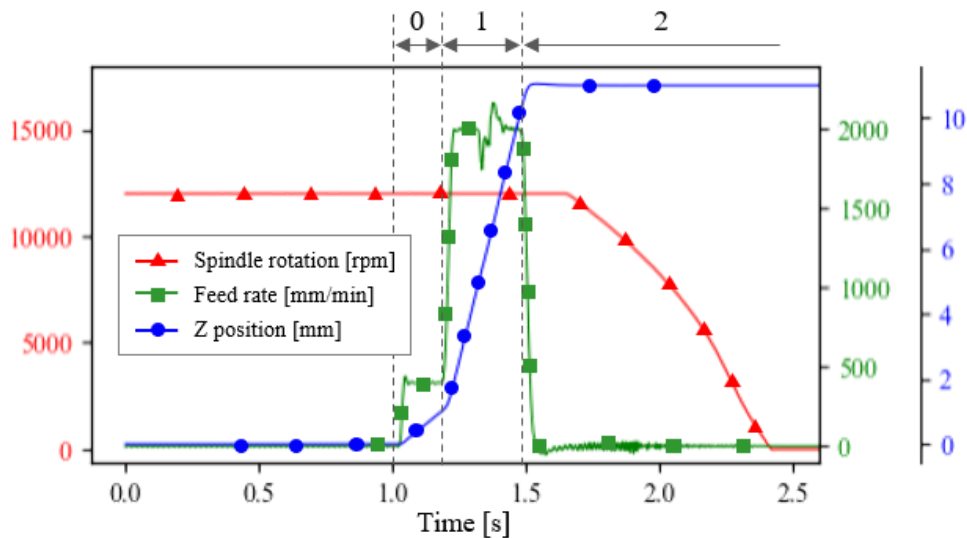


Figure 5 - Process parameter diagram on friction riveting in a composite part collected by the CNC machine. Phase 0: the spindle moves 5 mm above the plate until the contact with the rivet. Phase 1: the rivet starts its path in the composite part. Phase 2: the rivet and the composite part cool down before releasing the rivet from the assembly tool.

The spindle begins at a fixed position of 5 mm above the plate. It allows the spindle to reach the rotation speed before the beginning of the test. Once the spindle reaches its piloted rotation speed (Phase 0), it moves downwards at constant feed rate to perform the implantation phase. Based on Zocoller-Borba study [7], the speed control process parameters are set to match the force control process phases first. But after several tests, it seems that only one speed control process phase is enough to form the rivet in the plate (Phase 1). The feed rate chosen for each experiment is 2000 mm/min at different displacements with a rotation speed of 12000, 15000 and 18000 rpm. At the end of the piloted process, the rivet stops for few seconds before proceeding to the release of the rivet from the tool, allowing the consolidation phase while the assembly is cooling down.

2.4 Head forming phase

The feasibility of the closing phase by friction with a CNC machine [19] has been demonstrated and compared with an aluminum rivet. Figure 6 shows the assembly set-up. The friction tool is stored in the machine-tool collector and held by an ER32 collet. The rivet is held in a workpiece using a ER32 collet chuck (1) with a protection plate (2). The assembly is placed on the dynamometer.

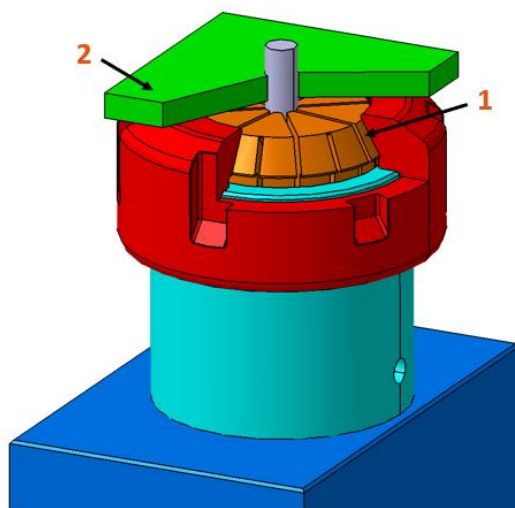


Figure 6 – Experimental set-up for head forming tests

At a rotation speed of 3500 rpm and a feed rate of 2 mm/min, the titanium rivet deforms by making layers of material while aluminum rivet happens to flow after a vibrational phase while heating up the material. These two different forming phenomena are illustrated in Figure 7.

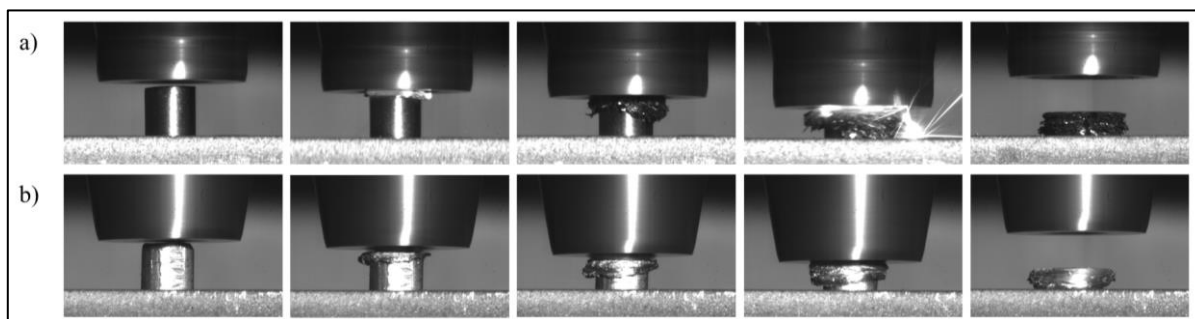


Figure 7 - Head forming process on a) Ti6Al4V rivet and b) AA6060 rivet

More experiments are realized using a friction tool made of tungsten-lanthanum alloy. The collet and the friction tool are assembled and positioned, as for the implantation phase, in the CNC machine. A rotation speed of 12000, 13000, 14000 and 15000 rpm to try to form the rivet head with the best configuration regarding the observation made on the aluminum rivet head forming. For these tests, the

plate placed on the collet to protect the screw interferes with the rivet head forming. So, the plate is removed for this study.

3. Results and discussion

3.1 Implantation phase

Many studies found in literature describe friction riveting process controlled by force. This work is about friction riveting on a CNC machine, which offers different capabilities. CNC machine cannot be controlled by force, so it is controlled by speed and position based on Direct Friction Riveting studies. Controlling this process requires to explore a range of feed rate to try to form the rivet in the composite plate for a given spindle speed.

As mentioned before, the implantation tests are performed as a single-phase process. CNC machine data are recorded such as tool position, powers and electrical current. Figure 8A shows a typical electrical current curve measured on the CNC during an implantation process at 15000 rpm and at 2000 mm/min for 6.5 mm displacement, and the evolution of the spindle position. This electrical current drives the motor that controls the Z-axis movement of the spindle and allow the estimation of the force applied as presented in Figure 8B. Recording of the CNC data begins 1 s before the start of the process. At this moment, the rivet tip is placed at 5 mm above the composite plate, which correspond to the beginning of the first signal peak and a contact after 0.15 s, until the beginning of the second peak. The rivet starts its path in the composite until the end of the last peak.

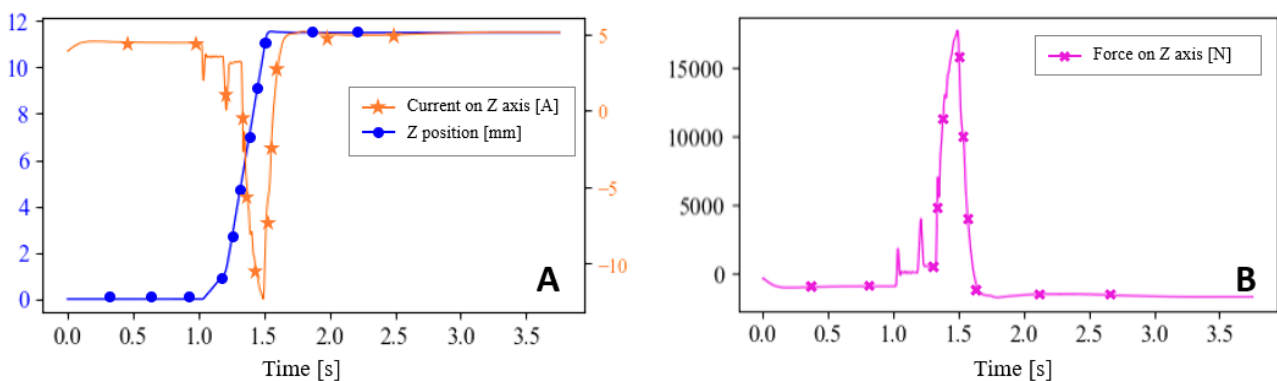


Figure 8 - A) Position and electrical current of the spindle on Z axis based on the CNC machine signal, B) Force estimated based on the electrical current on Z axis

Using a spindle speed of 12000 rpm, the implantation depth increases, from 4 mm to 6.5 mm, at a feed rate of 2000 mm/min. Taking the rivet sliding in the tool into account, the anchoring depth are respectively at 3.2, 4.8, 4.9 and 5.3 mm. At first, by the radiographies of the assembly shown in Figure 9, the rivet widens a little bit for a force of 14850 N. By increasing the implantation depth, higher forces are measured. The evolution of the force becomes constant at a level having 17200 N average. The rivet implantation depth increases until a state where the rivet is not going deeper but becomes wider.

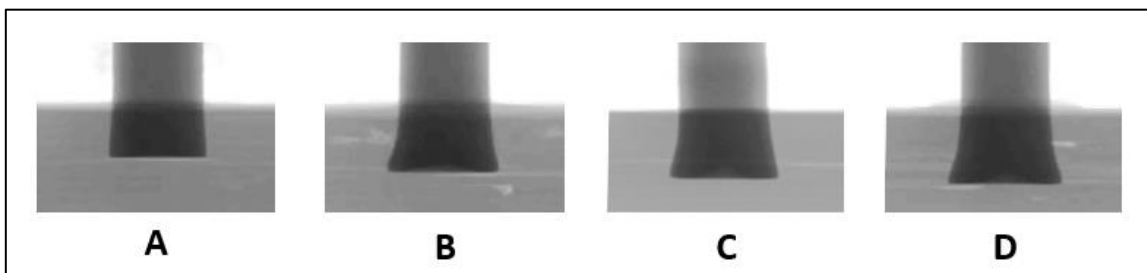


Figure 9 - Radiography of implantation test performed at 12000 rpm, 2000 mm/min and at a depth of A) 3.2 mm, B) 4.8 mm, C) 4.9 mm and D) 5.3 mm

The influence of the spindle speed can be observed too. At a feed rate of 2000 mm/min, while going at 6.5 mm displacement, so at 5.7 mm depth, the force generated by the spindle decreases from 14500 to 17700 N and does not become wider. This suggests a higher heat generation inside the composite due to the rivet friction against the composite and a softening of the rivet material.

An experimental problem occurs: the rivet slides into the collet chuck above a certain level of force. This sliding distance is obtained measuring the rivet length outside of the composite plate after the implantation phase. The CNC data shows some discontinuities when recording of the electrical current that pilots the Z axis of the spindle, as presented in Figure 10A. This could be explained by the rivet sliding and it can be depicted in Figure 10B where the sliding distance of the rivet is presented as a function of the implantation force calculated. The more the rivet slides, the less is the implantation force which impact the rivet formation in the composite plate.

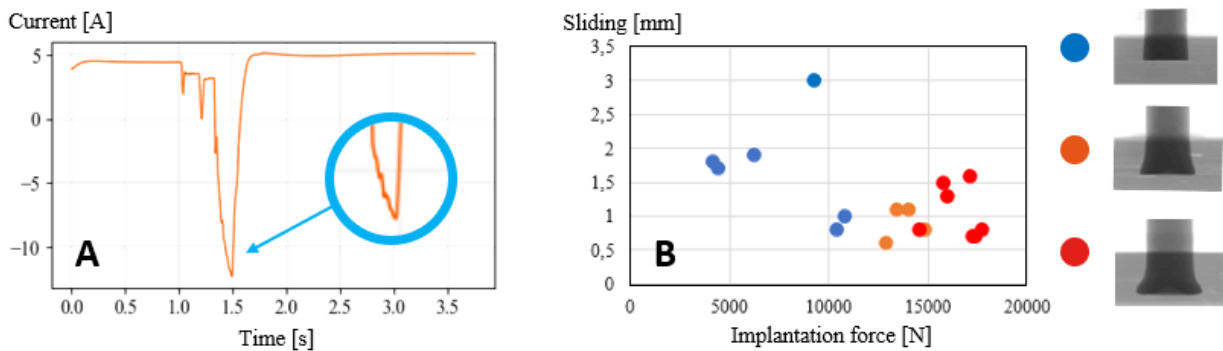


Figure 10 - A) Electrical current piloting the Z axis of the CNC machine during the implantation test at 12000 rpm, 2000 mm/min and 6.5 mm depth, B) Sliding versus implantation force

An IR camera is used to identify the temperature of the flash coming out during the implantation process. Figure 11B presents the evolution of the implantation force versus the measured temperature. The limit range of the camera is between 171.6 and 445.6°C. Rapidly, the temperature reaches the limit of the range measure of the camera. The temperature inside the composite during the process is supposed to be higher than the temperature reached by the flash. The degradation temperature of the AE 250 is evaluated at 573°C [18]. Microscopic observation of the composite around the rivet formed at 15000 rpm and 2000 mm/min is presented in Figure 11A. The fibers show a preferential movement around the rivet, taking the same direction than the spindle rotation. A void is observable between the rivet and the composite and could be explained by the retraction of the metal during the cooling phase, as observed by Altmeyer *et al.* [8] with short fibers. Matrix degradation can be observed in the middle of the fibers too, while taking the direction to follow the rivet movement.

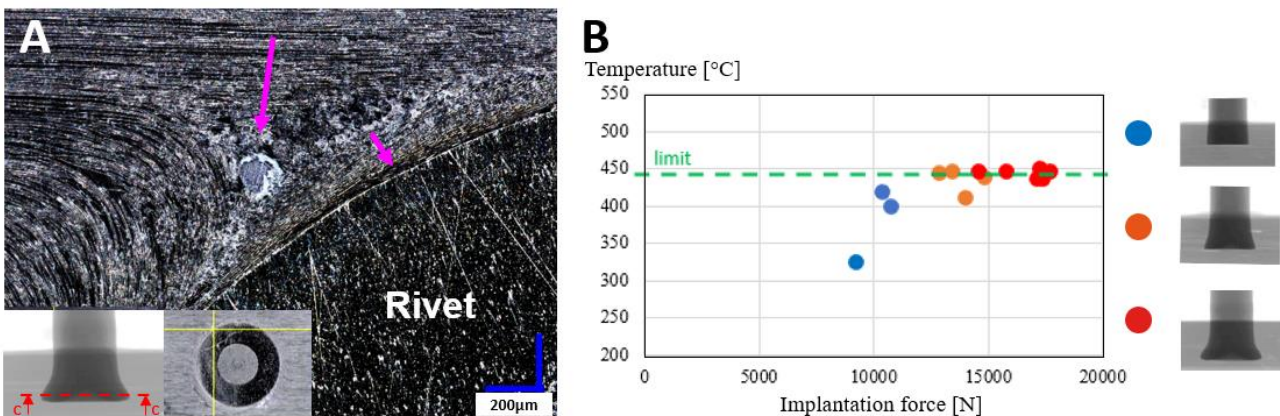


Figure 11 - A) Micrographic view of the composite around a rivet formed at 15000 rpm and 2000 mm/min, B) Maximum temperature measured versus the implantation force

From these observations, the parameters chosen to perform the full process of friction riveting are a rotation speed of 15000 rpm and a feed rate of 2000 mm/min using a predicted displacement of 6.5 mm.

3.2 Head forming phase

Rivet head formation have been experimented, with different tool trajectories and rotation speed. Figure 12 shows the evolution of the head formation phase process performed at 12000 rpm while the tool is pressing the rivet head at 6 mm/min for 3 mm down. The rivet heated up faster at 12000 rpm than being formed at 3500 rpm, looking at the white-hot point captured by the fast camera. For this experiment, the rivet head ends with a thickness of 2 mm and a diameter of 7.8 mm. These tests finally permit to reach the head shape observed with the aluminum rivet head forming.



Figure 12 - Friction forming of the rivet head at 12000 rpm and 6 mm/min

The influence of the tool material is also observed, when compared with a tungsten carbide tool. More instability occurs during the process when being performed with a tungsten carbide tool. For welding application, lanthanum is used to stabilize and concentrate the arc [20], which may explain the previous observations. A further detailed study will describe the methodology and results from these experiments focusing on different tool trajectories coming in contact with the rivet head and the influence of process parameters.

3.3 Application on the full process

Based on these two process studies, implantation phase and closing phase, process parameters are chosen to perform a full friction riveting process on thermoplastic composite plate. For the implantation phase, parameters that created a wider anchorage of the rivet are chosen. The rivet is implanted at 15000 rpm, with a feed rate of 2000 mm/min and at a displacement of 6.5 mm. For the head forming phase, parameters generating the least effort on the implanted rivet are chosen. The spindle speed is set at 12000 rpm and piloted to close the assembly by friction while the spindle presses the rivet head at 6 mm/min. The initial length of the rivet is 11 mm, based on the implantation parameters chosen, and on the final rivet shape of the rivet head forming test.

This full process experiment is performed in two phases with an intermediate phase. The intermediate phase permits first to wait for the consolidation of the formed rivet in the composite plate. It allows too to release the rivet from the collet chuck and to proceed to the changing of the tool in the tool machine storage in the CNC.

First experiment trying to form the head after an implantation by friction failed because of a too weak anchoring in the composite plate. Indeed, the rivet slides 1.5 mm during the implantation process resulting to a weak anchoring depth of 5 mm, as shown in Figure 13A. Another test is performed with an anchoring depth of 6 mm. The formation of the rivet head can be performed but layers of titanium does not stick to the main cylinder due to the composite flash formed during the implantation phase and is presented in Figure 13B. The implantation depth was determined to be an influencing parameter of the head forming phase. The results are encouraging for the remainder of the study.

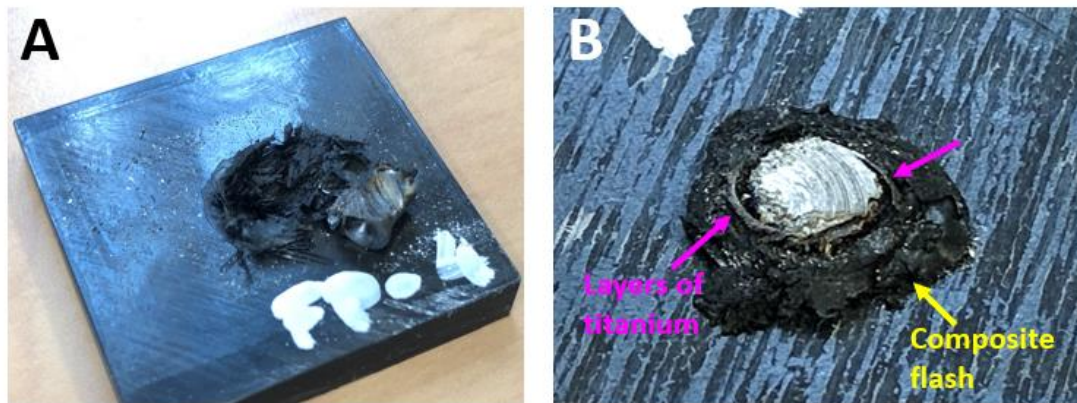


Figure 13 - A) Weak rivet anchorage, B) Uncompleted head formation

4. Conclusion and perspectives

The implantation of a Ti6Al4V rivet by friction in a composite plate has been performed with a CNC machine and showed a new way to process to an assembly by friction using speed and position control. These experiments demonstrated the feasibility of a rivet forming as a one phase process and settled up the first variable of this process. Some issues have been encountered, like the rivet sliding in the collet. The set up and the tools need to be improved to minimize this sliding during the implantation process.

Another thing to explore is the feed rate range during the implantation phase. These experiments have been performed with a piloted feed rate to a controlled position, generating an important implantation force. This force may be reduced by piloting the rivet slower at the beginning to control the implantation depth too and preserve the CNC machine life.

The head forming phase of the Ti6Al4V rivet has been experimented too, independently from the implantation phase and will be detailed in a further study. Based on this, a full process friction riveting experiment has been performed and highlighted a new process parameter. The anchoring depth of the rivet play a key role in the feasibility of the closing phase, while applying a load on the rivet head. New experiments are planned to determine the feasibility range.

Difficulties have been encountered during the transition between the implantation and the head forming phases. The implanted rivet must be released from the tool ER32 collet without damaging the newly created anchorage, while the composite plate remains fixed on the table. By removing the composite plate first, the release of the rivet can be secured.

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