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Experimental work on friction riveting process of Ti6Al4V in a CNC machine

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Abstract. Friction Forge Riveting (FFR) is now being considered as a good alternative for reinforcing multi-material assemblies in industrial applications with the aim of setting up a robotized assembly process. This paper investigates the feasibility of FFR through experiments using a CNC machine and force measurement instrumentation. Different combinations of parameters such as spindle speed and feed per revolution are tested to understand the forming mechanism of a Ti-6Al-4V rivet by friction. The results show that the evolution of forces in response to the load applied to the rivet by the machine is not constant. An oxide layer is observed on the surface of the rivet for a particular combination of parameters.

Introduction

Aerospace structures are assembled using a variety of processes. One of them, the riveting process, requires several steps such as drilling, milling, inserting and closing the rivet to achieve the final assembly. Plastic deformation of the rivet head is the most commonly used method to close the assembly by riveting. Special machines, pneumatic or electromagnetic [1], [2], are mainly used. To achieve plastic deformation of the rivet head, a force is applied to the fastener. Its amplitude and trajectory can vary according to the different techniques, but it can cause defects in the assembled sheets and/or in the rivet head, which can lead to fragilization of the assembly. Many studies mention this type of problem.

The impact of the process parameters on the assembly's quality have been studied by Korbel [3] and Cheraghi [4] 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 [5] 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 [6] 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 [7] 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 to conventional riveting process has been proposed by Ni et al [8] to prevent crack during riveting process: Friction Forge Riveting (FFR). This technique presents a great alternative regarding the forces applied during assembly as it is the technique studied in this article. The tool rotates and come in contact over the rivet head, which heats up, and is subjected to plastic deformation as per the tool load at a low feed rate against the rivet. As the rivet heats, this process enables to reduce the forces and consequently the risk of damaging the joint. These principal steps of the FFR are illustrated in Fig. 1 : Step 1 and 2 shows that the friction tool turning and moving towards the workpiece, on Step 3 the tool turns in contact to the deformed workpiece without any vertical movement and in Step 4 the tool is removed.

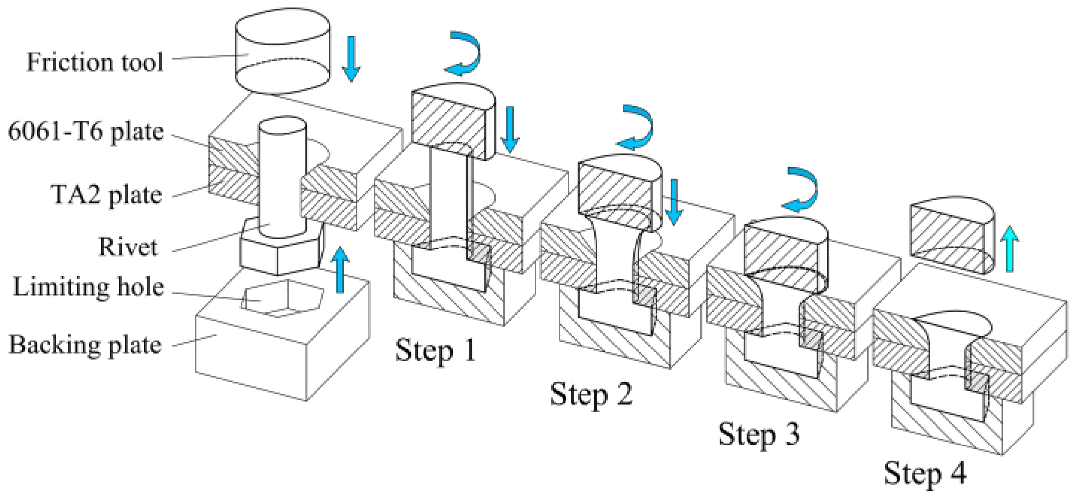

Fig. 1. Principal steps of Friction Forge Riveting process [9]

Ni et al [10] showed the feasibility of the FFR in forming the head of a titanium rivet using a tungsten alloy tool. The tungsten tools are chosen as per their mechanical and temperature limits. Lower forming forces are applied to homogenize the rivet head formation with the least defects possible in the assembly [9]. The influence of the spindle speed was studied closely as it plays an essential role in the head shaping. This brief literature review shows that there are different techniques and numerical approaches to model the riveting process.

The work of Ni et al associating the riveting process is closer to the activities that will be conducted in this study to develop a riveting process that, in the near future, will be implemented in a robot arm.

A previous study done by the same authors of this present article [11] presented the analysis of a first experimental campaign using a complete 2^3 factorial design of experiment for two materials (titanium and aluminum), three levels of spindle speed (3000, 3500 and 4000 rpm) and feed rate (1, 2 and 3 mm/min). A numerical simulation has been developed based on the observation of the aluminum rivet forming. This article completes the study, analyzing higher process parameters in titanium to understand the process in higher productivity.

Materials and methods

The rivets used in the experiments are in Titanium alloy (Ti-6Al-4V), they have 5 mm diameter and length of 20 mm. The choice of this titanium alloy is related to the use in aircraft construction, appreciated for its mechanical performances, corrosion resistance and light weight.

The rivet head is set in contact with a turning tungsten-lanthanum tool. A Tungsten material is used as per their hardness and wear and heat resistance.

The tests were performed using a CNC machine-tool: DMG DMU-85 monoBLOCK. The spindle speed and the vertical displacement are controlled by the machine PLC. The rivet is held by an ER32 collet chuck in a fixture designed for this FFR experiment. A free predrilled steel plate is placed over the collet to protect the surface of the clamper. The workpiece set is fixed on a dynamometer Kistler type 9257B that is clamped on the machine table. A charge amplifier Kistler type 5070A and a National Instruments analogic-digital card are connected to the dynamometer. The signal is recorded with 250 Hz acquisition frequency. The complete experimental set-up is illustrated on Fig. 2.

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Fig. 2. Photos of experimental set up (on the left with a high-speed camera and the dynamometer, and in the right the tool just before touching the rivet – the square protection plate is not attached to the rivet nor the cone)

A high-speed camera is used to capture the images to show the evolution of the head deformation. Photographs taken at various times during the tests are shown in Fig. 3.

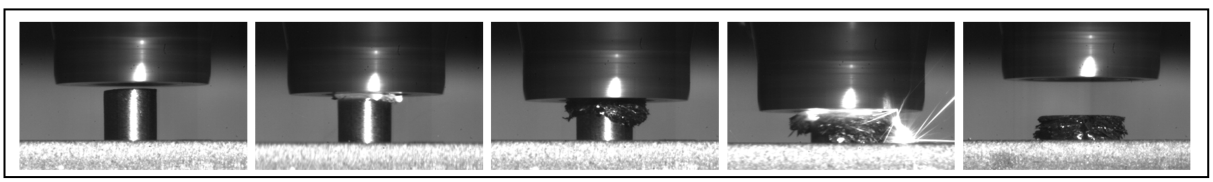

Fig. 3. Rivet forming by friction at 3500 rpm and 2 mm/min for a titanium rivet

The spindle speed parameters used in the experiments were clearly higher compared to the previous study (3000, 3500 and 4000 rpm using 1, 2 and 3 mm/min feed rates) which changes considerably the temperatures. The lower spindle speeds will be referred to DoE1.

In this case, the spindle speed values were: 10000 and 15000 rpm. The defined design of experiments includes feed rates 0.5, 2, 4, 6 and 8 mm/min, refered as DoE2. Although, it was not possible to use the lower feed rates (0.5 and 2 mm/min) with 15000 rpm because it was identified a risk of excessive heat generation, and it could not be completed. Table 1 shows the experimental parameters.

Table 1. Design of Experiments

	Spindle Speed (rpm)			Feed Rate (mm/min)				
Low Spindles (DoE1)	3000	3500	4000	1	2	3		
High Spindles (DoE2)	10000	15000		0.5	2	4	6	8

Results and discussion

Fig. 4 shows a typical force and torque evolution during FFR for low (Fig. 4a and 4b) and high spindles speed (Fig. 4c and 4d). The curve profile shows repeated peaks almost periodic with different average time intervals which are not related to the feed rate nor the spindle frequency.

For each experiment, the amplitude and periodicity (pattern) of these curves were analyzed and compared to the behavior of the observed deformation on the high-speed camera to understand the phenomena.

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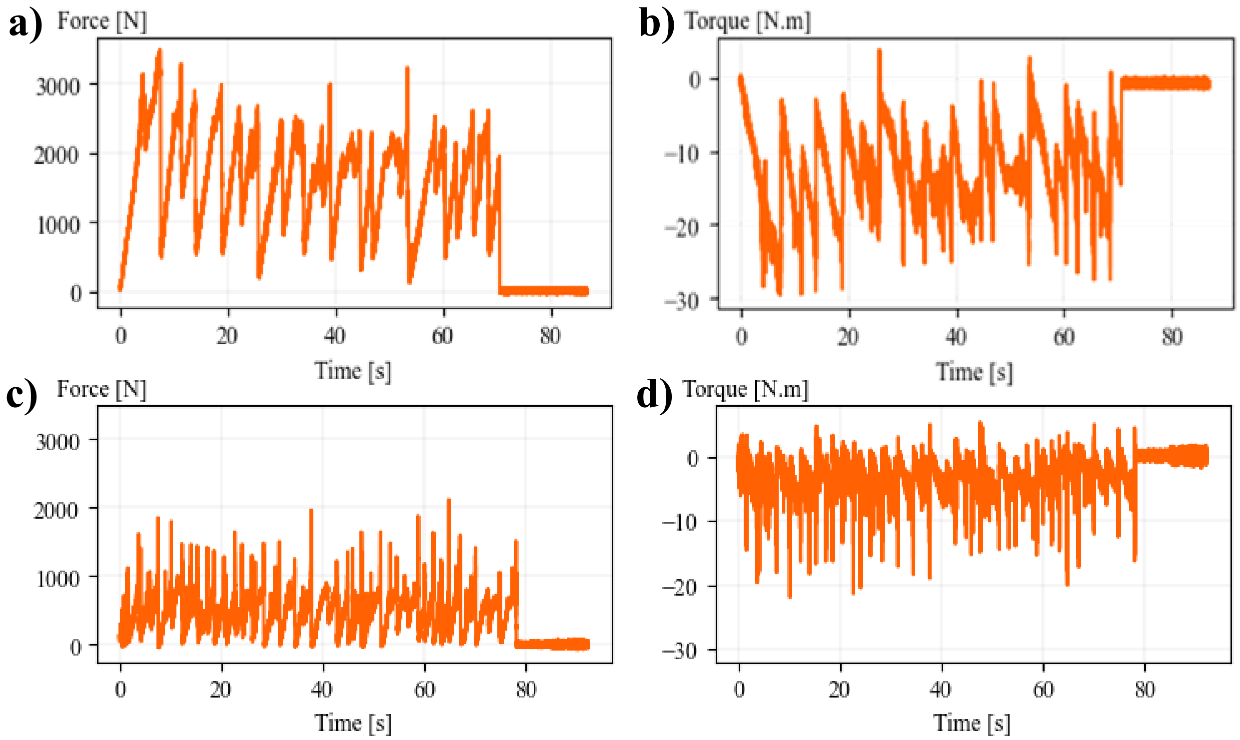

Fig. 4. Typical evolution of measured data during the friction riveting process at a) 3500 rpm and 2 mm/min, b) 10000 rpm and 2 mm/min

For all experiments, maximum forces and signal periodicity have been compared. Fig. 5 shows maximum forces observed: Fig. 5(a) and (b) show the maximum force and torque for DoE1 and Fig. 5(c) and (d) for DoE2, as a function of the feed rate. It was noted that higher spindle speeds produced lower forces on the rivet with the same tool displacement.

For DoE1, the force evolution seems to mainly increases as the feed rate increases looking at the evolution for parameters 3000 and 3500 rpm but not for 4000 rpm, that remained in the same level of 3500 N. The torque evolution shows the inverse tendency except that this decreasing behavior is observable for parameters 3000 rpm and 4000 rpm, and not for 3500 rpm.

For DoE2, force and torque decrease as the feed rate increases, except at 4 mm/min. At this state, the fluctuation of these variables could be due to a delay in the start of acquisition and so missing data at the beginning as it can be observable in Fig. 4. But this assumption would only be possible for forces measurements.

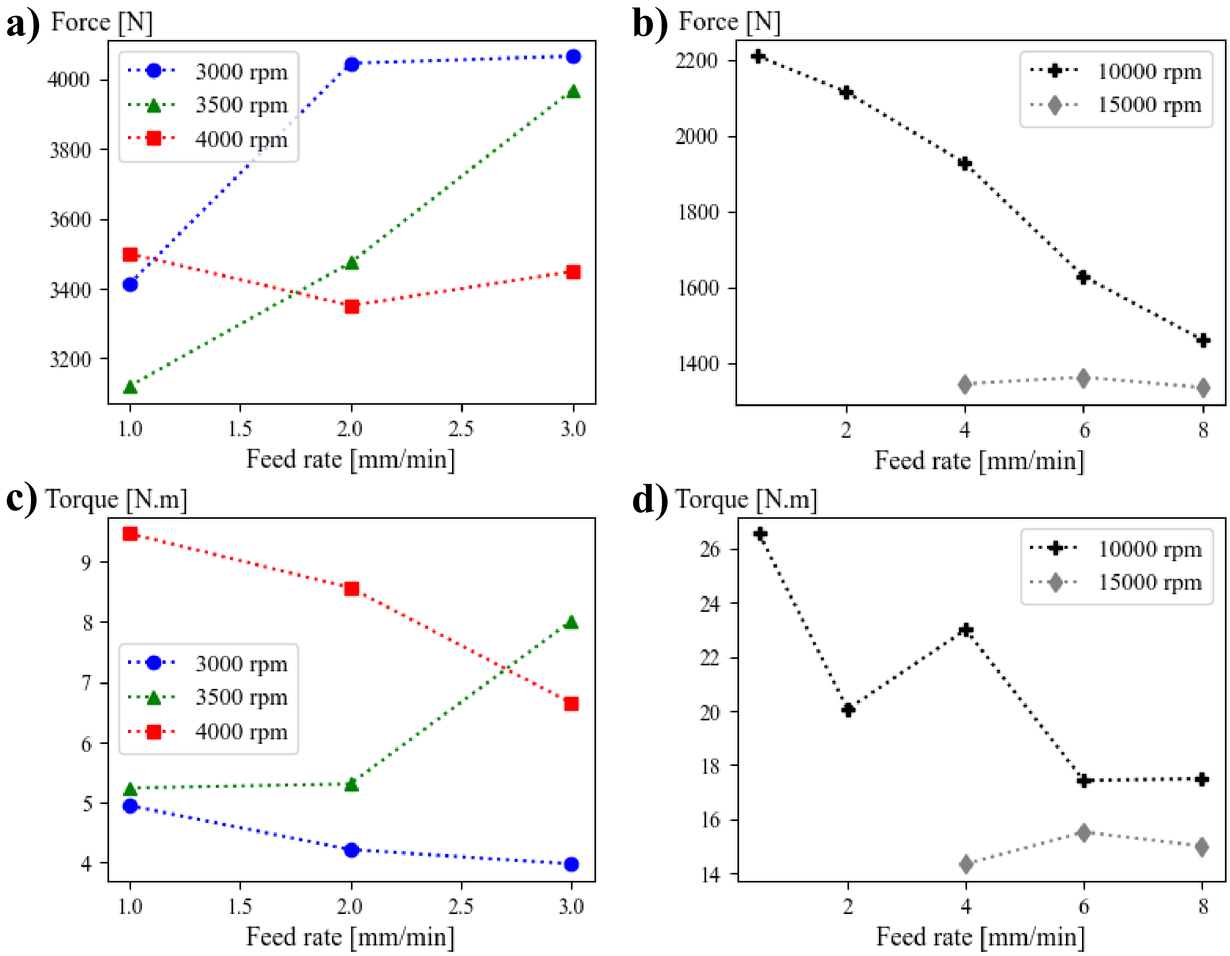

Fig. 5. Evolution of maximum force compared to feed rate for a) DoE1 and b) DoE2, and evolution of maximum torque for c) DoE1 and d) DoE2

In addition to the maximum forces, the signal patterns were analyzed from each signal. A periodicity of this pattern can be identified, as an average time between each peak. Fig. 6 shows the periodicity for DoE1 and DoE2 as a function of feed rate. Globally, the signal periodicity decreases as the feed rate increases, except for 15000 rpm.

The experiments using 15000 rpm presented a different pattern. These results could be explained by the apparition of an oxide layer which become darker as we increased the feed rate, as illustrated in Fig. 7 comparing the force and torque results for this specific case. Observing Fig. 7, it is as if the oxide apparition has broken the evolution of each variable. This oxide layer could have created a resistance to the forming process, generating the reduction (drop down) of the spindle values. The signal transmission interruption could explain the increase of the signal period. The assumption of a too important heat generated can be mentioned as well.

It would be very important to have temperature acquisition to complete the analysis. Two different set-ups were implemented to measure temperature. Using IR camera, the sparks and the range of measured temperature was not compatible with the different options of the equipment. Using thermocouples on the collet, the data was not trustable and very noisy. So, it was not possible to have trust data during the experiments to verify this assumption.

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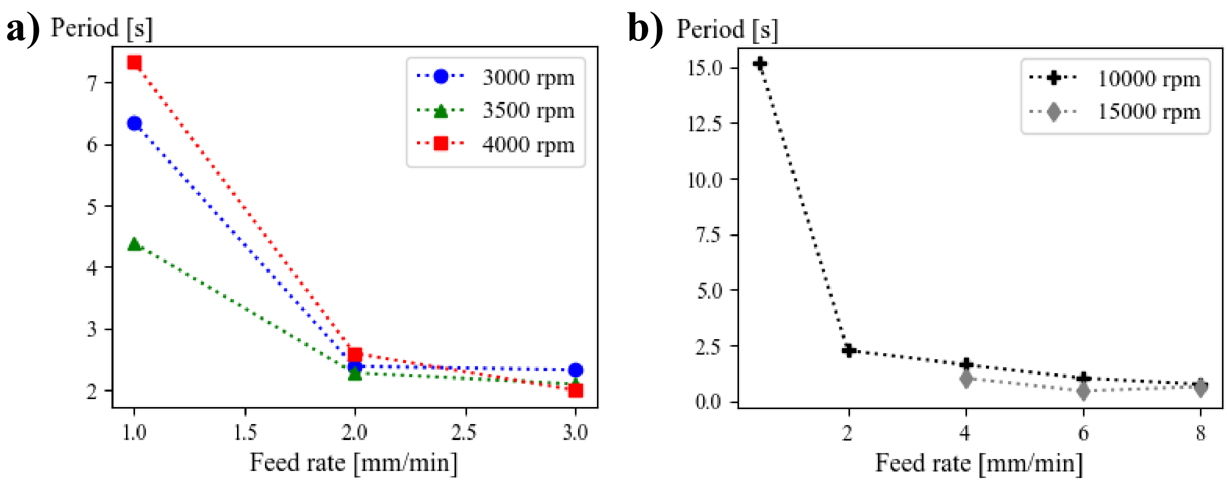

Fig. 6. Evolution of the force signal periodicity compared to feed rate for a) DoE1 and b) DoE2

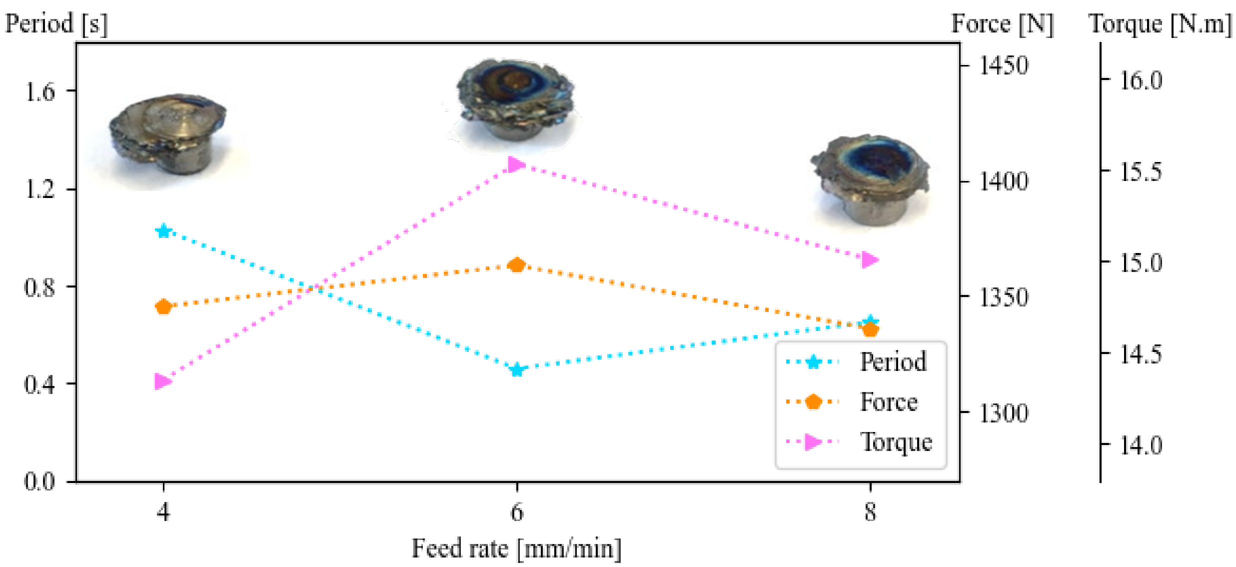

Fig. 7. Evolution of the force signal periodicity compared to feed rate at 15000 rpm (DoE2)

Conclusion and perspectives

Friction forming is a complex forming process which implies heat generation and potentially oxidation of the titanium head. Experimental tests of frictional riveting head formation were performed using special parameters that were not experimented before in the literature. The experimental acquisition (forces, torque and high-speed camera) during the tests allowed to observe and understand the rivet forming process. The results highlighted the influence of the spindle speed and feed rate on the behavior of forces on the rivet head using controlled vertical displacement. The force curves presented a special pattern that were not observed in the literature. Semi-periodic results allowed to identify the period of forces and to compare with the physical behavior of the rivet. These results should be analyzed to compare with the external sensor data. Temperature should be measured in a further study to allow numerical simulation studies. Further experiments are being developed, including temperature measurements, power and current (torque) data taken from the CNC PLC, to construct a digital twin with numerical simulation of the titanium forming rivet head.

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