

A Comparison between Regular and Vibration-Assisted Drilling in CFRP/Ti6Al4V Stack

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ABSTRACT

As aircraft programs currently ramp up, productivity of assembly processes needs to be improved while keeping quality, reliability and manufacturing cost requirements. Efficiency of the drilling process still remains an issue particularly in the case of CFRP/metal stacks: hot and long metallic chips are difficult to remove and often damage the surface of CFRP holes.

Low frequency axial vibration drilling has been proposed to solve this issue. This innovative drilling process allows breaking up the metallic chips in such a way that jamming is avoided.

This paper presents a case of CFRP/Ti6Al4V drilling on a CNC machine where productivity must be increased. A comparison is made between the current regular process and the MITIS drilling process. First the analysis and comparison method is presented. The current process is analyzed and its limits are highlighted. Then the vibration process is implemented and its performances are studied. Both processes are compared according to the following criteria: chip morphology, thrust force, power consumption, tool life, cycle time, holes quality and manufacturing costs.

Results show that the vibration drilling process is more productive and reliable, while maintaining the quality as well as reducing manufacturing costs. The paper also shows that the vibration drilling allows simplifying cutting tool design and reducing lubrication.

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INTRODUCTION

For many aircraft programs, ramp-up leads to increase the productivity of assembly lines. Improvements are notably focusing on drilling operations. Cycle times have to be reduced, as well as cleaning operations after drilling.

The paper deals with an industrial drilling process on a CFRP/Ti6Al4V aileron assembly line. Main issue is related to the productivity of this line that needs to be improved. First this case study is detailed and the causes of the lack of productivity are highlighted. Then a state of the art of potential solutions is presented and focuses on Vibration Assisted Drilling. Principle and benefits of this new technology are described. Initial process is analyzed and a new process is proposed for the case study that combines the Vibration Assisted Drilling and a new cutting tool with dry air blast instead of MQL. The whole tests are made on an instrumented test bench. Both processes are compared on the basis of productivity, quality and reliability criteria. Finally the new vibration drilling process is proved to be better than the initial one for the whole criteria.

Case Study

The case study deals with a drilling process on ailerons operated by CNC machines. The workpiece is made of a CFRP/Ti6Al4V stack. Drilling operation is realized in three steps. First a cutter is used for the CFRP layer. Then another cutter drills the Ti6Al4V layer. Finally the pre-hole is reamed. All operations are made under MQL lubrication. The study focuses on the titanium pre-hole drilling.

On the original process the titanium layer is drilled with a two-stage cutter. All features about the tool and the hole are gathered in the [Table 1](#).

Because of the ramp-up of the aircraft program, productivity must be increased on this production line. Indeed the current process does not fit with the required cycle time. Two issues are identified, which limit productivity optimization.

Table 1. details of the Titanium drilling case study

Workpiece	Material	Ti6AlV4
	Diameter (D)	D = 7.6mm
	Depth (L)	L = 9mm
Quality needs	Diameter Tolerances	+/- 0.1
	Roughness	R _a = 1.6µm
Cutter	Technology	Two-Stage Solid Carbide Cutter:
		D ₁ = 5.5mm
		D ₂ = 7.6mm
Cutting conditions	Cutting Speed (V _c)	V _c = 19m/min
	Feed (f)	F = 0.15mm/rev
	Peck-drilling	Every 1mm
	Lubrication	Internal MQL

First issue is related to cleaning operations after drilling. In fact, as MQL is used during titanium drilling, “carbon muds” still remain on the workpiece and need to be cleaned. This leads to long manual operations.

Second issue is linked to the titanium cutter and the cutting conditions. As the cutter is made of two stages it is longer than a one-stage cutter then it takes more time to realize the hole. Furthermore peck-drilling cycles are implemented to break titanium chips. Indeed hot and long titanium chips must be absolutely avoided to keep quality requirements in the CFRP layer. Therefore peck-drilling process requires much more time than, for example, a one-shot drilling process with internal full lubrication.

Both main issues result from usual physical phenomena in titanium cutting. Indeed continuous and confined cutting in titanium required to cool and interrupt it in order to maintain quality and reliability requirements at the cost of productivity. Different solutions have been proposed to solve these problems. These latest developments are summarized in the following paragraph.

State of the Art

In this paragraph the latest developments in drilling titanium are presented. All of these aim to cool the cut and/or to break the chips. Four main ways have been explored in the industry:

1. Optimization of the plan of procedure: pre-drilling operations;
2. Cutter geometry: coating [1], flute geometry [2], step drill [3], Web thinning [2][4][5];
3. Modification of the kinematics of drilling operation: Orbital drilling [6], peck drilling [2];
4. Particular cutting conditions: Feed “F” [7], lubrication [2][8].

The Table 2 summarizes these industrial solutions and compares their effects in terms of Productivity (“Product.”), Quality (“Qual.”), Reliability (“Reliab”) and Cost. This comparison has been made considering the specifications linked to the case study.

Different conclusions can be highlighted from this overview table. Three solutions are already implemented on our case study (Large Flute Geometry, Step Drill and Peck Drilling). Four solutions are inappropriate for our case study. More generally many solutions reduce the process productivity (Pre-Drilling, Step Drill, Peck-Drilling) while they increase process costs. In fact, all of them lead to a compromise. For example the current tool could be optimized by adding a coating and Chip Breaker geometry but the tool cost would be much higher. Another solution would consist in making trim cutting edges on the cutter (like honing for example); but with this kind of cutter thrust force would increase very much that could be a drawback in the current industrial case where flexible parts are drilled. Given this state of the art we can conclude that the current process is 100% of its potential.

Table 2. industrial solutions for continuous and confined cut

Industrial solutions		Feasibility	Prod.	Qual.	Reliab.	Cost
Plan of procedure	Pre-drilling	yes	▼	▲	▲	▼
Cutter	Coatings	yes	▲	▲	▲	▼
	Large flutes	applied	▲	▲	▲	▼
	Trim cutting edges	Inappropriate for the case study				
	Multi-step	applied	▼	▲	▲	▼
	Chip breaker	yes	▲	▲	▼	▼
Cutting kinematics	Orbital drilling	Inappropriate for the case study: important modifications of the machine-tool				
	Peck drilling	applied	▼	▲	▲	▼
Cutting conditions	High feed	Inappropriate for the case study (quality concerns)				
	High-pressure lubric.	Inappropriate for the case study (need to minimize or even suppress the lubrication)				

However Table 2 does not bring the Vibration Assisted Drilling solution out, which benefits could be very relevant for this application. It consists in adding axial oscillations to the regular feed in order to break the chips. Resulting chips are smaller and can be evacuated in a much easier and faster way than regular chips. Two main families of Vibration Assisted Drilling solutions can be considered. A first one relies on generating vibrations with small magnitude (<20µm) and high-frequency (>5 kHz). These ultrasonic oscillations are generated by piezoelectric actuators. With this kind of systems the tool does

not get out of the material but the thickness of chips is varying that leads to breaking points [9][10][11]. A second approach consist in generating low-frequency oscillations (<1 kHz) with a magnitude close to the feed. In this second category technologies are more numerous. It is possible to generate the vibration by imposing an oscillating movement with a piezoelectric system [12], a linear motor [13] [14], an eccentric gear train [15], a mass-spring system (self-sustained vibrations based on chatter effects) [2][17] or a cam system [16].

Forced Low Frequency Axial Vibration Drilling

The MITIS Company has patented, developed and distributed its vibration drilling systems since 2007. The technology is based on a roller bearing with sinusoidal rings [11] (Figure 1). Axial oscillations are created by the relative rotation of both rings: one of those rings is turning with the spindle and the other is fixed in the machine frame. Two parameters have to be tuned: the magnitude (A) and the frequency (W) which is determined by the number of undulations of the rings.

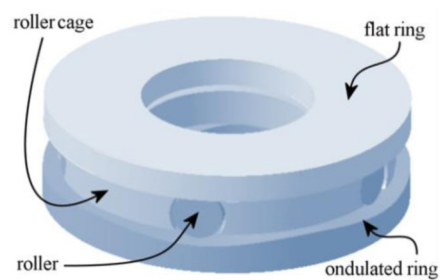


Figure 1. MITIS core system for vibration drilling

These new cutting parameters modify the trajectory of cutting edges and cut kinematics as shown on Figure 2.

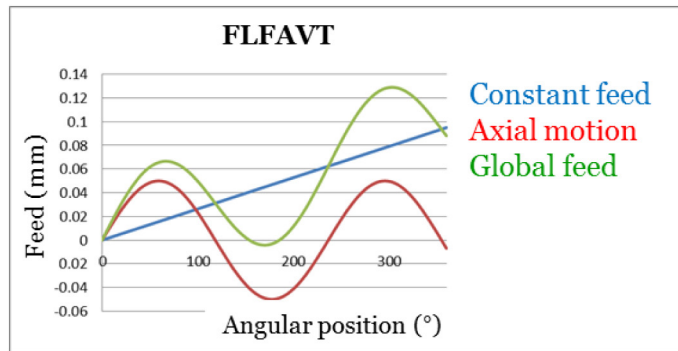


Figure 2. vibration drilling feed

Laporte et al. have modeled the kinematics of those kinds of systems [19]. They also described their main benefits whatever the material, among which:

1. getting small and fragmented chips ();
2. good control of chips evacuation;
3. decreasing the temperature during the cut.



Figure 3. small chips with MITIS drilling system

These advantages are particularly interesting for the case study of this paper. Benefits n°1 and n°2 allow drilling without peck-drilling cycles and with a straight cutter (no step). Benefit n°3 allow reducing the lubrication and replacing it by only dry air blast. Thus Low Frequency Axial Vibration assistance could be a competitive solution to improve productivity by solving both main issues identified in the paragraph “Case study”: avoiding carbon muds and reducing the cutting time. This new drilling process has been implemented in the following paragraph. Then a comparison has been made with the initial process.

COMPARATIVE ANALYSIS BETWEEN REGULAR DRILLING AND MITIS PROCESS

In this part regular drilling and vibration-assisted drilling processes are implemented on an instrumented test bench and analyzed. Criteria are proposed in order to compare both processes.

Criteria, Test Bench and Program Test

The Table 1 presents all criteria considered in this study to qualify and compare both processes according to the industrial needs of Productivity, Quality, Reliability and Manufacturing Cost.

Table 3. Criteria used for the comparative study

Industrial needs	Criteria	Units
Productivity	Cycle time	Second (s)
Manufacturing cost	Machine cost per hole	€/hole
	Cutter cost per hole	€/hole
Quality	Diameter	mm
	Roughness (R _a)	µm
	Capability indicators (C _p and C _{pk})	
Reliability	Tool life	Number of holes per tool
	Axial thrust force F _z [20]	Newton (N)
	Spindle power [20]	Watt (W)
	Chip morphology	