2019-01-1861 Published 16 Sep 2019

High Speed Orbital Drilling Optimization and Fatigue Life Enhancement by Orbital Roller Burnishing for Aluminum Alloy

Landry Arnaud Kamgaing Souop, Yann Landon, and Johanna Senatore Université Paul Sabatier Ups

Alain Daidie INSA Toulouse

Mathieu Ritou Université de Nantes

Citation: Kamgaing Souop, L.A., Landon, Y., Senatore, J., Daidie, A. et al., "High Speed Orbital Drilling Optimization and Fatigue Life Enhancement by Orbital Roller Burnishing for Aluminum Alloy," *SAE Int. J. Advances & Curr. Prac. in Mobility* 2(2):774-786, 2020, doi:10.4271/2019-01-1861.

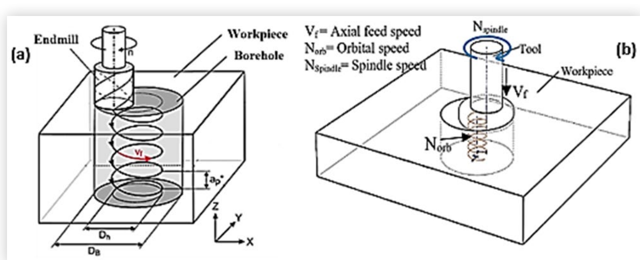
Abstract

Orbital drilling has proved to be advantageous to achieve aeronautical-level quality drilling (surface roughness, geometry control…) fully adapted for complex assemblies in a single operation. However, compared to conventional drilling method, this process leads to a drastic change in structure's fatigue life probably due to a non-optimised level of residual stress. The control of the mechanical behaviour of parts obtained by orbital drilling is the goal of the European-CleanSky collaborative R&D project RODEO (Robotized Orbital Drilling Equipment and Optimized Residual Stresses, GA no.738219). In this work, an orbital drilling unit (ORBIBOT) allowing high speed machining conditions was developed by PRECISE France, that can be integrated on a lightweight industrial robot. Cutting parameters were determined through an original Tool-Material Couple optimization strategy dedicated to orbital drilling, developed with MITIS Engineering and carried out on 2024-T351 Aluminum alloy. In order to enhance the mechanical behaviour of the system (fatigue, surface hardening…), an innovative mechanical surface treatment has been introduced for investigations: orbital roller burnishing, performed right after orbital drilling. The burnisher follows a helical path around the hole axis. Orbital burnishing and its associated tool have been patented by PRECISE (N°FR16 60693). A comparative study between axial drilling, orbital drilling and orbital drilling+burnishing was done in terms of hole diameter, surface roughness, burr height, fatigue life…. Performances and quality levels obtained by using orbital drilling (with or without burnishing) are significantly different compared to conventional drilling. On open-hole samples, a significative fatigue life improvement was exhibited using orbital drilling, even more important with burnishing. Tests were performed also on filled-hole configurations. The innovative coupling of orbital drilling and burnishing tools suggested by PRECISE offers new high-speed machining opportunities, especially in the controlled strain hardening and residual stresses domains.

Introduction

Orbital drilling is a holemaking process by milling, in which an endmill rotates around its own axis while describing an helical path around the hole axis (Fig. 1a). It has become increasingly popular in hole drilling processes, particularly in aerospace industries. Compared to conventional drilling, orbital drilling has proved to be particularly advantageous to achieve aeronautical-quality drilling through complex assemblies of materials in a single operation [1, 2, 3, 4, 5]. However, this process still needs to be improved not only in terms of operating conditions, but also in terms of mechanical properties of drilled parts. In fact, up to the recent past, orbital drilling were performed only with unit

FIGURE 1 Kinematics of the orbital drilling. (a) and orbital roller burnishing (b) processes



whose rotational speed were limited to a few per minute [6]. Hence, orbital drilling was essentially a low-speed machining operation. Moreover, Deitert showed that orbital drilling induces - despite the better hole quality (diameter tolerance, roughness, burr height) - fatigue life decrease in Aluminum alloys compared to axial drilling [6]. His investigations pointed out less compressive residual stresses on orbital drilled hole walls; which might lead to this decrease of fatigue life. Nevertheless, he stated that orbital drilling could be optimized in terms of fatigue life by defining suitable operating conditions and tools. Sun showed for instance that orbital drilling could give better fatigue life than axial drilling on AA2024-T351 [7]. But their studies were still conducted in very low-speed machining conditions due to their tools and orbital drilling unit. Nowadays, it is possible to perform orbital drilling in high speed machining (HSM). Therefore, it is important to establish strategies for optimized orbital drilling process, more importantly in HSM conditions.

Regarding compressive residual stresses, it could be enhanced by various mechanical surface treatments. Several authors [8, 9, 10, 11, 12] have shown that burnishing introduces compressive residual stresses, and improves the roughness and the hardening of parts. Delgado et al. also noted that roller burnishing gives a better state of residual stresses and hardening compared to shot peening and laser shock peening [13]. Hassan and Al-Bsharat have shown that burnishing increases the fatigue life of aluminum pieces [14]. As a novel mechanical surface treatment, orbital roller burnishing (or helical roller burnishing) appears to be an excellent solution to the orbital drilling lifetime problem insofar as it can be applied immediately after orbital drilling. The main specificity of this innovative roller burnishing technique lies in the kinematics of the tool (Fig. 1.b). However, its impact on fatigue life needs to be investigated.

In the present studies, optimization of orbital drilling in HSM conditions will be investigated on 2024-T351 Aluminum alloy firstly. It will be done by applying a novel Tool-Material Couple strategy specially elaborated for orbital drilling. Then, the orbital roller burnishing (ORB) impact with the prescribed conditions will be analysed in terms of surface integrity, holes geometry and residual stresses on 2024-T351 Aluminum alloy samples. Fatigue life tests on open and filled holes will be done also. All these criteria will be compared to orbital drilling and axial drilling. Regarding fatigue tests, as one of the main advantages of orbital drilling is the drilling and assembly of different material stacks without disassembly [1, 2] [6] [15], the impact of deburring operation on fatigue life are also studied.

Orbital Drilling Optimization Strategy: Tool-Material Couple for Orbital Drilling

Tool-Material Couple (TMC) is a standardized method (French norms NF E66-520-1 to NF E66-520-4) to define a correct tool operating domain for a given material. It is done by minimizing the specific energy $K_{C,P}$ (or specific cutting force $K_{C,F}$) and identifying the eigenfrequencies of the dynamic machining system. $K_{C,P}$ is the cutting power (Pc) per unit of chips flow rate (Q); it is defined by Eq. (1).

$$K_{C,P} = \frac{P_c}{Q} = \frac{P_c}{\frac{\pi D^2}{4}.V_{fa}} \tag{1}$$

$$K_{C,Fc} = \frac{F_c.V_c}{\frac{\pi D^2}{4}.V_{fa}} \tag{2}$$

$K_{C,P}$: Specific energy
P_C: Cutting power
F_C: Cutting force
D: Tool diameter
$K_{C,Fc}$: Specific cutting forces
Q: Chips flow rate
V_C: Cutting speed
V_{fa}: Axial feed rate

For axial drilling, there is only 2 independent parameters for TCM: Cutting speed Vc and axial feed rate V_{fa}. Hence, the correct tool operating domain is obtained through measurements of Kc in 2 steps;

- a measuring series with variable cutting speed at fixed axial feed;
- a measuring series with variable axial feed at the cutting speed determined earlier.

Analysis of the 2 curves of Kc exhibits the operating range for the given tool-material.

For orbital drilling, it is different because there are more parameters involved; and moreover, some of these parameters are dependent. The most important ones are:

- spindle speed (Ns): which gives cutting speed with Eq. (3)
- axial feed (f_a): which gives axial feed rate with Eq. (4)
- orbital speed (Norb);
- pitch (p): which depends on V_{fa} and Norb by Eq. (5)

$$V_C = 2\pi.R_{tool}.\frac{N_s}{1000} \tag{3}$$

$$f_a = \frac{V_{fa}}{N_s} \tag{4}$$

$$\mathrm{p} = \frac{V_{fa}}{N_{orb}} \tag{5}$$

Determining operating domain will be done in multiple steps.

1. *Determination of suitable Ns*
   - p and fa remain fixed; Ns varies. (V_{fa} and Norb also vary, in order to keep fa and p fixed)

- Kc=f(Ns) curve is plotted and the Ns equivalent to the minimum Kc is determined.

2. *Determination of suitable p*
   - Ns, fa and V_{fa} remain fixed; p varies (Norb varies, in order to keep V_{fa} fixed)
   - Kc=f(p) curve is plotted and the p equivalent to the minimum Kc is determined.

3. *Determination of suitable V_{fa}*
   - Ns, and p remain fixed; V_{fa} varies (Norb varies, in order to keep p fixed
   - Kc=f(V_{fa}) curve is plotted and the V_{fa} equivalent to the minimum Kc is determined.

The suitable value of Norb will then be calculated from Eq. (4).

In the end, the optimized values of Ns, Norb and Vfa for orbital drilling are determined.

Apparatus

Orbital Drilling Unit

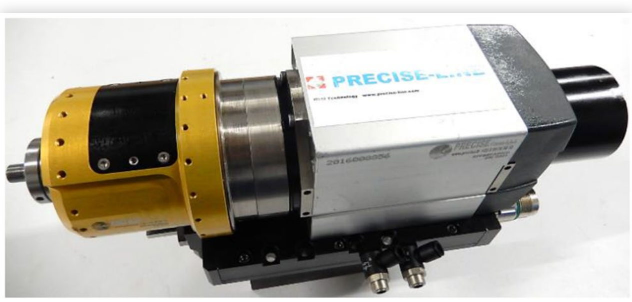
The ODU (ORBIBOT) used in this study was supplied by PRECISE (Fig. 2). It is an HSM orbital drilling device which has as motion range:

- up to 60000rpm for spindle speed (Ns)
- up to 2000rpm for orbital speed (Norb)
- 1.1 - 1.95mm for offset diameter

The ORBIBOT has been mounted on a CNC machine (DMG DMU85eVo). Axial feed was therefore

The CNC machine is equipped with a Kistler 9257B dynamometer (which measures machining forces). In order to report machining forces and powers, a CompactDAQ system from National Instrument with NI 9201 and NI 9215 I/O modules respectively are used. 2 accelerometers are fixed on the ORBIBOT. The software used for data acquisition and processing was WITIS. This CNC machine was also used to performed axial drillings.

FIGURE 2 PRECISE Orbital Drilling Unit - ORBIBOT



Tools and Samples

In this study, drilled holes have 6.35mm (1/4”) as final diameter.

For axial drillings, two configurations are studied:

- *Axial drilling in a single operation*

The drill is a carbide tool developed and used for aeronautical applications by HAM FRANCE (Fig 3.a)

- *Axial drilling + Reaming*

Drillings are performed with a 6.1 diameter HSS tool and reaming with a carbide reamer for aeronautical applications (Fig 3.b).

Orbital processes (orbital drilling and orbital drilling + ORB) are performed with an orbital drilling tool designed specifically for the study (Fig. 4). It is a machining/burnishing carbide dual tool for orbital drilling. Its endmill has four teeth. The tool body includes a burnishing portion spaced from the cutting end. It will induce residual stress and hardening in hole side wall without removing material. Advantages of this tool is firstly to realise orbital drilling and ORB in a single operation. Moreover, coaxiality of drilling and ORB will be maintained and burnishing depth will be regular around the hole. Endmill and burnisher diameters are respectively equal to 4.85mm and 4.89mm; which gives a burnishing depth of 20µm.

The 2024-T351 Aluminum alloy samples (solution treated, cold worked, naturally aged and stress relieved) were extracted from a 6mm thickness sheet form material. Their final thickness was 3.175mm. Their length and width were respectively 200mm and 19.05mm. The longitudinal directions of samples are all in the rolling plate direction.

FIGURE 3 Axial drilling tools.

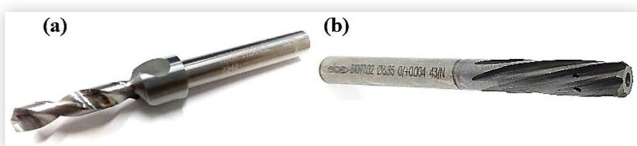
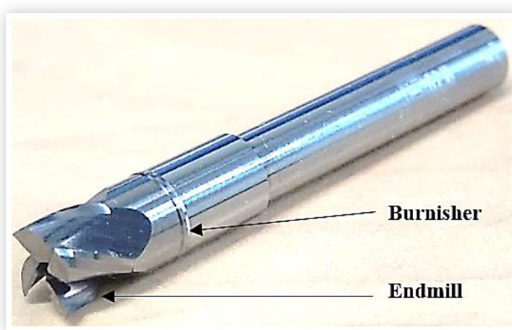


FIGURE 4 Orbital drilling and burnishing tool



Application of the Orbital Drilling TMC

In order to carry out TMC for orbital drilling, the following conditions are established:

Spindle rotation speed (N): 22080 rpm - 57720 rpm
Orbital rotation speed (N_{orb}): 588 rpm - 2000 rpm
Axial feed rate (V_f): 22.9 - 60 mm/min
Offset diameter (e): 1.5 mm
Lubrication: External MQL Boelub

Orbital drillings performed with the ORBIBOT could be up-milling (orbital and spindle rotations are both clockwise) and down-milling (orbital and spindle rotations are direct and clockwise respectively) operations.

Results presented in the following paragraphs are done in down-milling conditions.

Orbital Cutting and ORB Forces

Fig 5 shows a record of machining forces during orbital processes. Low-pass filter with a limiting frequency of 20Hz has been applied on those signals. Orbital drilling+ORB operation can be divided in 3 main phases: orbital drilling (phase 1 on fig 5), ORB with the tool feed motion (phase 3) and ORB opposite to the tool feed motion (phase 5). It is important to outline that during phase 5, spindle and orbital rotations remain unchanged. Fig 5 highlights very small orbital cutting forces (lower than 14N); ORB forces are even smaller than orbital cutting ones. In addition, the smaller burnishing depth the smaller ORB forces.

Determination of Optimized Spindle Speed Ns

The initial prescribed values given by ORBIBOT manufacturer (PRECISE) were Ns=40000rpm, Norb=1000rpm, V_{fa}=40mm/min; which give p=0.04mm. Thus, the initial fixed pitch was p=0.04mm. fa=0.001mm/rev (Spindle revolution). The Kc,p=f(Ns) curve is represented by Fig 6. This figure shows

FIGURE 5 Orbital cutting and ORB forces

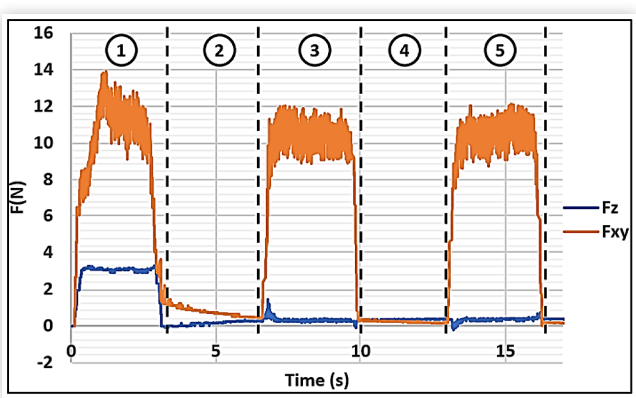


FIGURE 6 Specific energy Kc as function of spindle speed Ns

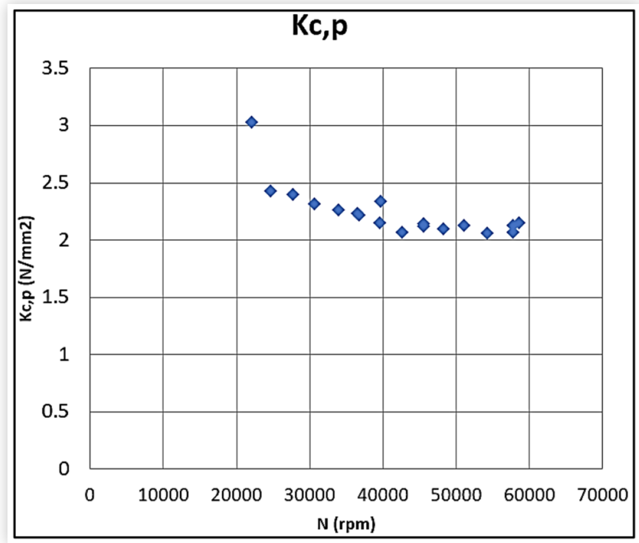
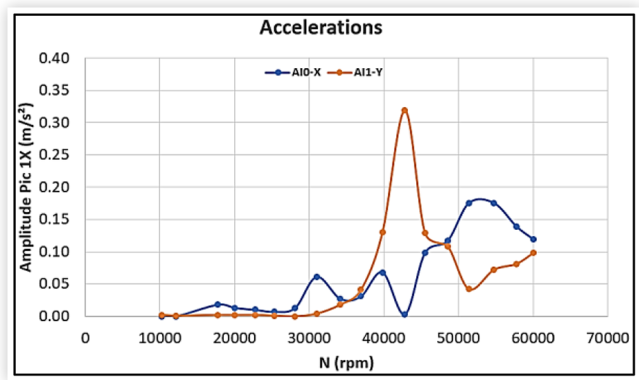


FIGURE 7 Accelerations



that the minimum specific energy is obtained for Ns≃60000rpm. But analysis of accelerations shows eigenfrequencies of the dynamic machining system at Ns>40000rpm (Fig 7). Therefore, the best spindle speed is equal to 40000rpm.

Determination of Optimized Pitch p

Ns=40000rpm, fa=0.001mm/rev and V_{fa}=40mm/min. The Kc,p=f(p) curve (Fig. 8) doesn't show any clear trend on optimized pitch. So the normalized specific cutting forces curves $K_{C,Fxy}$ and $K_{C,Fz}$ are plotted (Fig. 9). These 2 curves give an operating point at p=0.04mm.

Determination of Optimized Axial Feed Rate V_{fa}

Ns=40000rpm and p=0.04mm. The Kc,p=f(V_{fa}) curve is represented by Fig 10. This figure shows that the minimum specific energy is obtained for V_{fa}=60mm/min. This optimized value of V_{fa} and p give (from Eq. (5)) Norb=1500rpm as optimized orbital speed.

FIGURE 8 Specific energy Kc,p as function of pitch p

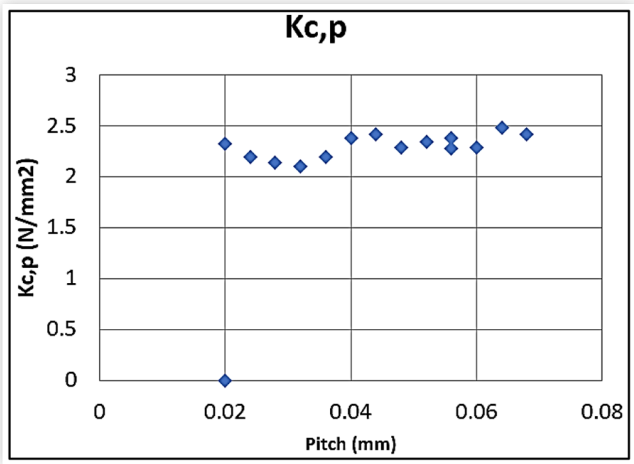


FIGURE 9 Normalized specific energies $K_{C,F}/Max(K_{C,F})$ as function of pitch p

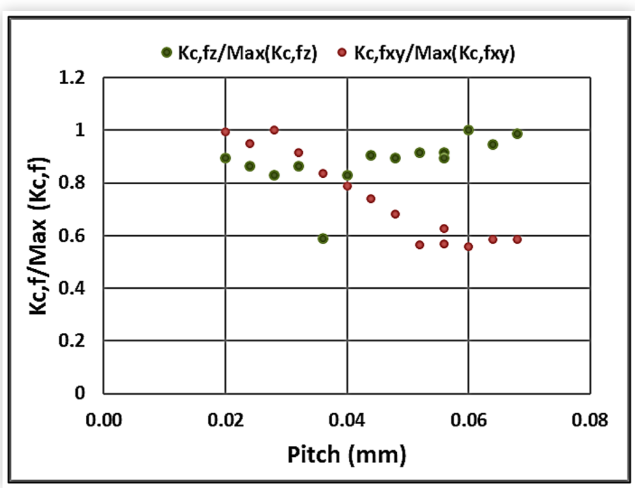
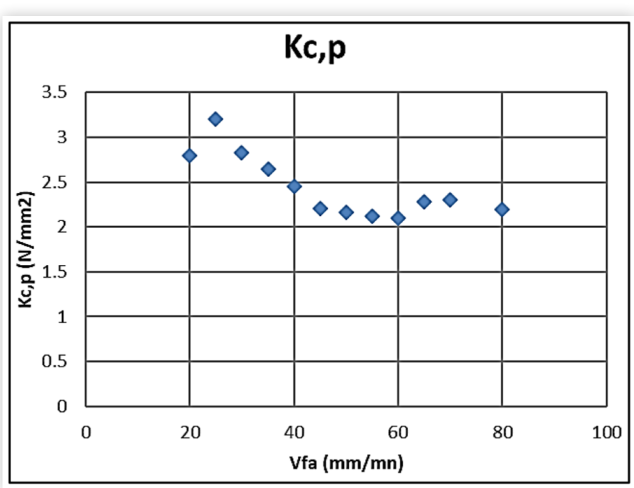


FIGURE 10 Specific energy Kc,p as function of axial feed rate Vfa



In summary, the optimized orbital drilling parameters based on specific energy for these couple of tool and material are:

$$\textbf{Ns} = \textbf{40000rpm} \text{ and } \textbf{Norb} = \textbf{1500rpm} \text{ and } \textbf{V}_{fa} = \textbf{60mm}/\text{min}.$$

This TMC strategy had been done also in up-milling orbital drilling operation. Results gave the same optimal process parameters in down-milling configuration (Cf Appendix A).

Comparative Study between Drilling Processes

Parameters used in this study for each process are summarized in Table 1. Axial drilling and reaming parameters are given by tool manufacturers and were specifically determined for 2024-T351 Aluminum alloy. It is important to remind that the burnishing depth is equal to 20µm.

Results and Discussions

Holes Diameters

Holes diameters measurements have been done with a 2-points electronic inside micrometre. For each drilling processes, measurements have been done in the longitudinal and transversal direction of 5 samples (5 measurements per direction on each sample). Fig. 11 shows one example of hole diameter measurement in the longitudinal direction. Fig. 12 shows average values of holes diameters. It exhibits that holes drilled holes have good circularity, whatever the drilling process.

Fig. 13 is the average values of longitudinal and transversal holes diameters measurements. It can be noted that all diameter values are in accordance with the aeronautic hole specification (6.35±0.018mm, represented as red dot-lines). Moreover, the diameters of axial drilled holes are always slightly smaller than the ones of orbital drilled holes, although

TABLE 1 hole-making parameters

	Axial drilling	Reaming	Orbital drilling	Orbital drilling + ORB
Spindle rotation (rpm)	9000	2000	40000	40000
Axial feed rate (mm/min)	900	501	60	60
Orbital speed (rpm)	-	-	1500	1500
Offset diameter (mm)	-	-	1.5	1.5
Cutting speed (m/min)	180	40	608.3	608.3
Axial feed (mm/rev)	0.1	0.25	0.0015	0.0015
Lubrication	External MQL Boelub	External MQL Boelub	External MQL Boelub	External MQL Boelub

© 2019 SAE International. All Rights Reserved.

FIGURE 11 Hole diameter measurement in the longitudinal direction

FIGURE 12 Average holes diameters values in longitudinal and transversal sample directions

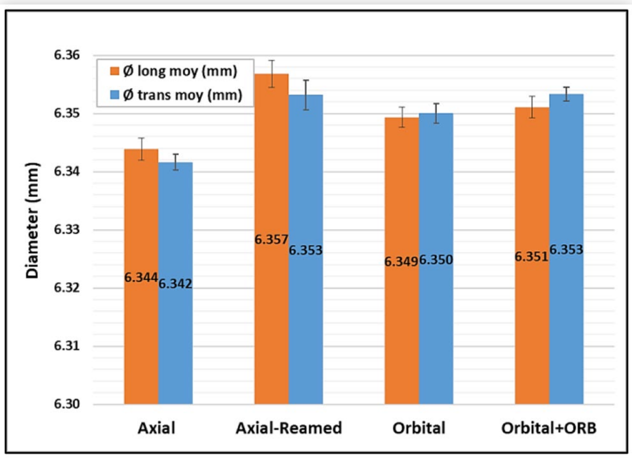
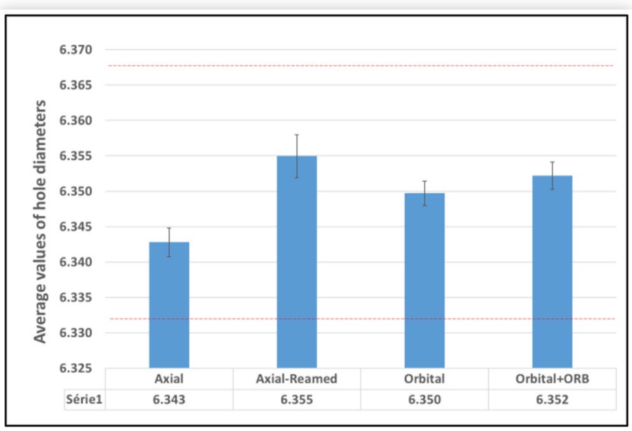


FIGURE 13 Hole diameters

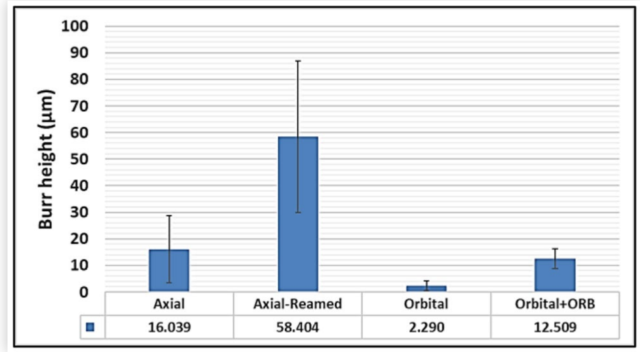


it is in the tolerance. It can be explained by the axial tool diameter which is slightly less than the nominal value 6.35mm.

Burr Height

Burr height measurements have been conducted with an optical profilometer (Alicona Infinite Focus SL) on exit faces

FIGURE 14 Burr height



of samples. For each configuration, measurements have been done on 4 samples; and each sample had 8 measuring points regularly distributed on hole edges. Based on Fig. 14, burr height values remain under the maximal admitted burr height in aeronautics (0.1mm). Orbital drilled holes exhibit the lowest burr height values (almost burr-free) and are less scattered. Compared with orbital drilled samples, orbital drilled+ORB samples exhibit slight greater values. This is explained by the fact that during ORB, plastic deformations are induced on borehole surface layers and material is repelled below the burnisher. At the tool exit, that repelled material is push out as a burr. Axial drilled+reamed samples present also very high burr height values. That burr comes from material layers on the pilot boreholes which, considering the reamer axial feed, are popped out with its exit.

High scatterings were observed on both axial drilled samples, with the highest on axial drilled+reamed ones. This is due to the fact that holes presented important burr on some measuring points, whereas very little burrs were present on the other measuring points. This phenomenon was not observed on orbital drilling processes. This could be explained by the difference between process axial feeds. In fact, high axial feeds do not allow the repelled material to be uniformly distributed around hole edges when tool exits the sample.

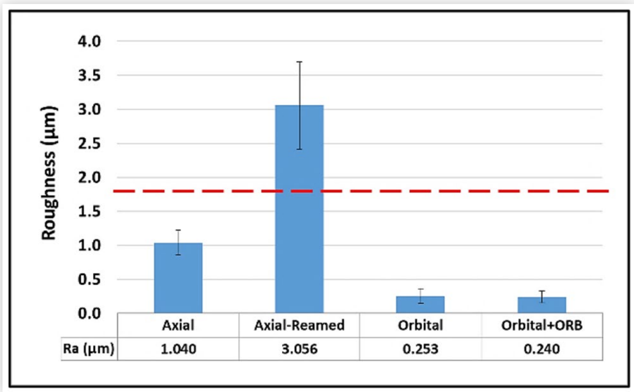
Roughness

Roughness was measured with a MITUTOYO portable surface roughness tester (SJ-301 Series). For each configuration, measurements have been done on 4 samples; and each sample had 2 opposite measuring paths on boreholes and 3 measurements were done on each path. As shown on Fig. 15, the arithmetic roughness of the orbital drilling processes (with and without burnishing) provide a better roughness than the axial drilling processes. It can be noted also that all these values are in accordance with aeronautics requirements (holes Ra≤1.6µm) except reamed samples that show a too high Ra, probably due to the high axial feed used during reaming.

Residual Stresses

Residual stresses evaluation by X-ray diffractions on a 2024-T351 Aluminum alloy is a complex task for many reasons.

FIGURE 15 Holes arithmetic roughness Ra



In fact, this method relies on several hypotheses among which [16]:

- grain size should be very small: in order to irradiate a large number of grains;
- samples should not have crystallographic texture: it should be an isotropic material
- Sample must be flat

But 2024-T351 Aluminum alloy have large grain and presents texture following the rolling direction of the sheet plate [17]. All this would introduce significant scatter in X-ray diffractions residual stress measurements. [18] applied this technique on a 2000 series aluminum alloy and showed that the tolerance was greater than the measured value itself, due to all these above drawbacks. Moreover, residual stresses evaluation would have been more relevant on holes walls. But these surfaces are not flat, and opening hole would release (in an unknown proportion) residual stress held in the material.

In order to bypass these issues, a specific test campaign has been designed. It consists in milling and then burnishing the edge of specimens (planar surfaces) cf Fig. 16. The tests are realized with the designed orbital tool, used as milling tool (no orbital rotation). To make these tests representative of orbital drilling and ORB, the feed of the tool (Vf) is defined as the tangential feed in orbital drilling (given by the orbital rotation speed), and the axial pitch between two successive paths is defined as the axial pitch in orbital processes. But these tests cannot be conducted to represent axial drilling.

Results of X-ray diffraction are shown on Fig. 17. It appears that orbital drilling on theses surfaces induces compressive residual stresses; -70MPa and -119MPa following Axial and orthoradial directions respectively. And regarding the ORB, induced compressive residual stresses levels are up to -169.5MPa and -273.5MPa in Axial and orthoradial directions respectively.

These tests showed that orbital drilling with the optimized parameter generates compressive residual stress on surface layer of holes walls. Furthermore, it also shows that ORB induces more compressive residual stresses.

Fatigue

The fatigue tests were carried out on an electro-mechanical equipment SCHENCK hydropuls PSB 100kN. Fatigue tests were conducted on open and filled holes.

Fatigue Tests on Open Holes The following requirements have been considered for all open holes fatigue tests:

- Cycling frequency: f=15Hz
- Temperature: Room temperature
- Tensile-Tensile tests: σ_{max} = 150MPa on net section, R=0.1.

Impact of the Deburring Operation: Chamfered vs. Undeburred vs. Deburred. The chamfering operation consisted in the realization of a 0.3mm chamfer on the borehole edges according to aeronautics standards. But it induces a high material removal ratio on the sample thickness (20% if done on both edges). Thus, a deburring operation has also been considered for open-hole fatigue tests. The deburring operation consists of slight grinding of the entrance and exit borehole edges with small grains sand paperin sight to remove the burr.

FIGURE 16 Configuration of the milling and burnishing of planar surfaces

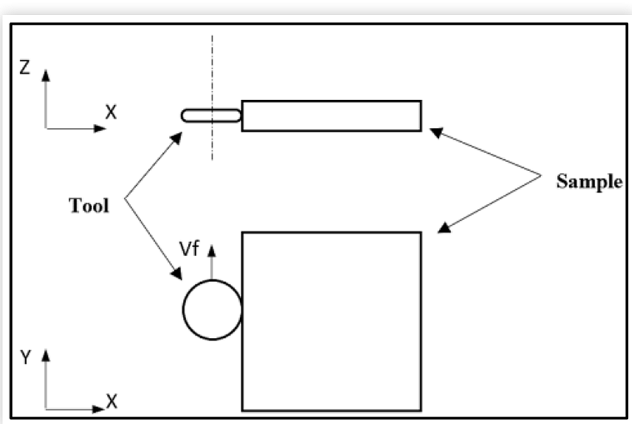
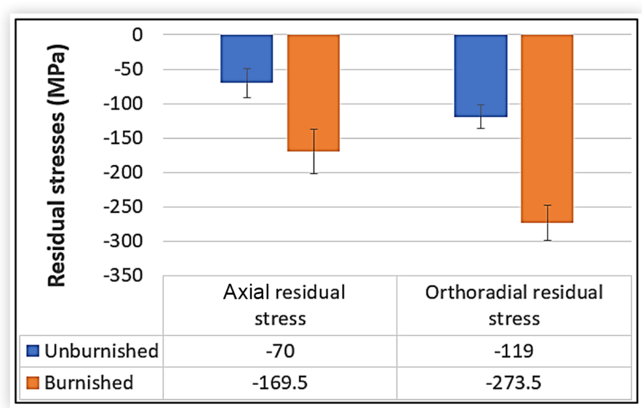


FIGURE 17 Residual stresses after orbital drilling and orbital drilling+ORB on planar surfaces



Tests were done on 5 samples per process. Results on open-hole specimens are analysed comparing just axial only drilled and orbital drilled+burnished samples (in order to reduce the DoE levels). The results (Fig. 18) obtained were very scattered, especially for the chamfered and undeburred specimens. Indeed, 3 tests led to unexpectable results:

- one sample in orbital drilling+burnishing, chamfered, fractured at 2 546 643 cycles while the other specimens in this configuration were around 340 000 cycles
- one sample in orbital drilling+burnishing, undeburred, fractured at 908 549 cycles VS. around 210 000 cycles for the other tests in this configuration
- one sample in orbital drilling+burnishing, deburred, fractured at 415 961 cycles VS. around 230 000 cycles for the other tests in this configuration

For a better results interpretation, those 3 single values were not considered in the analysis.

Fatigue life of axial samples are quite similar in-between chamfered, undeburred and deburred configurations, even if chamfered samples have a slightly less fatigue life.

It is difficult to have a strong assertion about the deburring operation on orbital drilling+ORB. If the same conclusion could be made between deburred and undeburred holes (approximatively the same fatigue life), the chamfered configuration shows a much more important fatigue life, despite the thickness reduction on the hole edge. However, even if one result was removed from that latter configuration, (the one at 2 546 643 cycles to failure), results are still very scattered. So, the big material removal due to that chamfering leads consequently to scattered results.

Thus, aside from orbital drilling+ORB chamfered specimens, it seems that the burr removal operation has no significant impact on the fatigue life. This could be explained by the low values of burr height measured on the hole edges (Fig. 14); which minimize potential stress concentration on holes edges. Thus, the crack initiates at the core of the sample before growing up to the edges as it was observed on the fracture surface (Fig. 19).

Comparison between Processes. The overall comparative study between drilling processes are summed up on Fig. 20. Moreover, orbital processes were done both in up-milling (UM) and down-milling (DM). As it was established before, process parameters in both orbital drilling configurations were determined by the TMC strategy and were the same; (only orbital rotations were reversed). All the samples tests considered here were deburred. There were 5 samples per configuration.

With these results, it clearly appears that the orbital processes (without ORB) provides better fatigue results than the axial process. Addition of the ORB operations enhances even more the fatigue behaviour. Furthermore, orbital-DM provides greater fatigue life compared to orbital-UM, whatever orbital roller burnished or not. Axial drilling+reaming tends to give the least fatigue life; this could be correlated with its arithmetic roughness which was the highest one.

FIGURE 18 Results of open-hole fatigue tests: Chamfered vs. Undeburred vs. Deburred

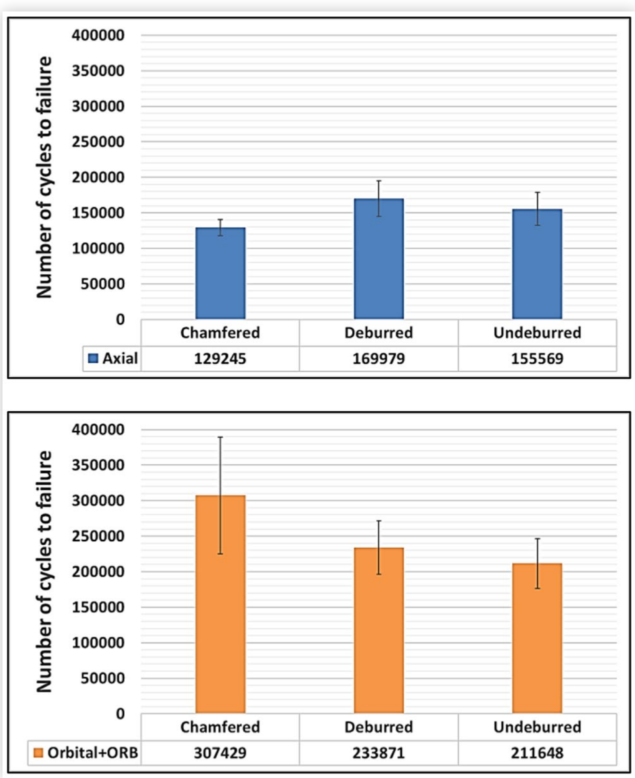


FIGURE 19 Fractures on open-hole samples (a) deburred, (b) chamfered, (c) undeburred

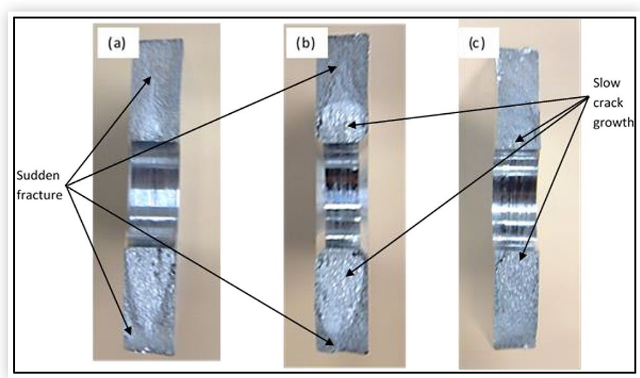
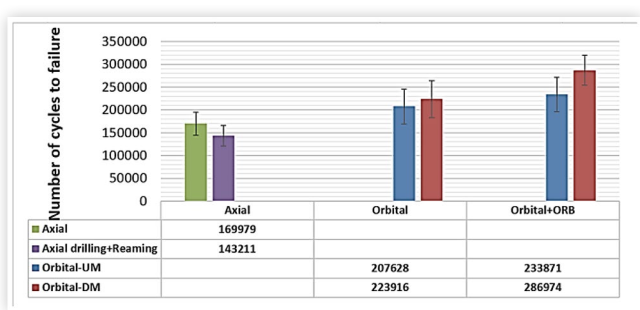


FIGURE 20 Results of open-hole fatigues tests: Axial vs. Axial+reaming vs. Orbital vs. Orbital+ORB



Compared with axial drilling, the fatigue life enhancements due to orbital drilling and orbital drilling+ORB (both up-milling) are:

- Orbital drilling / Axial drilling: +22.15%
- Orbital drilling+ORB (UM) / Axial drilling: +37.59%
- Orbital drilling+ORB (UM) / Orbital drilling: +12.64%

Some others comparisons are as followed:

- Orbital drilling (DM) / Orbital drilling (UM): +7.84%
- Orbital drilling+ORB (DM) / Orbital drilling+ORB (UM): +22.70%.

Wöhler Curves. In order to have no interactions related to fasteners and enough data to have a good comparison, Wöhler curves on open holes samples were also plotted Fig. 21. The following parameters were observed.

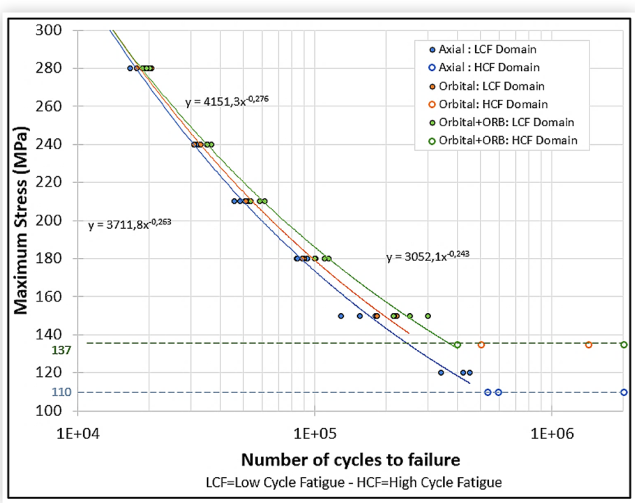
- Tensile-Tensile tests: σ_{max} = [120; 280]MPa on net section, R=0.1
- Cycling frequency: f=15Hz
- Temperature: Room temperature
- 3 samples per stress level and per process

Orbital processes were only Up-milling ones.

From these results, the following findings appeared:

- Regardless of stress level, the number of cycles to failure for orbital drilling+ORB is always greater than the orbital drilling one which in turn is always greater than one.
- Fatigue limits of orbital drilling and orbital drilling+ORB are quite similar.
- Fatigue limits of orbital processes are greater than the axial one.Explanations of all these results exhibited by open holes fatigue test could be explained by the compressive residual stresses and hardening on surface layers of holes walls; even though, up to now, it is very difficult to evaluate the axial drilling ones.

FIGURE 21 Wöhler curves for each drilling processes



Fatigue Tests on Filled Holes In order to evaluate the benefit of optimized orbital processes with fixation inside holes, double-lap bearing strength tests (Fig. 22) had be done. Sample dimensions were chosen in accordance with the standard ASTM E238-17a [19]. Fasteners are made up with a titanium bolt and a steel nut and clevis with 35CD4 steel. Tests were carried out on 4 samples per configuration; and following requirements were considered for all filled holes fatigue tests:

- Cycling frequency: f=15Hz
- Temperature: Room temperature
- Tensile-Tensile tests: σ_{max} = 59.65MPa on net section, R=0.1. This stress level was calculated based on stress level and stress concentration factor of open holes samples (σ_{max} = 150MPa, Kt=3.46) so as to have the same real maximum stress level.

In order to investigate exclusively optimized orbital drilling and ORB (Up-milling operation only) benefits on filled holes, some considerations had been done:

- Assemblies are realised with clearance fit to avoid interference benefits;
- PTFE washers were placed between each side of the sample and the clevis so as to restrict interactions between clevis and sample.
- The prescribed minimal tightening torque according to aeronautical requirements for this configuration is 6.3Nm. But a tightening torque of 4Nm had been chosen so that there would be no preload on fastener and thus, no load transfer through it.

Results (Fig. 23) show that optimized orbital drilling processes allow to reach a better fatigue life in comparison

FIGURE 22 Filled holes fatigue tests samples

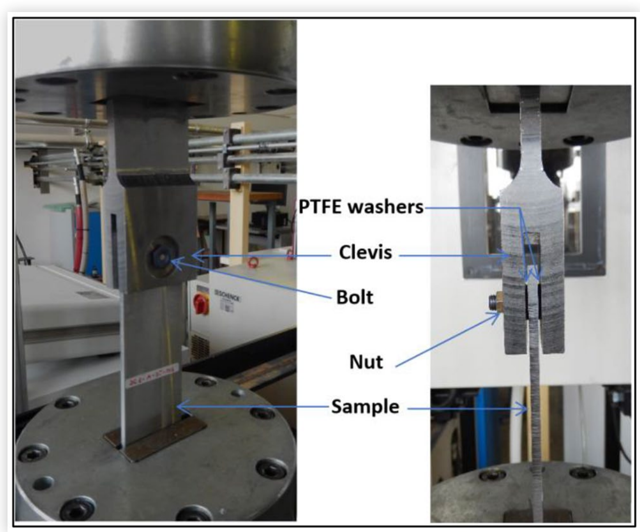
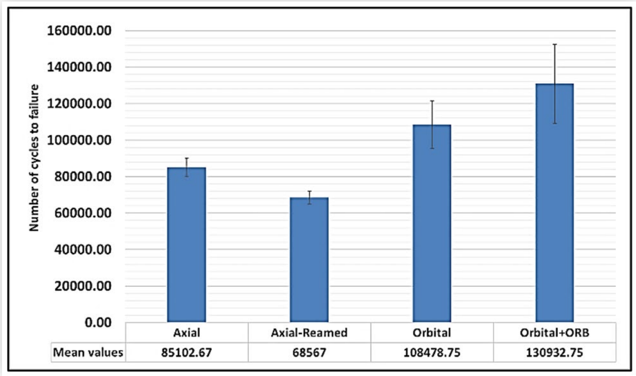


FIGURE 23 Filled holes fatigue tests results



with axial drilling (+27.47% for orbital drilling/axial drilling and +53.85% for orbital drilling+ORB/axial drilling). Moreover, the ORB improvement compared with optimized orbital drilling is still noticeable (+20.7%). Axial drilling+reaming gives less fatigue life compared to axial drilling (-19.43%).

These outcomes are in accordance with open holes fatigue tests results.

Summary/Conclusions

This study concerned optimization of orbital drilling, especially in High-Speed Machining conditions on 2024-T351 Aluminum alloy and also the benefits of a novel mechanical surface treatment. In sight to determine the most suitable orbital drilling operating conditions, a Tool-Material Couple dedicated to orbital drilling has been elaborated. Its application allowed the identification of the optimized operating conditions for orbital drilling, based on specific energy minimization. Thereafter, these parameters have been used to analyse holes drilled with orbital drilling process, on several criteria (holes geometry and diameters, surface integrity, residual stresses and fatigue life). It has been shown that orbital drilling process (orbital drilling and orbital drilling+ORB) with those parameters produce holes which have excellent circularity and dimensions. Their burr heights and arithmetic roughness are even lesser than the axial drilled ones. Axial drilled+reamed holes presented the highest burr height values and arithmetic roughness and also the least fatigue life. This could be explained by the axial feed prescribed by the tool manufacturer which was too high.

Considering all issues of X-ray diffraction on 2024-T351 Aluminum alloy material, it has been elaborated a specific test to evaluate residual stresses induced by orbital processes. It turns out that the determined optimized parameters generate compressive residual in both radial and orthoradial directions; And these compressive residual stresses level are higher when ORB is applied.

Fatigue tests on open holes samples showed that burr height produced by orbital drilling is too small to have a relevant impact on fatigue life. Consequently, the deburring operation is not really necessary with orbital drilling on assembly lines like it is done nowadays. These tests also highlighted that optimized orbital drilling provides a better fatigue life than axial drilling. And this fatigue life is more enhanced if ORB is applied right after this orbital drilling. These findings were also observed on filled holes fatigue tests. In addition, Wöhler curves pointed out that fatigue limits of orbital process are greater than the axial one. Benefits of the developed orbital drilling and orbital drilling+ORB in High Speed Machining conditions are hence demonstrated and very relevant. The optimized operating parameters allow to reach, for open-hole specimens, a better fatigue life than with axial drilling. This could be justified by the high compressive residual and hardening stresses induces on surface layers of holes walls.

Regarding further work, it shall be interesting to find a way to evaluate compressive residual stress on drilled holes. The curvature method seems to be suitable. Moreover, a detailed study on orbital drilling following the up-milling and down-milling configurations shall be relevant; in order to explain the difference observed in terms of fatigue life. Finally, a complete filled hole fatigue test campaign considering interactions in material stacks, fixation interference and tightening torque could give more information about the benefits of orbital drilling and orbital drilling+ORB in High Speed Machining conditions.

References

1. Whinnem, E., Lipczynski, G., and Eriksson, I., "Development of Orbital Drilling for the Boeing 787," *SAE Int. J. Aerosp.* 1(1):6, doi:10.4271/2008-01-2317.
2. Marguet, B., Wiegert, F., Lebahar, O., Bretagnol, B., Okcu, F., and Ingvar, E., "Advanced Portable Orbital-Drilling Unit for Airbus Final Assembly Lines," in *Aerospace Technology Conference and Exposition*, 2007. doi:10.4271/2007-01-3849.
3. Iyer, R., Koshy, P., and Ng, E., "Helical Milling: An Enabling Technology for Hard Machining Precision Holes in AISI D2 Tool Steel," *International Journal of Machine Tools and Manufacture* 47(2):205-210, Feb. 2007, doi:10.1016/j.ijmachtools.2006.04.006.
4. Olvera, D., de Lacalle, L.N.L., Urbikain, G., Lamikiz, A. et al., "Hole Making Using Ball Helical Milling on Titanium Alloys," *Machining Science and Technology* 16(2):173-188, Apr. 2012, doi:10.1080/10910344.2012.673958.
5. He, G., Li, H., Jiang, Y., Qin, X. et al., "Helical Milling of CFRP/Ti-6Al-4V Stacks with Varying Machining Parameters," *Trans. Tianjin Univ.* 21(1):56-63, Jan. 2015, doi:10.1007/s12209-015-2360-9.
6. Deitert, L., "Orbital Drilling," in *Aerospace Technology Conference and Exposition*, 2011. doi:10.4271/2011-01-2533.
7. Sun, D. et al., "Hole-Making Processes and Their Impacts on the Microstructure and Fatigue Response of Aircraft Alloys," *Int J Adv Manuf Technol* 1-8, Dec. 2016, doi:10.1007/s00170-016-9850-3.
8. Yen, Y.C., Sartkulvanich, P., and Altan, T., "Finite Element Modeling of Roller Burnishing Process," *CIRP Annals*

54(1):237-240, Jan. 2005, doi:10.1016/S0007-8506(07)60092-4.

9. Balland, P., Tabourot, L., Degre, F., and Moreau, V., "An Investigation of the Mechanics of Roller Burnishing through Finite Element Simulation and Experiments," *International Journal of Machine Tools and Manufacture* 65:29-36, Feb. 2013, doi:10.1016/j.ijmachtools.2012.09.002.
10. Wagner, L., "Mechanical Surface Treatments on Titanium, Aluminum and Magnesium Alloys," *Materials Science and Engineering: A* 263(2):210-216, May 1999, doi:10.1016/S0921-5093(98)01168-X.
11. García-Granada, A.A., Gomez-Gras, G., Jerez-Mesa, R., Travieso-Rodriguez, J.A., and Reyes, G., "Ball-Burnishing Effect on Deep Residual Stress on AISI 1038 and AA2017-T4," *Materials and Manufacturing Processes* 32(11):1279-1289, Aug. 2017, doi:10.1080/10426914.2017.1317351.
12. Balland, P., Tabourot, L., Degre, F., and Moreau, V., "Mechanics of the Burnishing Process," *Precision Engineering* 37(1):129-134, Jan. 2013, doi:10.1016/j.precisioneng.2012.07.008.
13. Delgado, P., Cuesta, I.I., Alegre, J.M., and Díaz, A., "State of the Art of Deep Rolling," *Precision Engineering* 46:1-10, Oct. 2016, doi:10.1016/j.precisioneng.2016.05.001.
14. Hassan, A.M. and Al-Bsharat, A.S., "Improvements in Some Properties of Non-Ferrous Metals by the Application of the Ball-Burnishing Process," *Journal of Materials Processing Technology* 59(3):250-256, May 1996, doi:10.1016/0924-0136(95)02149-3.
15. Ni, W., "Orbital Drilling of Aerospace Materials," 2007. doi:10.4271/2007-01-3814.
16. Lu, J. *Handbook of Measurement Residual Stresses* (US, Society for Experimental Mechanics, 1996), Chap 5, ISBN 0-88173-229-X.
17. Pauze, N., "Fatigue corrosion dans le sens travers court de tôles d'aluminium 2024-T351 présentant des défauts de corrosion localisée," Ecole Nationale Supérieure des Mines Saint-Etienne, Saint-Etienne, 2008, https://tel.archives-ouvertes.fr/tel-00359611.
18. Ball, D.L. and Lowry, D.R., "Experimental Investigation on the Effects of Cold Expansion of Fastener Holes," *Fracture of Engineering Materials and Structures* 21(1):17-34, 1998, doi:10.1046/j.1460-2695.1998.00430.x.
19. ASTM E238-17a, "Standard Test Method for Pin-Type Bearing Test of Metallic Materials," ASTM International, West Conshohocken, PA, 2017, www.astm.org.

Acknowledgments

This work was carried out within the framework of the RODEO project, which is funded by the Clean Sky 2 European Research and Innovation Program H2020, under approval number 738219. We therefore wish to express our sincere thanks to the different actors of this project: PRECICE France, MITIS Engineering, KUKA Systems Aerospace France.

Definitions/Abbreviations

HSM - High Speed Machining

ORB - Orbital Roller Burnishing

ODU - Orbital Drilling Unit

TMC - Tool-Material Couple

Appendix A: Specific Energy Curves for TMC in up Milling Orbital Drillings Operation

Considering the machining system dynamic, the suitable minimum specific energy is obtained for Ns≃40000rpm.

The Kc,p=f(p) curve (Fig. A2) doesn't show any clear trend on optimized pitch. So the specific cutting forces curves $K_{C,Fxy}$ and $K_{C,Fz}$ are used to find the optimal pitch. On fig. A3, these curves intersect at p≈0.03mm. Nevertheless, a pitch equal to 0.04mm induces a high decrease of $K_{C,Fxy}$ (-15.372N/mm²) while the increase of $K_{C,Fz}$ remained low (+0.003N/mm²). Thus, the optimal pitch is equal to 0.04mm.

Based on the Kc,p=f(V_{fa}) curve (Fig. A4), the minimum specific energy is obtained for V_{fa}=60mm/min. This optimized value of V_{fa} and p give (from Eq. (5)) Norb=1500rpm as optimized orbital speed.

Optimal orbital drilling process parameters in Up-milling configuration are:

$$\mathbf{Ns = 40000rpm} \text{ and } \mathbf{Norb = 1500rpm} \text{ and } \mathbf{V_{fa} = 60mm}/\mathrm{min}$$

FIGURE A1 Specific energy Kc,p as function of spindle speed Ns

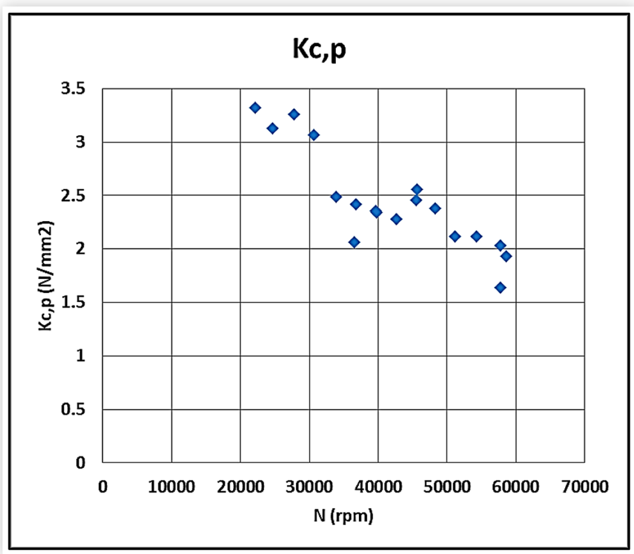


FIGURE A2 Specific energy Kc,p as function of pitch p

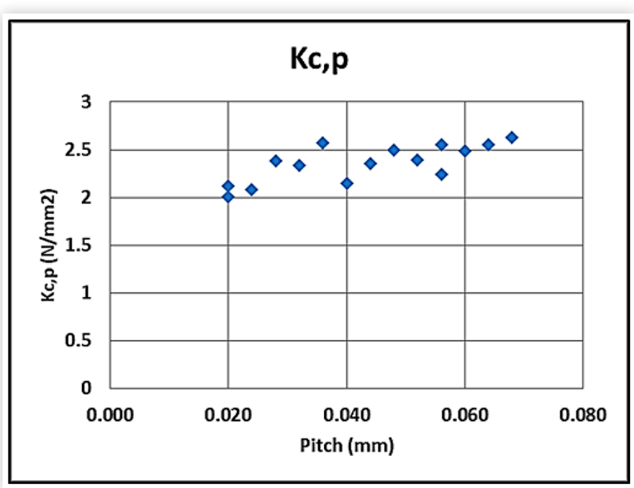


FIGURE A3 Specific energy $K_{C,Fxy}$ and $K_{C,Fz}$ as function of pitch p

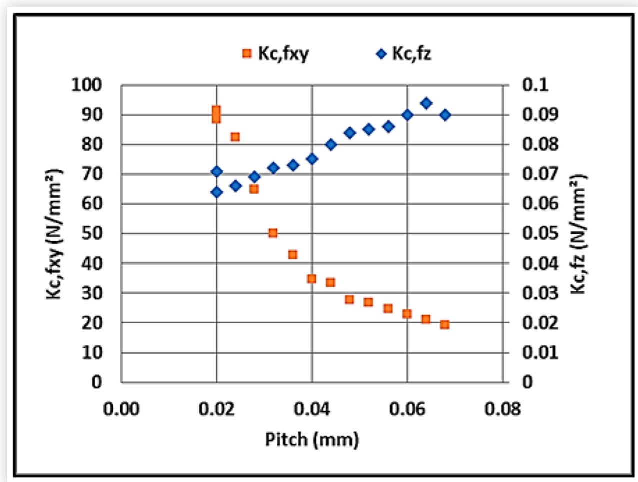
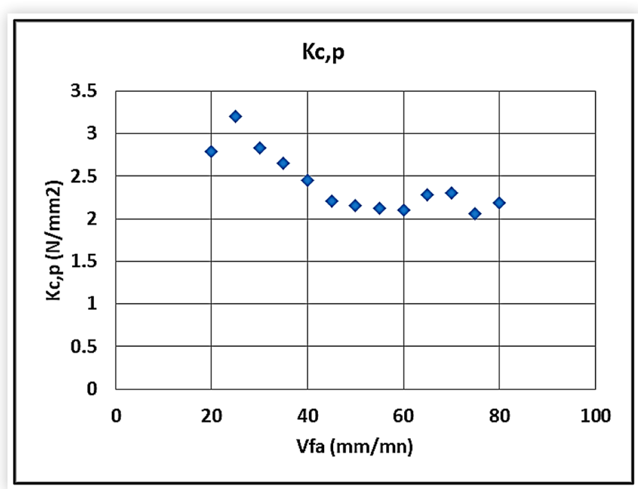


FIGURE A4 Specific energy Kc,p as function of axial feed rate Vfa



Appendix B: Images of Some Experiments

FIGURE B1 (a) Burr height measurement - (b) Example of height profile

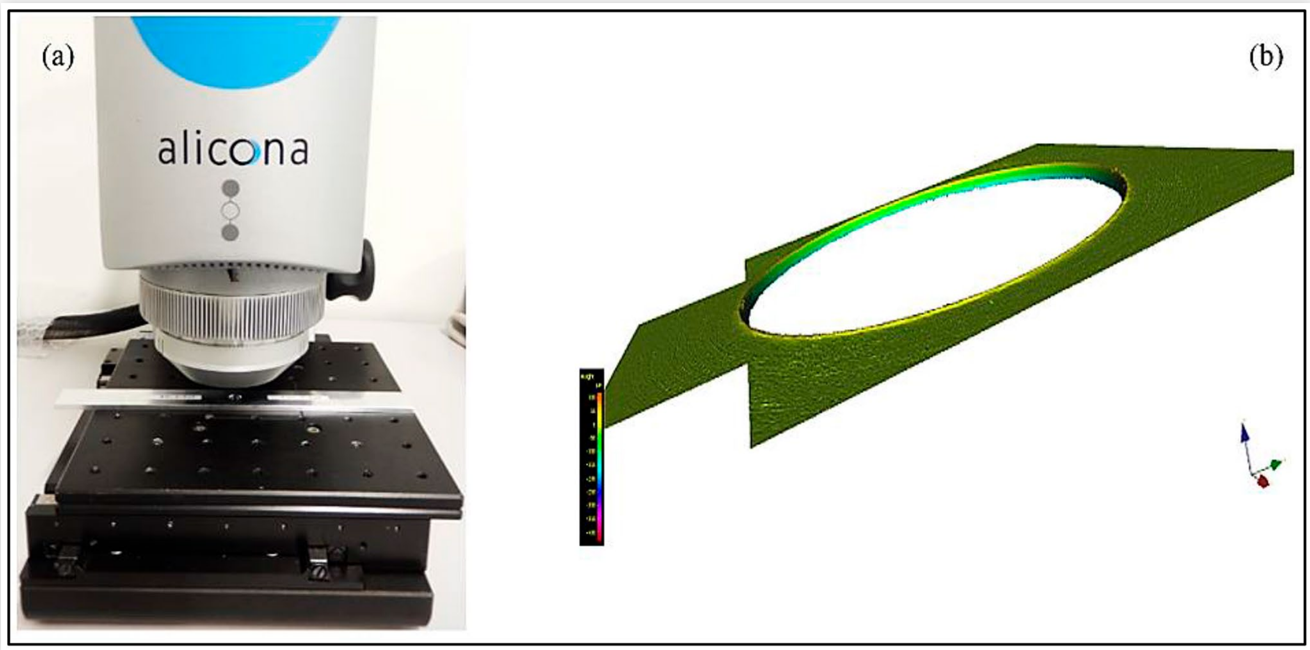
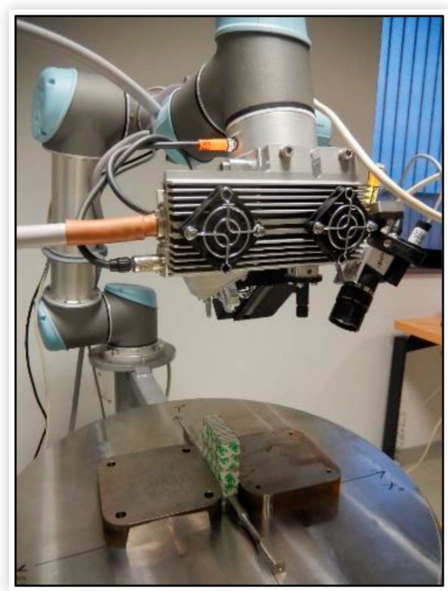


FIGURE B2 Roughness measurement

FIGURE B3 X-ray diffraction on samples



e-ISSN 2641-9645