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Impact of the drilling process on the surface integrity and residual fatigue strength of 2024-T351 aluminum parts

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Abstract

This paper investigates the influence of the drilling process on an aluminum 2024-T351 part in terms of surface integrity and fatigue strength. Two drilling processes (axial; orbital) are considered. The surface integrity is studied through surface roughness measurements, microstructure and hardening analysis and residual stress assessment. An innovative Hole Opening Comparative Technique is set up to assess the residual stress state. Fatigue tests are conducted with open-hole specimens, and on filled-hole samples (double-lap bearing strength tests). The strain hardening of the hole subsurface seems to be the main factor influencing the fatigue behavior, associated with a residual stress state.

Keywords: Surface integrity; Drilling of aluminium alloys; Fatigue strength.

1. Introduction

In the aeronautical sector, fasteners (bolts or rivets) are used for aircraft structures assembly. This requires the drilling of the fastening holes, that represent critical areas where fatigue cracks can initiate due to high stress concentration. An important issue is that the fatigue life of the structure can be affected by the hole surface integrity, which depends mostly on the drilling process [1-3].

Orbital drilling (also called helical milling) is a holemaking process in which an endmill rotates around its own axis while describing a helical path around the hole axis. It has become increasingly popular in the recent years, particularly in aerospace industries [4]. Compared to conventional drilling, orbital drilling has proved to be particularly advantageous to achieve aeronautical-quality drilling (diameter, roughness, burr height) through multi-materials stacks in a single operation [5-7]. However, despite a better hole quality, this process may induce a fatigue life decrease in aluminum alloys compared to axial drilling [8]. This result seems to be explained by less compressive residual stresses on orbital drilled hole walls. At the opposite, Sun et al. showed that orbital drilling could reach better fatigue life than axial drilling on AA2024-T351 [9]. Thus, the impact of the drilling process on surface integrity, and the consequences in terms of fatigue life need to be studied more deeply, especially for AA2024-T351 aluminum alloy.

The surface integrity usually includes the surface topography, the residual stress state and the metallurgical condition of the material subsurface (microstructure and microhardness). There is a lack of study on the surface integrity of holes drilled in aluminum alloys, probably due to the experimental difficulties encountered for its characterization and measurement in relation to the particular thinness of the material layer affected by the drilling process. A preliminary finite element study simulating the lateral cutting of a drilling process in a 2024-T351 aluminum alloy (Fig.1a) has been led in order to evaluate this depth of subsurface material affected, based on the one developed by Atlati [10]. The lateral cutting

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in drilling was assumed to be orthogonal cutting. The results obtained showed that the depth of the subsurface material affected by plastic strain (Fig.1b) and residual stresses (Fig.1c) after drilling was of an order of magnitude of 20 to 40 µm. This depth is very small compared to the one usually considered in the literature (from 100µm to few millimeters) [1,8-9,11].

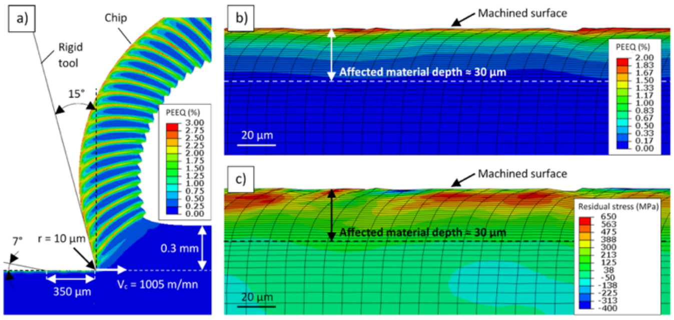

Fig.1. Simulation of the depth of the affected layer in orthogonal cutting.

Several works have been carried out to investigate the relationships between the machining process, the surface integrity and the associated fatigue life, for various materials and machining processes [11-14]. The main conclusions concerning the impact of the surface integrity parameters are:

- The lower the surface roughness, the longer the fatigue life as the micro-notches induce stress concentration areas where a local plastic strain field can be generated when a stress is applied, thus defining a path for the crack.
- Compressive residual stress improves the fatigue strength due to the crack closure effect, which slows crack propagation. At the opposite, tensile stress reduces the fatigue strength through the crack opening effect.
- The fatigue life increases with the material hardening of the surface, which increases the surface yield strength.

However, a machining operation impacts all the surface integrity parameters and some parameters depend on one another. Moreover, the significance of a parameter may depend on its value. For instance, Siebel et al. showed that the surface roughness impacts significantly the fatigue life only when the groove depth exceed a critical value [15]. Thus, the relationship between the surface integrity and the fatigue strength seems very complex, especially for the case of holes drilled in aluminum alloys.

This paper presents the study of the impact of the hole surface integrity on the fatigue life in drilling 2024-T351 aluminum. This alloy is commonly used in the aircraft industry due to its low density and its high fatigue performance. As axial and orbital drilling processes can lead to different results in terms of fatigue life [8,9], these two processes were considered in the study in order to generate potential differences in hole surface integrity and bring elements of understanding. To carry out the study, fatigue tests (open-hole and filled-hole) and surface integrity analysis (roughness measurements, hardness measurements, metallographic observations and residual stresses analysis) were performed on drilled samples.

2. Experimental setups and surface characterization

2.1. Test specimens

The samples were extracted from a 2024-T351 sheet so as to align their longitudinal axis with the rolling direction.

Fatigue specimens were T-Type samples (Fig.2), with a length of 200 mm and a width equal to 3 times the nominal hole diameter (D). The holes were obtained by a one-step drilling operation followed by a deburring operation. Two drilling diameters were considered in the study: 6.35 mm (4/16”) and 9.52 mm (6/16”). The fatigue specimen thickness was chosen according to industrial applications: 6.35 mm for the specimens with D = 6.35 mm and 10 mm for D = 9.52 mm.

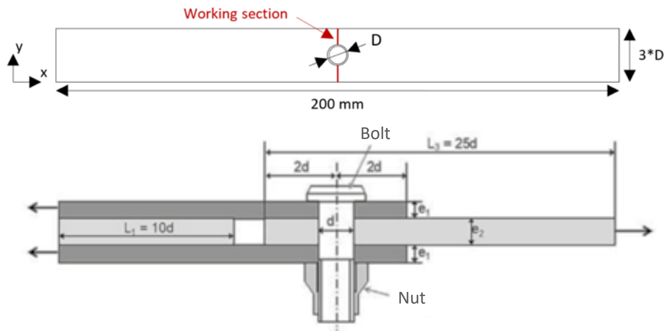

Fig.2. Geometry of the fatigue samples for Open-hole and Filled-hole test.

The stress concentration factor in the working section of the specimens was 3.5. This value ensured that the initiation of cracking took place at the hole edge.

2.2. Drilling processes

In this study, industrial axial and orbital drilling processes corresponding to industrial applications were used. Drilling tests were carried out on a DMG DMU85eVo CNC machine. For axial drilling operations, the spindle of the CNC machine was used. For orbital drilling operations, a specific PRECISE France – ORBIBOT orbital spindle was fixed on the Z-axis of the CNC machine.

For all tests, the tools used and associated cutting parameters corresponded to industrial applications (Table 1). For all tests, an external MQL lubrication was applied.

2.3. Surface integrity assessment

Surface roughness was measured considering 2D and 3D parameters. 2D roughness parameters (Ra, Rq, Rz) were measured along the height of the hole using a profilometer (cut-off length of 0.8mm). 3D roughness parameter (Sa, Sq, Sp, Sv, Sz, Sdq, Ssk, Sku) were measured using an ALICONA InfiniteFocus device (optical surface topology measurements through the focus variation principle). A magnification of 10x and a vertical resolution of 200 nm were used.

Table 1. Drilling parameters.

	D = 6.35 mm		D = 9.52 mm	
	Axial drilling	Orbital drilling	Axial drilling	Orbital drilling
Tool	Carbide helicoidal drill	Carbide end mill 4 teeth	Carbide helicoidal drill	Carbide end mill 4 teeth
Tool diameter (mm)	6.35	4.85	9.52	8.00
Cutting speed (m/min.)	180	610	120	1005
Axial feed (mm/rev.)	0.1	0.0015	0.1	0.0015
Orbital pitch (mm)	-	0.04	-	0.04

Vickers microhardness measurements were made on the hole surface of the fatigue specimens previously cut in the working section. The indentations were made with a load of 1 kgf and an indentation time of 15 s. Because of the cylindrical shape of the hole, a corrective factor was applied to the results as recommended by [ASTM E92-82]. In order to complete the microhardness results and to identify the material depth affected by a variation in hardness, nanoindentation tests were also conducted. The indentations were made at mid-thickness of the fatigue specimen in the (x,y) plane. Specimens were extracted from fatigue samples and set in a resin in order to be polished using emery papers (down to 4000 grit), then using diamond paste (1 µm) and finished with OP-S suspension. The applied load and the indentation matrix were determined on the basis of the results of the preliminary numerical study, which predicted an affected material depth of a few tens of microns (Fig.1). Hence, the indentation matrix was 5x20 indents equally spaced 5 µm apart, with the first column located around 5 µm from the hole edge (Fig.3). The nanoindentation tests were performed with a Berkovich diamond indenter and a maximum load of 5 mN (load-controlled tests). Load-displacement curves obtained were analyzed using the Oliver & Pharr method [16].

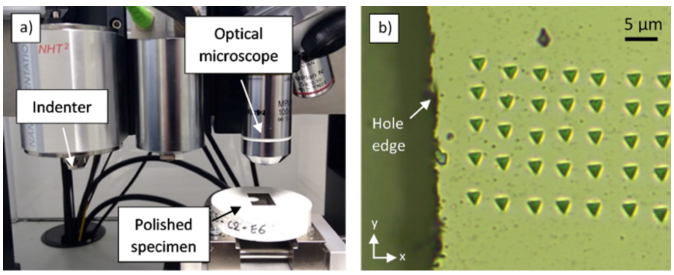

Fig.3. (a) Nanoindentation test set-up and (b) nanoindentation matrix.

In order to estimate residual plastic strain, the Electron Back-Scatter Diffraction (EBSD) technique can be used through the analysis of local changes in the crystal orientation [17]. The Grain Reference Orientation Deviation (GROD), which represents the misorientation between a given pixel and the average orientation of the grain, was studied as a plasticity marker. This technique permitted to assess the strain hardening state of the hole subsurface. EBSD observations were carried out using a Feg Jeol JSM 7100 F Scanning Electron Microscope (SEM) equipped with an Oxford Instruments Nordlys Nano detector (Centre de microcaractérisation Raimond Castaing, CNRS UMS 3623, Toulouse, France). They were performed on a section at mid-thickness of the fatigue specimen in the (x,y) plane. The observed section was prepared with a cross section polisher, to preserve the microstructure and avoid polishing artefacts. For the measurements, the sample was tilted to 70° relative to the incident beam and a voltage of 20 kV was used. An area of 600x200 µm^2 was scanned with a step size of 0.5 µm.

Current techniques for residual stress evaluation (X-ray diffraction and incremental hole drilling) were first considered in the study. However, these techniques were difficult to implement due to the cylindrical shape of the hole, the large grain size of the material and the thinness of the material layer affected. Therefore, a novel method, the Hole Opening Comparative Technique (HOCT) was set up, inspired by crack opening methods as the splitting method [18]. The HOCT consists in opening the hole (by Electrical Discharge Machining) and measuring the induced specimen deformation (with ALICONA) (Fig.4a). The specimen deformation level indicates the residual stress level: the greater the residual stress in the hole edge area, the greater the specimen deformation. The shape of the deformation profile indicates the residual stress nature: a convex profile corresponds to tensile residual stress whereas a concave profile corresponds to compressive residual stress (Fig.4b).

The different steps of the HOCT are given below:

1. Drilling of a hole in a specimen
2. Measurement of the profile of the specimen
3. Machining of the slot by EDM
4. New measurement of the profile of the specimen
5. Analysis of measured specimen deformation.

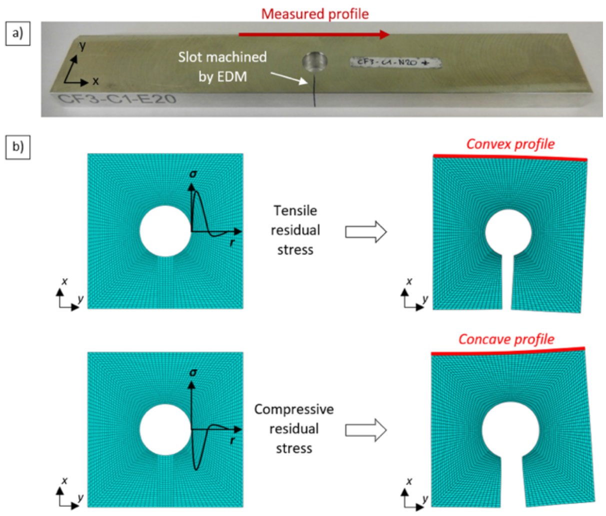

Fig.4. Novel HOCT method for residual stress analysis.

Thus, the HOCT allows to evaluate the residual stress state in the hole edge area in drilled specimen in a qualitative way and can be used as a quick comparative test.

With the treatment T351, the material considered in this study is stretched for stress relief after being solution heat treated. Therefore, the samples can be assumed to be free of residual stress before drilling. Besides, with the HOCT, the hole opening is done by EDM, avoiding to introduce significant residual stress in the specimen. Thus, the measured specimen deformation can be assumed to be essentially related to the residual stress introduced during the drilling operation.

2.4. Fatigue tests

Fatigue tests were performed using a Schenk servo hydraulic machine equipped with a 100 kN load cell, at room temperature. The load was applied in the longitudinal direction of the specimen as a cyclic (sinusoidal) tensile-tensile load with a load ratio of 0.1 and a frequency of 20 Hz. Fatigue tests were carried out for various stress levels in order to obtain S-N curves (Wöhler curves). The maximum stress level applied in the working section varied from 100 MPa to 280 MPa.

For filled-hole fatigue tests, double-lap bearing strength tests were done (Fig.5). Fasteners were composed of a titanium bolt and a steel nut. The tensile-tensile tests were performed with a load ratio of 0.1 and a maximum stress of 59.65 MPa on net section. This stress level was calculated based on stress level and stress concentration factor of open-hole samples (σmax=150 MPa, Kt=3.5) so as to have the same maximum stress level. In order to investigate exclusively the impact of the drilled surface integrity, some considerations have been done:

- Assemblies were realized with clearance fit to avoid interference benefits.
- PTFE washers were placed between the sample and the clevis to restrict interactions between clevis and sample.
- A tightening torque of 4 Nm was chosen minimal to avoid any preload on fastener and any load transfer through it.

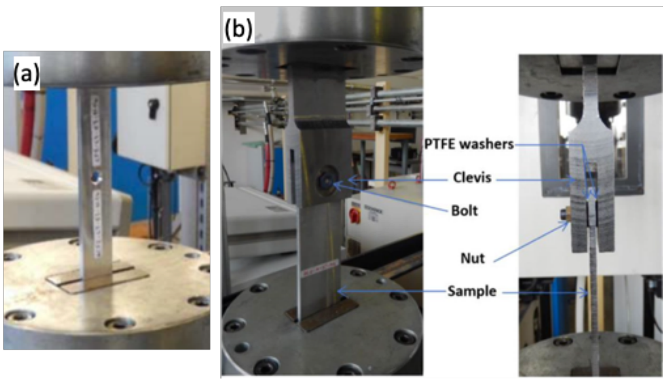

Fig.5. (a) Open-hole test setup (b) Filled-hole fatigue test set-up.

3. Results and discussion

Concerning the fatigue test results, it has first to be mentioned that for all specimens, the crack initiated in the hole edge area and no difference in failure mode was noted between the different configurations.

Open-hole fatigue test results are presented as semi-log S-N curves (Wöhler curves), with S corresponding to the normalized stress in the working section of the specimen and N corresponding to the number of cycles leading to failure (Fig.6a-b). Moreover, in the aircraft industry, the fatigue performance is commonly evaluated by the Airbus Fatigue Index (AFI), which corresponds to the stress S associated with a forecast fatigue life of 100 000 cycles. Thus, AFI values were determined for all configurations from S-N curves and are presented as a ratio to the maximal value (obtained for axial drilling at D = 9.52 mm) (Table 2).

S-N curves obtained for D = 6.35 mm show no difference in fatigue strength between the two drilling processes, and similar AFI values can be observed for both drilling processes (orbital drilling is slightly better than axial drilling). In contrast, S-N curves obtained for D = 9.52 mm show a significant increase in fatigue life for the specimens drilled by the axial technique. This gain in fatigue life can be observed for all stress levels but is greater for the lower ones. For this diameter, a gain in AFI of 15% is visible with the axial drilling process.

Filled-hole fatigue tests confirmed these observations as results were in accordance with the ones of open-hole fatigue tests. For D = 6.35 mm, a slight increase in fatigue life can be observed with orbital drilling. Conversely, for D = 9.52 mm, axial drilling brought a significantly better result.

Thus, the drilling configuration can have a significant influence on the fatigue strength of the drilled part but it has no impact on the failure mode of the specimen. The differences in fatigue life observed between the drilling configurations were probably related to differences in the hole surface integrity.

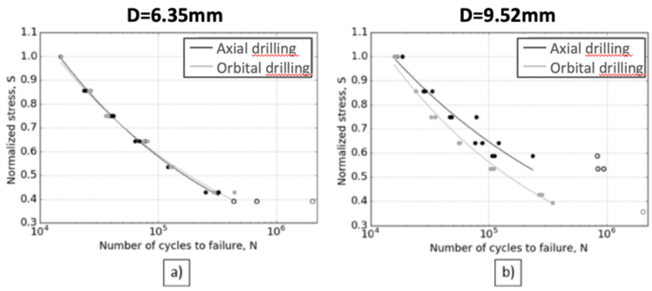

Fig.6. Open-hole fatigue test results.

Table 2. AFI results (as a ratio to the maximal value).

	D = 6.35 mm		D = 9.52 mm	
	Axial drilling	Orbital drilling	Axial drilling	Orbital drilling
AFI ratio	0.895	0.906	1.000	0.873

In this study, surface roughness appeared not to be a major factor influencing fatigue life. In this paper, among all the roughness parameters measured, only the results of arithmetic average height of profile (Ra) are presented through normalized values (Table 3). For all drilling configurations, the aeronautical specification is largely respected. A significant difference is observed between the two drilling processes for D = 6.35 mm, whereas no difference in fatigue life is noticed for this hole diameter. This is probably related to the low Ra values measured [15]. However, if the roughness reaches high values, its influence could be significant.

This conclusion was also set for all other surface roughness parameters (2D and 3D). No correlation with the fatigue test results were observed. In this study, the drilled hole surfaces present small defect sizes, leading to a negligible influence on the fatigue strength and to a crack initiation mainly controlled by the microstructural state of the material [15].

Table 3. Normalized Ra results (as a % of the Ra specification).

	D = 6.35 mm		D = 9.52 mm	
	Axial drilling	Orbital drilling	Axial drilling	Orbital drilling
Ra normalized (%)	57.5	31.6	16.5	12.2

The Vickers microhardness measurements carried out in this framework are presented through normalized values (ratio to the maximal value) in Table 4. For D = 6.35 mm, similar microhardness levels are noted for bot processes, whereas a significant difference of 29% is observed for D = 9.52 mm. These results show a correlation with fatigue life results: the increase in hole microhardness for axial drilling at D = 9.52 mm could explain the gain in fatigue life observed for the same configuration (Fig.6).

Table 4. Normalized HV results (as a ratio to the maximal value).

	D = 6.35 mm		D = 9.52 mm	
	Axial drilling	Orbital drilling	Axial drilling	Orbital drilling
HV ratio	0.824	0.831	1.000	0.778

To study this result further, nanoindentation tests were performed. The test results are presented in Fig.7 in terms of evolution of the nanohardness according to the distance from the hole edge.

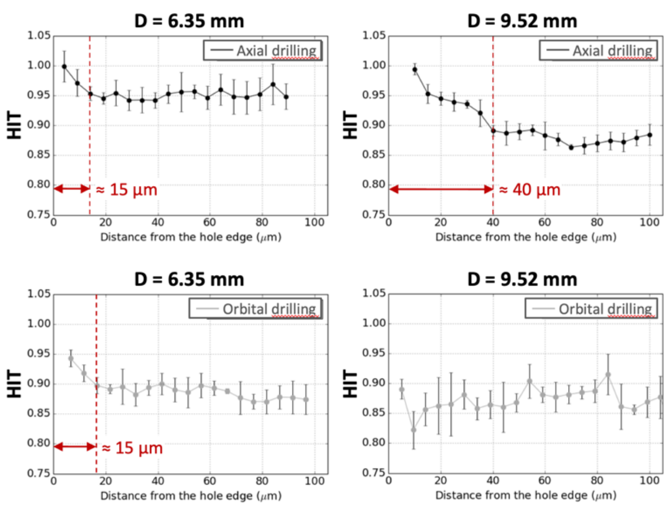

Fig.7. Normalized nanohardness results.

For D = 6.35 mm, a similar material depth is affected by hardness variation, around 15 µm for both drilling processes. In contrast, for D = 9.52 mm, a significant difference in material depth affected is observed, around 5 µm for orbital drilling vs. around 40 µm for axial drilling. Also, during indentation tests for this last configuration, the first indents column presented small and irregular prints from which no hardness value could be calculated. Thus, the nanohardness of the hole subsurface for this configuration seems to be high.

These results highlight the thinness of the subsurface material layer affected by the drilling operation of a 2024-T351 aluminum part, in agreement with the numerical model. Nanohardness and microhardness results are in accordance.

The hole hardness has a significant positive influence on the fatigue life of the drilled part in this study. In order to identify the phenomena responsible for the difference in hole surface hardness, a metallographic analysis was carried out. GROD maps of the hole edge area obtained through SEM-EBSD analysis (Fig.8) were analysed.

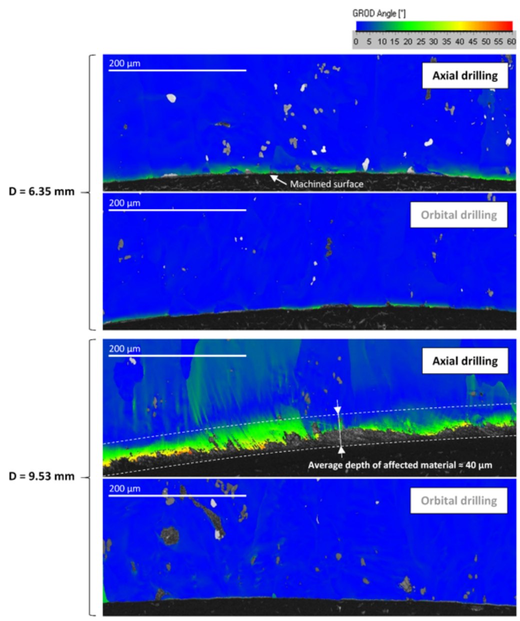

Fig.8. GROD maps obtained with SEM-EBSD analysis.

A significant material depth affected by grain misorientations, around 40 µm depth, was noted for axial drilling at D = 9.52 mm. This corresponds to a strain hardened material layer. In contrast, almost no grain misorientation was observed for the other configurations. Thus, axial drilling at D = 9.52 mm induces a significant strain hardening of the hole subsurface compared to other drilling configurations.

Besides, the SEM analysis showed no increase in the number or size of the precipitates. Thus, it seems that the thermal loading has no significant influence on the hole surface integrity in this study.

Finally, residual stress of the drilled part was analysed through the novel HOCT technique developed. Specimen deformations obtained with HOCT are presented Fig.9.

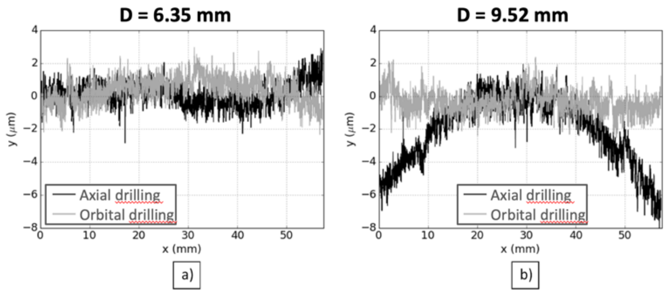

Fig.9. Specimen deformation obtained with the HOCT.

A significant deformation is observed for axial drilling at D = 9.52 mm whereas no deformation of the specimen is noticed for the other configurations. This drilling configuration induces significant residual stress fields in the hole edge area compared to the others. This result shows a correlation between the residual stress state and the fatigue life. Furthermore, a high residual stress state is associated with a significant hole hardness. These 2 aspects seem correlated, as residual stress remain in the part because of the strain hardened material layer.

4. Conclusions

This study focused on the impact of the drilling processes and associated hole surface integrity parameters on the fatigue strength for a 2024-T351 aluminum drilled part. Two different drilling processes were considered: axial and orbital drilling. Fatigue tests were carried out on open- and filled-hole specimens and the hole surface integrity was characterized with a study scale and techniques suitable for aluminum drilled surfaces. An innovative technique for the residual stress evaluation, the HOCT, was implemented. The main conclusions of the study are as follows:

- Due to low roughness levels, the hole roughness has no significant influence on the fatigue strength;
- The hole hardness has a significant positive influence on the fatigue life;
- The increase in hole hardness is mainly due to strain hardening of the subsurface, which slows crack initiation;
- A high hole hardness is associated with a significant residual stress state of the part in the hole edge area;
- Compared to orbital drilling, conventional axial drilling can lead to a significant increase of hardness and residual stress in the hole edge area, with a larger thickness of affected material layer. This may depend especially on the tool used.

In future works, the impact of the drilling process (tool geometry, cutting parameters…) will have to be studied in more details in order to explain the observed surface integrity. Also, it would be interesting to develop a numerical model capable to determine the residual stress state corresponding to the fatigue specimen deformation obtained with the HOCT.

Acknowledgements

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