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Abstract. The assembly process in the aeronautical sector mostly uses mechanical fastening. It requires the drilling of hundreds of thousands of fastening holes. These holes are critical areas for the assembly fatigue life, thus he drilling operation is a key point. The fatigue performance of a machined surface can be correlated to the surface integrity, but this correlation seems very broad and complex, especially for the drilling of aluminum alloys (commonly used in the aircraft industry). Moreover, different drilling processes may be used, such as axial drilling or orbital drilling. Orbital drilling is particularly interesting for limiting burrs and improving chip evacuation. But the process can impact also the fatigue life of drilled parts. To study this impact, the hole surface integrity needs to be analyzed and its influence on fatigue strength must be investigated. The main challenge concerns the interactions between the surface integrity factors. Moreover, the affected layer in drilled aluminum parts is particularly thin, and the access to the hole surface is geometrically restricted. The characterization of the surface integrity is thus a complex task. In this paper, the correlations between the hole surface integrity and fatigue life of drilled 2024-T351 aluminum alloy are addressed. The study considered both orbital and axial drilling processes. The generated surface integrity was characterized in terms of surface roughness, metallographic observations, hardness, and residual stress. Fatigue tests were performed and correlated to the surface integrity results.

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

1 Introduction

In the aeronautical filed, the final assembly process requires the drilling of a large number of fastening holes. The drilling operation is particularly critical because it is performed on high-value parts during the last steps of the aircraft assembly process. Moreover, drilled holes are stress concentration zones, and thus are critical according to the assembly fatigue strength. But different drilling parameters can generate different surface integrities, that could lead to different fatigue strength of the drilled part [1-3].

The orbital drilling process (also called helical milling) consists on milling a hole using an endmill, with a smaller diameter than the hole, driven along an helical trajectory. It has been more and more considered in aerospace industries in the last years [4], especially due to a better hole quality (in terms of diameter, roughness and burr) in comparison to axial drilling for hybrid stack drilling [5-7]. Though, it was reported by Deitert that orbital drilling also generates less compressive residual stress, leading to a reduced fatigue life for aluminum drilled parts [8]. The opposite conclusion was stated by another study on the same material (AA2024-T351), showing that orbital drilling could permit to obtain an improved fatigue strength [9]. This question remains thus open for this alloy. The influence of the different drilling processes in terms of global hole surface integrity, and the impact on the fatigue life, must be studied further.

The surface integrity can be defined as a set of geometrical (surface topology), microstructural (microstructure, hardness) and mechanical (residual stress) parameters. Its global characterization requires specific methods, and appears to be a challenge for drilled aluminum parts. Indeed, the affected layer thickness after drilling is particularly thin in this alloy, which makes difficult any surface analysis. In order to assess the thickness of the affected layer after cutting, a preliminary FEM model was set up, based on the work of Atlati [10]. To represent the cutting involved in drilling that impacts the hole surface, the lateral cutting was considered as orthogonal cutting. The simulated depth of the affected layer was between 20 and 40 µm, largely lower than the depth usually encountered in the literature (over 100µm) [3,8-9,11].

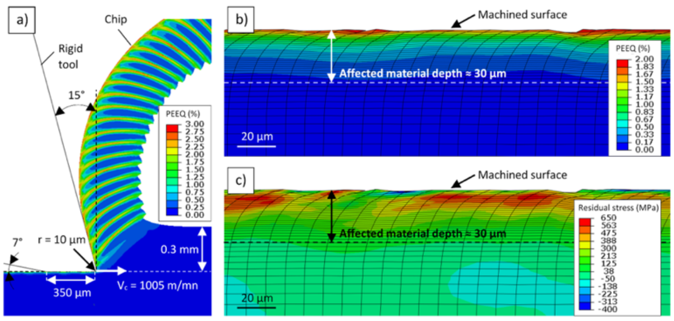

Fig. 1. Simulation of drilling lateral cutting. (a) Data and chip formation. (b) Plastic strain. (c) Residual stress.

The correlations between machining processes, surface integrity and related fatigue strength were widely studied in the literature [11-14]. From these works the following conclusions can be established:

- A lower surface roughness leads to a better fatigue life. It is explained by the micro-topology of the surface. The micro- grooves and scratches act as critical spots for fatigue crack initiation.
- A greater compressive residual stress leads to a better fatigue life. It is explained by the effect of crack closure that limits the propagation of the crack. A tensile stress acts at the opposite, with an opening effect.

- A significant material hardening leads to a better fatigue life. It is explained by the local increase of the yield strength.

Thus, the impact of each surface integrity parameter was studied independently. But first, strong interactions exist between these parameters (e.g. between residual stress and material hardening or microstructure). Also, surface integrity has to be considered globally (e.g. high compressive stress associated with important roughness). And finally, the influence of a parameter is not linear (e.g. surface roughness impacts the fatigue life only when the depth of the scratches exceeds a given level) [15].

These issues, associated to the difficulty encountered for the characterization of the surface, make the determination of the impact of the surface integrity on the fatigue strength for drilled 2024-T351 aluminum parts a challenge. This paper presents the study of the correlations observed between the hole surface integrity parameters and the associated fatigue life. For this purpose, two drilling processes were considered (axial drilling and orbital drilling), in order to obtain different combinations of surface integrity parameters. On the drilled holes, surface characterization methods were carried out to analyze surface roughness, microstructure and hardening, and residual stress state. Samples were also drilled in the same conditions to perform open-hole (without fastener) and filled-hole (with fastener installed) fatigue tests. S-N curves and Airbus Fatigue Index (AFI) were reported and analyzed. Correlations with the surface integrity are finally set.

2 Materials and methods

2.1 Drilling processes

Two drilling processes were considered in this study: axial drilling and orbital drilling. The axial drilling tests were conducted on a CNC machine DMG DMU 85 eVo. The orbital drilling tests were carried out using a specific orbital spindle PRECISE France – ORBIBOT. All tests were performed under external MQL lubrication.

Two hole diameters were tested: 6.35mm (4/16”) and 9.52mm (6/16”). The used cutting tools and cutting conditions corresponded to industrial applications (Table 1).

Table 1. Drilling tools and associated cutting parameters.

	D=6.35mm		D=9.52mm	
	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	6.35mm	4.85mm	9.52mm	8.00mm
Cutting speed (m/min.)	180	610	120	1005
Axial feed (mm/rev.)	0.1	0.0015	0.1	0.0015
Orbital pitch	-	0.04mm	-	0.04mm

2.2 Fatigue test samples

The fatigue test samples were T-Type specimens (Fig.2), with a width equal to 3 times the hole diameter (D) and a thickness equal to 6.35mm for the hole diameter D=6.35mm and 10mm for the hole diameter D=9.52mm. It permitted to obtain a stress concentration factor equal to 3.5 and thus to ensure a crack initiation at the hole edge. The length of the specimens was set equal to 200mm for open-hole fatigue tests, and to 25 times the hole diameter for filled-hole fatigue tests. An overlap of 2 times 2.D was considered for filled-hole fatigue samples.

The samples were drilled and deburred before performing the fatigue tests.

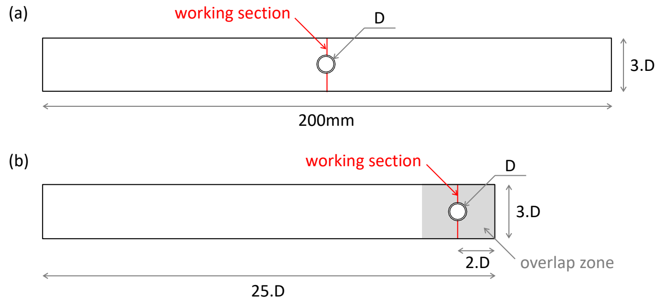

Fig. 2. Geometry of the samples for (a) open-hole fatigue tests and (b) filled-hole fatigue tests.

2.3 Surface integrity characterization

The surface integrity was characterized through surface roughness measurements, hardness measurement, microstructure analysis, and residual stress evaluation.

For the surface roughness characterization, a profilometer (measurement of Ra, Rq and Rz parameters with a 0.8mm cut-off) and an optical microscope (ALICONA InfiniteFocus to measure Sa, Sq, Sp, Sv, Sz, Sdq, Ssk and Sku parameters with a vertical resolution of 0.2µm) were both used.

For hardness characterization, Vickers microhardness measurements and nano-indentation tests were conducted. After cutting the samples along the working section, Vickers microhardness was measured using a 1kgf loading applied during 15s. The obtained results were corrected according to [ASTM E92-82] to consider the cylindrical shape of the surface. For nano-indentation tests, the samples were cut at mid-thickness and polished (with emery paper, diamond paste, and OP-S suspension). The tests were carried out using a Berkovich diamond indenter under a 5mN force. According to the results of the preliminary FEM simulation, a tightened matrix of indentation was set to 5 rows of 20 indents spaced 5µm apart. The first indents were located 5µm distant to the hole edge (Fig.3). The Oliver&Pharr method was used to analyze the results in [16].

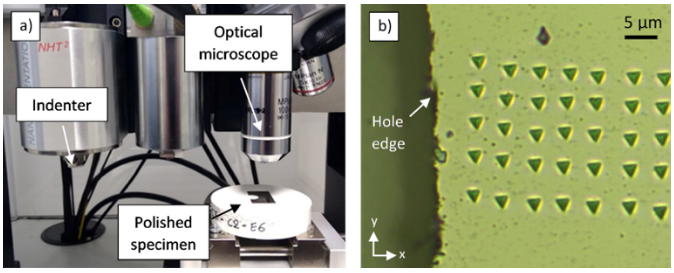

Fig. 3. (a) Nanoindentation device. (b) Matrix of indents obtained.

For the analysis of the material hardening, Electron Back-Scatter Diffraction technique (EBSD) was carried out with a Feg Jeol JSM 7100F Scanning Electron Microscope equipped with an Oxford Instruments Nordlys Nano-detector (done at the Centre de microcaractérisation Raimond Castaing, CNRS UMS3623, Toulouse - France). The plastic strain was studied through the observation of the local changes in the crystal orientation using the GROD criteria [17]. The analyzed surface of 600x200µm^2 (scanning pitch of 0.5µm) was the section located at mid-thickness of the samples around the hole, polished with a cross-section polisher. All measurements were conducted with a 20kV voltage and a tilt of the sample of 70°.

For the evaluation of the residual stress state, X-ray diffraction and incremental hole drilling techniques were firstly used. Due to the shape and dimension of the hole and the large grain size of the aluminum alloy, X-ray diffraction did not give valuable results. The incremental hole drilling technique did not manage to give better results, due to the low depth of affected layer. To overcome these obstacles, a novel technique was developed, inspired by crack opening methods as the splitting method [18]. The proposed Hole Opening Comparative Technique (HOCT) consists in drilling a hole in a specimen, measuring a profile along the specimen edge, then opening the hole (by Electrical-Discharge Machining) and finally measuring again the profile on the specimen edge to deduce the specimen deformation (Fig.4a). This deformation is the consequence of the release of the residual stress. Thus, a large deformation is obtained for samples presenting a high residual stress level around the hole. The direction of the deformation also informs about the nature of residual stress. A compressive (respectively tensile) stress leads to a (concave (respectively convex) deformation (Fig.4b).

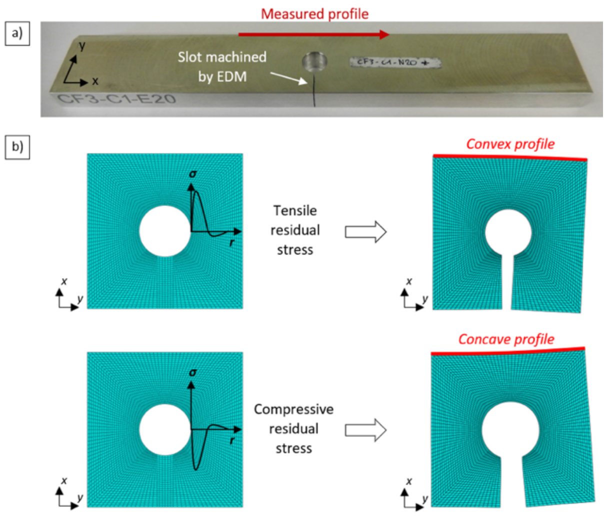

Fig. 4. HOCT novel method for the analysis of residual stress.

It has to be noted that the material considered is treated T351. It implies a stress release stage (under tension load) after a solution heat treatment. Thus, the material was assumed free of stress before being drilled.

2.4 Fatigue tests

Open-hole fatigue tests were carried out at room temperature on a servo-hydraulic machine equipped with a 100kN load cell. A sinusoidal tensile-tensile load (R 0.1) was applied with a frequency of 20Hz. S-N curves (normalized stress S in the specimen working section reported as a function of the number of cycles N) were plotted thanks to different stress levels tested (from 100MPa to 280MPa at the maximum in the working section).

For filled-hole fatigue tests, a double-lap configuration was considered (Fig.5). The fasteners used were bolts in titanium with steel nuts. Again, a sinusoidal tensile-tensile load (R 0.1) was applied. The maximal stress (in the working section) was set to 59.65MPa. This value corresponds to a real maximal stress level equivalent to the one of open-hole tests at 150MPa. To study the impact of the hole surface integrity, the following points were considered:

- All assemblies presented a clearance fit (avoiding interference interactions).
- The tightening torque applied on the fastener was set at the minimum (4Nm) to avoid any load transfer through the fastener.
- PTFE washers were used to limit interactions (Fig.5).

For all fatigue tests, the fracture surface was observed and showed the same failure mode for all configurations, with crack initiation in the area of the hole edge.

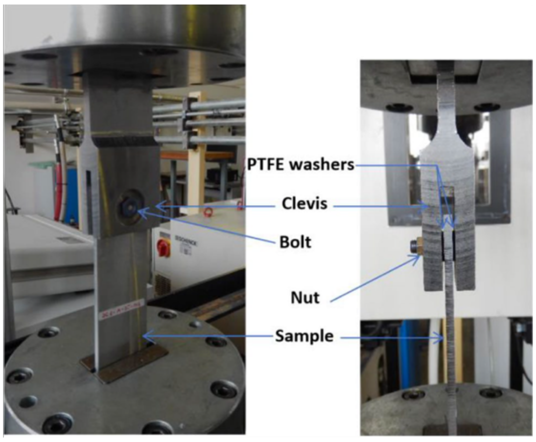

Fig. 5. Set-up for filled-hole fatigue tests.

3 Results and discussion

The results for open-hole fatigue tests are presented Fig.6. Fig.6a-b present the obtained S-N curves. Fig.6c-d present the Airbus Fatigue Index (AFI) results for each configuration. The AFI represents the stress value S leading to a fatigue life of 100 000 cycles. In this paper, the AFI results are presented as a ratio to the maximal value (obtained for axial drilling at D=9.52mm).

The results (S-N curves and AFI ratios) obtained for D=6.35mm showed no significant difference between the 2 drilling processes. The results for D=9.52mm are different. A significant decrease in fatigue life is observed on S-N curves with the orbital drilling process, especially for low stress levels. This leads to a loss of 15% in AFI ratio.

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

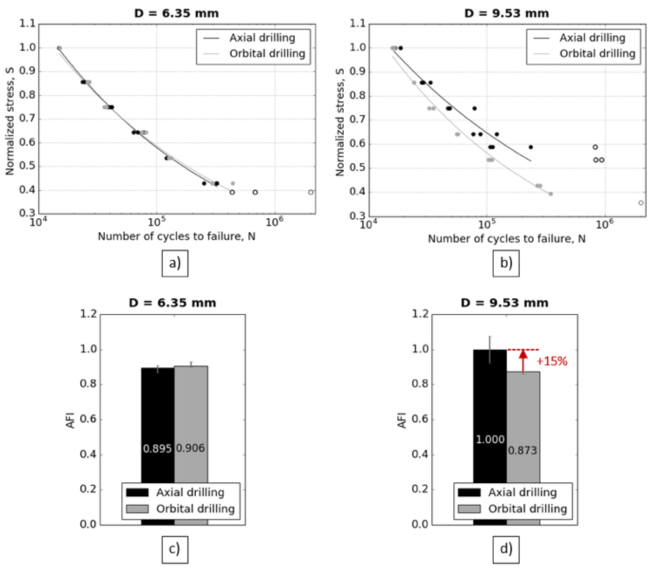

Fig. 6. Open-hole fatigue test results.

The results show that the drilling process can impact significantly the fatigue life of the drilled parts. The possible correlations between this impact and the hole surface integrity have to be studied.

In this study, it seemed that surface roughness has no significant impact on fatigue life. The results of arithmetic roughness (Ra) are presented in Table 2, as a percentage of the Ra specification. For all configurations, the aeronautical specification is largely respected (percentage less than 100%). For D=6.35mm, orbital drilling leads to a largely better roughness Ra than axial drilling. But no difference was noted in fatigue life for this diameter. For D=9.52mm, orbital drilling gives again a better roughness Ra but led to a worst fatigue life. The same observations were made for all other surface roughness parameters (2D and 3D).

It can be concluded that there is no correlation between surface roughness and fatigue life in this study. In this work, small defect sizes were obtained. It confirms that surface roughness could impact the fatigue life only when it exceeds a given level and that the fatigue crack initiation seems to be mainly due to microstructural changes [15].

Table 2. Normalized Ra results (as a % of the Ra specification).

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

The results in terms of Vickers micro-hardness are presented through normalized values in Fig.7. For D=6.35mm, similar micro-hardness levels are noted for both processes, whereas a significant difference of 29% is observed for D=9.52mm. A clear correlation with fatigue life observations can be set. The loss of fatigue strength with orbital drilling could be explained by a significant decrease of the surface micro-hardness for this configuration.

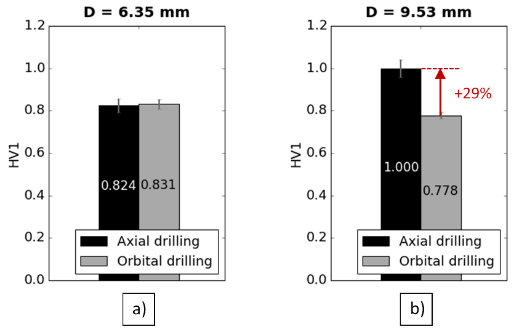

Fig. 7. Normalized microhardness results (as a ratio of the maximum value).

To confirm this observation, nano-indentation test results were analyzed. They are presented in Fig.8 in terms of evolution of the nano-hardness in relation to the distance to the hole edge.

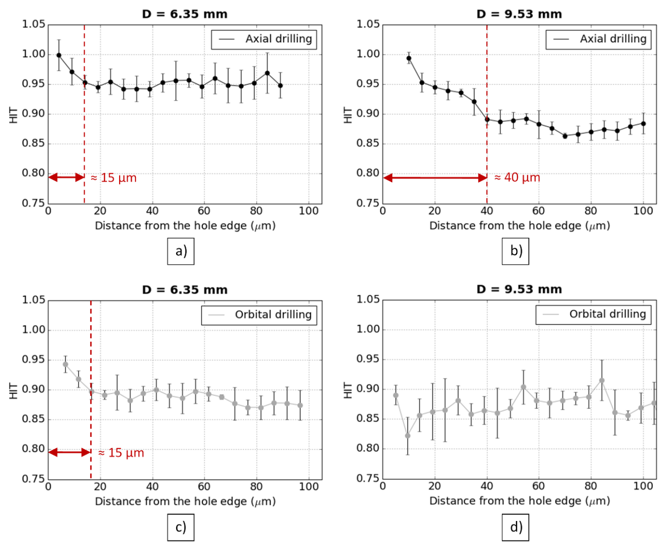

Fig. 8. Normalized nanohardness results (as a ratio of the maximum value).

For D=6.35mm, a similar depth of affected layer (around 15µm) can be observed for the two drilling configurations. For D=9.52mm, this depth is around 5µm for orbital drilling whereas it is around 40µm for axial drilling. The difference is significant and the results confirm the thinness of the affected layer predicted with the preliminary FEM simulations. During drilling 2024-T351 aluminum alloy, the depth of affected layer is particularly small.

The same observation can be made from the maximal nano-hardness measured. It is in accordance with the micro-hardness results.

It has to be noted that, for D=9.52mm and axial drilling configuration, indents close to the hole edge were irregular and no nano-hardness value could be stated. It probably expresses a high value of nano-hardness on the hole edge vicinity.

It can be concluded that the hole surface hardness could have a significant influence on fatigue life in this study. To go further, the microstructural cause of hole surface hardening was analyzed through EBSD observations, using the GROD criterion evolution in the hole edge area (Fig.9).

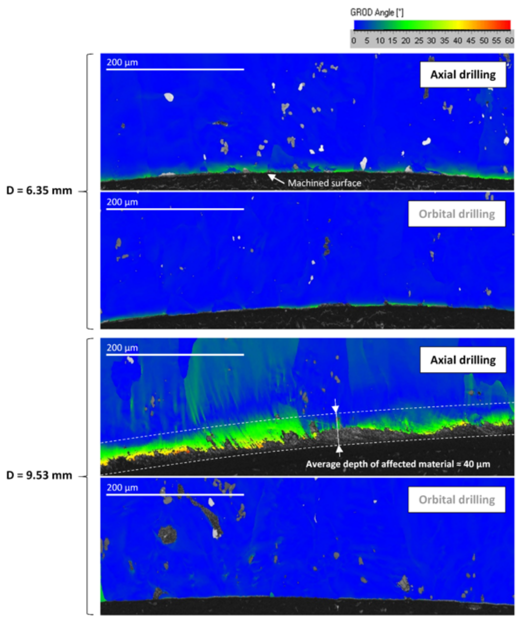

Fig. 9. GROD mapping in the hole edge area.

For D=9.52mm and axial drilling configuration, grain misorientations can be clearly observed. A layer affected by strain hardening was noted, of around 40µm deep. This configuration generates a significant strain hardening of the hole surface. For other configurations, no clear grain misorientation can be noted. These observations confirm the previous hardness results.

Finally, residual stress was analyzed with the help of the HOCT novel technique developed. The results in terms of measured deformations are presented Fig.10.

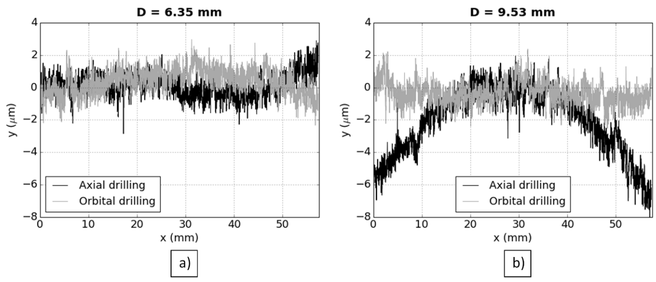

Fig. 10. Specimen deformation profiles obtained with the HOCT.

For D=9.52mm and axial drilling configuration, a significant deformation can be noted, whereas no deformation is noticed for the other configurations. It expresses the presence of higher residual stress in the hole edge area with this configuration in comparison to the others. Again, a clear correlation can be set with the fatigue test observations. Moreover, the high residual stress is in association with an important hole surface hardening. These 2 aspects seem correlated, as residual stress relates to the strain hardened material layer.

4 Conclusions

In this paper, correlations between the hole surface integrity parameters and the fatigue life were studied for drilled 2024-T351 aluminum parts. Open- and filled-hole fatigue tests were performed. The parameters describing the hole surface integrity were characterized. For residual stress assessment, a novel technique was developed (HOCT). From this study, the following conclusions can be made:

- Due to small defect sizes, the hole surface roughness levels were low and were not correlated to fatigue strength results in this study;
- The hole surface hardness and the residual stress fields in the hole edge area seem to have a significant impact on fatigue life;
- The increase in hole hardness is mainly caused by a strain hardening of material in the subsurface, which slows crack initiation;
- The residual stress state seems to be associated with the surface hardness.

In future works, the impact of the drilling process (tool geometry, cutting parameters…) will have to be studied in more details to explain the obtained surface integrities. Also, a numerical model will be developed to quantify the residual stress from the HOCT deformation measurements.

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