Study and 3D analysis of the drilling process influence on notched single crystal superalloy specimens

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ABSTRACT. *Cooling holes in nickel based monocristalline turbine blades for engine applications induce stress concentrations that impact crack initiation lifetime and cause stress gradients which effect must be taken in account in the lifetime computation methodology. A non-local method of 3D averaging is used to calculate a mean stress on a finite volume which is representative of the material. In this paper the influence of the drilling process is discussed through the identification of this method based on a series of fatigue tests under stress control at 5Hz* $R=0^{+}$ *950°C on laser perforated sheets. They are compared to the results of Electrical Discharge Machined (EDM) specimens lifetimes obtained in the same conditions. We show that laser and EDM drilling lead to different lifetimes that can be modeled in the averaging method by a material parameter that macroscopically take in account microstructure and holes shape.*

INTRODUCTION

The emergence of single crystal Ni-based turbine blade cooling technology has raised news issues in fatigue lifetime computation because of the multiaxial state of stress and of the stress gradient occurring around hole. Initially notch problematic was solved by using Neuber local types approaches [1] that are very simple to use but give conservative results because stress is always over-estimated. More recently non-local models have been proposed and are categorized as point, line, surface or volumetric methods [2-5]. An example of point method proposed by Papadopoulos [6] is to introduce the local gradient in a modified Crossland fatigue limit criterion with some news parameters. Volumetric methods that are used in the study are based on the averaging of the state of all the points in a finite volume. A 3D averaging method was studied by Kaminski [7] in the case of single crystal superalloy. It showed that gradient effect and size effect could be taken in account in the lifetime computation through a material parameter called integration length (IL noted λ) that defines a volume where stress is averaged with a given shape function. The simplification adopted by Kaminski was to consider the volume as a λ radius sphere with a shape function equal to 1 in the sphere and 0 outside. This method was later extended to the averaging of damage following the same procedure.

The identification of the integration radius that can be seen as a characteristic length of the material was done by an inverse method based on a series of fatigue tests on perforated sheets with various hole diameters. As we know the microstructure of the material has an impact on the IL, the new microstructure near the hole induced by the drilling process may have an impact as well. Because Kaminski samples were perforated by Electrical Discharge Machining (EDM) [8] it is important to study another process to see the impact on crack initiation. The aim of this study is to realize an experimental campaign on similar laser perforated samples and to compare experimental lifetimes. The experimental campaign on EDM specimens won't be discussed here and only lifetime will be presented. Experimental tests will be modeled using the Finite Element (FE) code ZéBuLoN that will be used to identify the IL.

EXPERIMENTAL

Sample

Samples are plates made in AM1 monocrystalline nickel based alloy. They were machined from two casted sheets by directional solidification process. Surface is then finished to a roughness of 0.2mm. Final dimensions of the sheets are 75x18x2mm with a hole in the middle. Because a Digital Image Correlation (DIC) method could be applied in post-treatment, the sample surface may be either polished or patterned. Three different hole diameters were realized: 0.4, 0.8 and 2.0mm. The small one is representative of cooling holes on blades and the large one has a low gradient that is useful for the identification of the averaging method.

Drilling

Drilling is realized at the PIMM (ex-LALP) laboratory with a millisecond laser process [9]. Unlike other drilling processes the hole is not cylindrical but quasi-conical. Indeed front face diameter (entry side of the beam) in bigger than back face diameter (side of the beam exit). For the identification step we will consider the hole as cylindrical with a diameter equal to the one aimed. Two types of drilling are available depending on the wanted hole diameter. For small holes (0.1-0.8mm) percussion drilling is used and consists in one impulsion that locally evaporates the material. For larger holes (>0.8mm) trepan drilling is employed. It is made with repeated impulsions and a beam displacement. The Φ0.4 holes are made by percussion whereas Φ0.8 and Φ2.0 are made with trepan. Holes SEM observations on Fig 1 show the conicity and the smooth surface state of laser percussion drilled samples as well as the surface roughness of trepan and EDM drilled specimens. Heat Affected Zone (HAZ) thickness is between 10 and 40µm for laser and around 2µm for EDM, where micro-cracks may exists according to the literature [10].

Fatigue equipments

A LOS system hydraulic fatigue test machine is used for all the tests with a MTS 793 model electronic. Its capacity is ±100kN in force and ±25mm in displacement.

Specimens are heated to 950°C using a middle frequency aperiodic induction system. Crack initiation detection and crack growth following is made with an electrical potential method synchronized with the maximum of the cycle [11,12]. The considered crack initiation criterion is a crack of 300µm length. Two thermocouples are welded near the hole to check the temperature while an IR Impact 140 pyrometer scan all the surface. A camera is used to take photos of the surface to measure the crack optically.

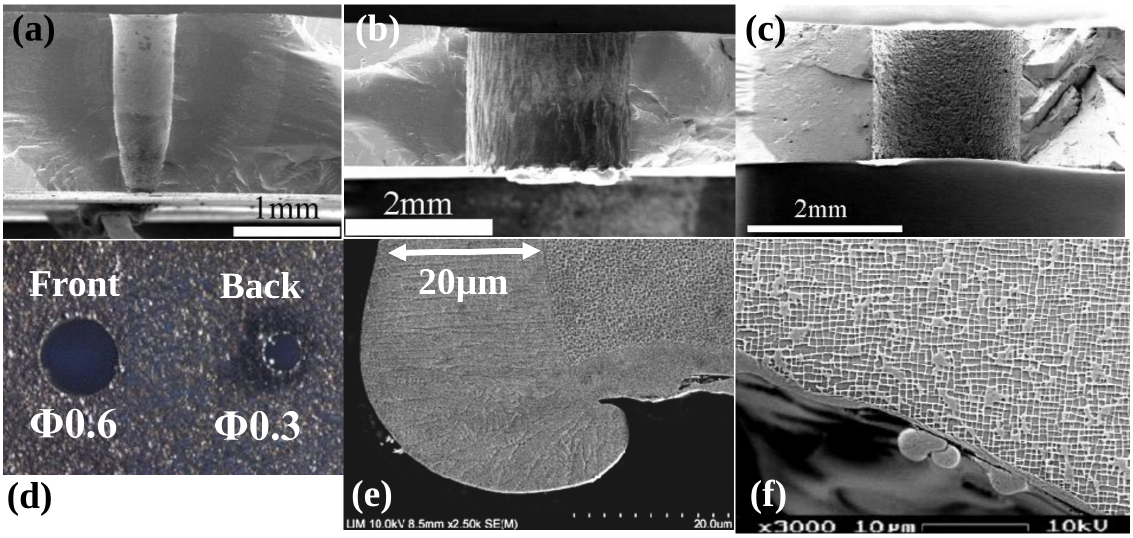

Figure 1. Morphologies of holes (a) percussion laser (b) trepan laser (c) EDM (Kaminski) (d) difference of diameters for a percussion laser hole (PIMM) (e) local bending on the back face of a laser hole (PIMM) (f) HAZ for EDM drilling (Kaminski).

RESULTS

Fatigue tests

All tests were performed under a 5Hz repeated cycle ($R=0^+$) so that we can eliminate buckling problems. High and low stress levels were calculated in order to obtain between 10^4 and 10^6 cycles because aimed lifetime for this application is 10^5. Moreover the low loading level is representative of an elastic stress state whereas high loading level implies localized plasticity near the hole.

A SN diagram shows crack initiation lifetime for laser and EDM specimens on Fig 2. We can see that dispersion is in the same order as on smooth specimens (tested at R=-1 50Hz 950°C). Compared with the case of EDM specimens, greater lifetime can be seen on small holes of laser ones. The middle hole has an opposite behavior with smaller lifetime for laser specimens. For the largest one, lifetimes seems to be similar.

Fracture analysis

Some fractured specimens were observed optically and in SEM (Zeiss DSM982 GEMINI) to know the localization of the initiation and if it was caused by porosity due to the casting process. Optical observation on Fig 3 shows multi-initiation on the surface of the hole.

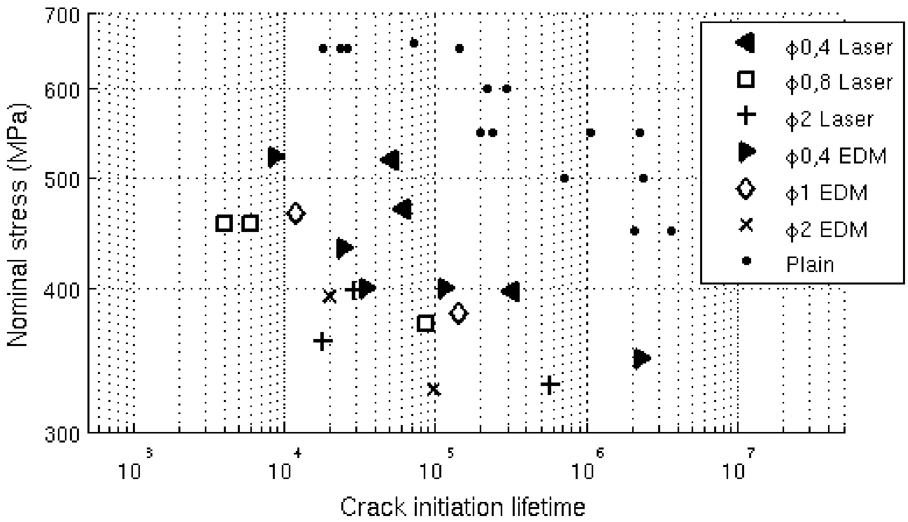

Figure 2. Fatigue tests results.

SEM observations show fracture surface oxidation and several porosity near the surface. According to the observed specimens, none crack initiation started on a porosity neither on a major visible defect but always on the surface. It's important to note that on the smooth specimens used for the identification of the damage model [13], crack mainly started on porosities. As it is not the case on perforated samples, because solicited volume is much lower, it leads to a difference of parameters in the model that should be fitted on a fictitious material without porosity.

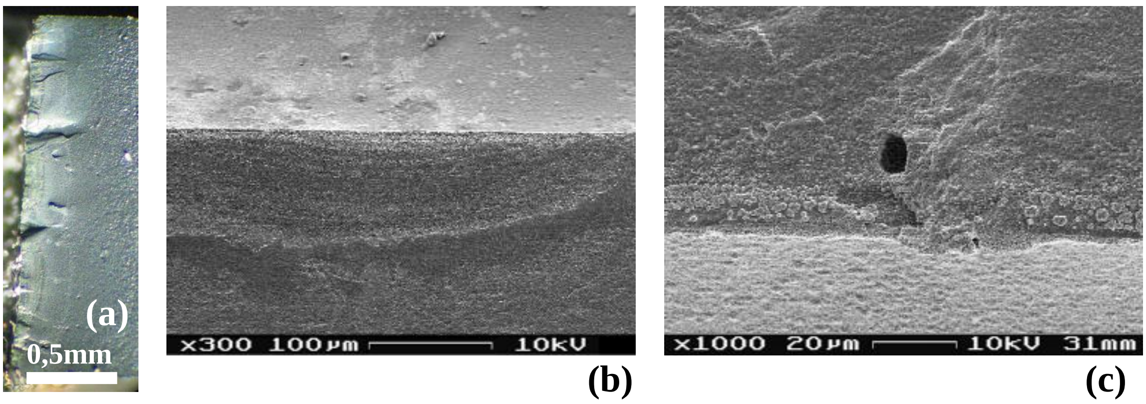

Figure 3. Fracture analysis of initiation (a) optical observation (b) crack initiation close up (c) surface porosity which can be responsible of some crack initiation

FE ANALYSIS

Calculations are realized on the FE code ZéBuLoN. The sample is simulated with a rectangular sheet with a hole in the middle. Because the specimens are oriented against the material cubic directions, only one quarter of the sample is simulated in the case of conical holes and 1/8 for cylindrical holes as shown on Fig 4 (a).

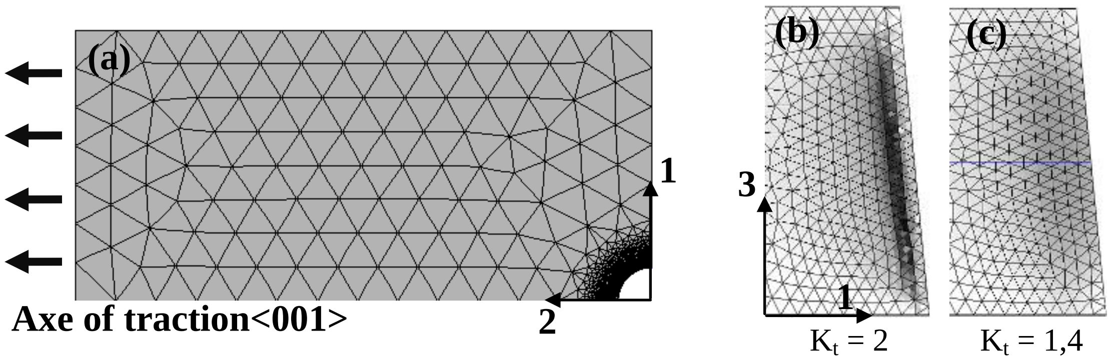

Figure 4. FE calculations (a) Specimen meshing (b) σ_{22} (c) σ_{22} with averaging

Lifetime computation consists in realizing a cyclic elastoviscoplatic calculation [14] in which stress will be redistributed around the hole until it reaches a stabilized state. The behavior model is based on cubic and octahedral slip systems and a Schmid criterion. Damage model is applied in post-treatment on the stabilized cycle.

The averaging method is possibly applied on stress, strain, damage or energy following Eq 1 :

$$\bar{\xi}(x) = \frac{1}{\int_V \phi(x,y)dV} \int_V \xi(y)\phi(x,y)dV \qquad (1)$$

Parameter to average is ξ and ϕ is a shape function defined on volume V. Let's consider an effective volume Ω^* that corresponds to the effective matter include in a sphere which radius is the IL. Choosing the shape function equal to 1 in Ω^* and 0 outside leads to Eq 2 :

$$\bar{\xi}(x) = \frac{1}{\Omega^*(x)} \int_{\Omega_r(x)} \xi(y)dy \qquad (2)$$

This method has been implemented in ZéBuLoN and an example of application on stress is shown on Fig 4 (b,c). Stress field is smoothed and the K_t factor at the notch is reduced. Averaging in the case of a multiaxial stress state is done for each component of stress tensor, which may lead to some problems. In the damage model, multiaxiality is taken into account with a Sines Criterion for fatigue limit on the maximal principal stress. As damage is isotropic, D is a scalar so there no problem of averaging. Transposed in the FE approach the integral becomes a sum over Gauss points in the effective volume.

Identification of IL is done by an inverse method. Damage model parameters have to correspond to the fictitious material without porosity. They are identified using the point of maximum lifetime keeping the same slope than the original material. Because stress concentration is only seen as a vertical translation of curves as shown on Fig 5 we try to find the intercept that minimize the difference between experimental points and the curve. Then stress to get 10^5 cycle lifetime is calculated. A new viscoplastic stabilized cycle is calculated and averaging is applied for various IL.

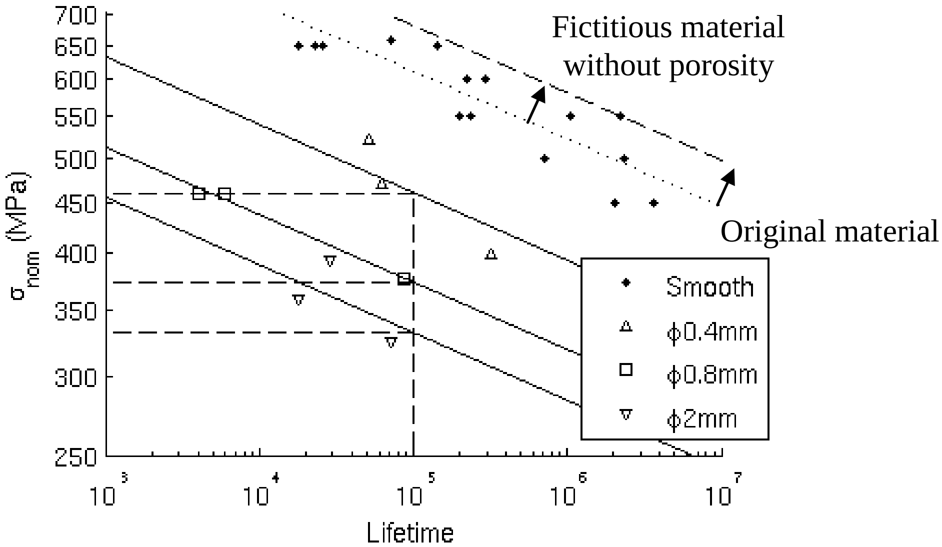

Figure 5. Identification stress calculation

If we make the assumption that scale effect is the same for all specimens, there is a unique IL which leads to the targeted lifetime of 10^5. The intersection of curves at 10^5 cycles will then give the IL as we can see on Fig 6.

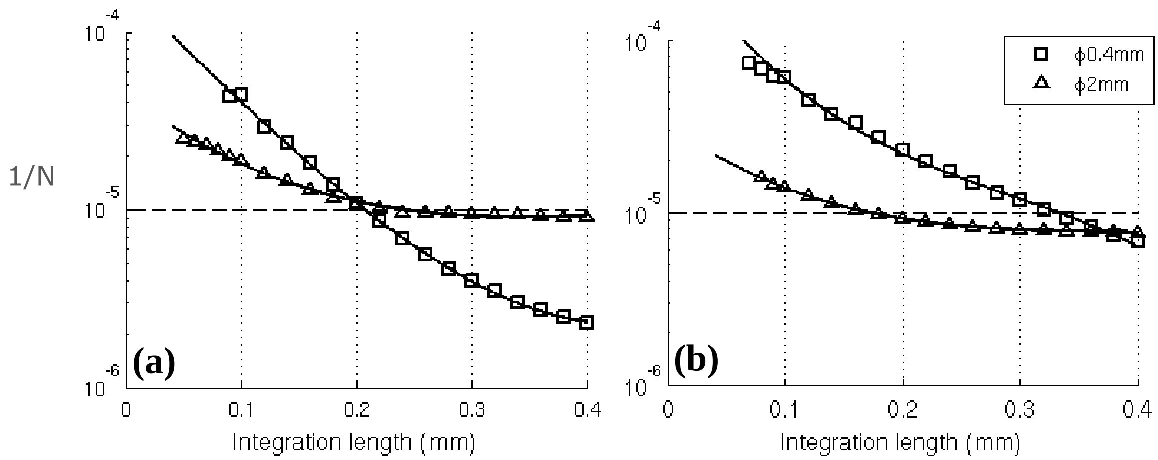

Figure 6. IL identification (a) stress averaging (b) damage averaging

Results for EDM and laser are grouped in Tab 1. We can see that laser has a larger IL. This is the fact of laser drilled specimens with a high gradient that have larger lifetimes than EDM ones. Indeed those specimens have a great importance in the identification process.

$\lambda_\sigma^{EDM} = 0{,}09\mu m$	$\lambda_\sigma^{Laser} = 0{,}20\mu m$
$\lambda_D^{EDM} = 0{,}19\mu m$	$\lambda_D^{Laser} = 0{,}37\mu m$

Table 1. Integration length for stress and damage averaging for EDM and Laser drilling

Those IL are injected in simulations so that we are now able to calculate a new lifetime for all specimens. Comparison between experimental and computed points shows good results in lifetime calculation as shows in Fig 7. It has the second advantage of reducing randomness that is important in experimental fatigue tests.

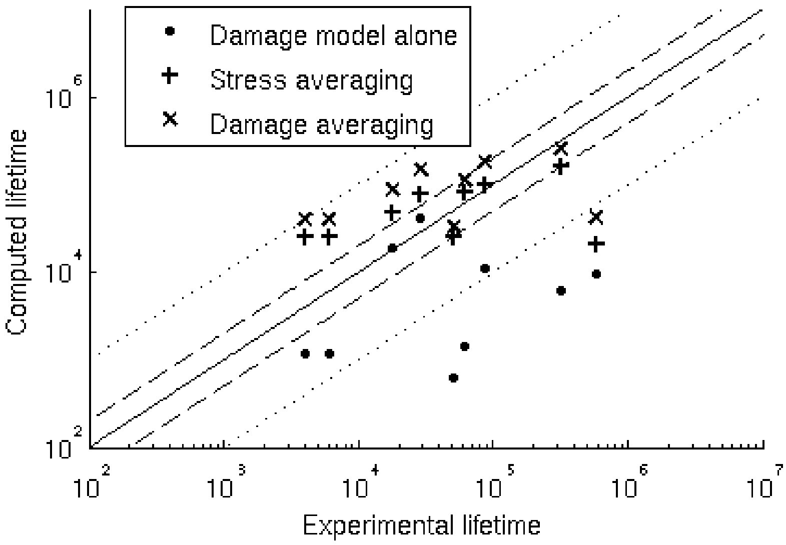

Figure 7. Experimental and computation comparison with averaging method

DISCUSSION

Experimental tests show a difference between laser and EDM drilling that may be caused by a difference of microstructure and thickness of the HAZ and also to the surface roughness. Moreover FE results on cylindrical holes show that it is a plane strain state. In the case of conical holes it is no longer the case because conicity implies a triaxial state of stress that may also lead to different lifetimes.

Those effects are modeled with the averaging method through a different identification of the material parameter λ that include macroscopically substrate and HAZ properties. As we can see, λ is larger for laser because stress (or damage) has to be averaged on a larger zone to get a lower stress at the initiation point. For the stress tensor averaging, multiaxiality is taken into account by the averaging of the tensor components because this operation has to be done in the same base and this is why we do not consider averaging on invariants. Damage method hides problems of tensorial averaging because damage is calculated on each point following the same process and the averaging is applied on the scalar damage value. This method also simply takes in account anisothermal temperature that can't be treated directly by the former method.

To get consistent results, averaging has to be done on several gauss points and because $\lambda_D > \lambda_\sigma$ the mesh can be less refined with the damage averaging technique. As long as convergence is reached for EVP analysis one can use coarser mesh and save computation time.

CONCLUSIONS

The experimental results show that lifetime of EDM and laser specimens are different. This leads to identify two IL using two series of fatigue tests. The identification process has shown that laser IL is greater than the EDM one. It is the fact of small diameter holes lifetimes, which have a greater influence on IL than larger hole. Damage and stress averaging give similar improvement in lifetime computation and is around a decade in the case of perforated sheets. To further validate this method it has to be tested in various conditions such as anisothermal temperature fields, multiaxial and complex loadings and complex shape specimens.

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REFERENCES

1. Neuber H. (1968) *Konstruktion* 20: 245-51.
2. Pijaudier-Cabot G. & Bazant Z.P. (1987) *J. Eng Mech* 113: 1512-33
3. Bazant Z.P. and Jirasek M. (2002) *J. Eng. Mech*. 21120: 1019-49
4. Adib-Ramezani H., Jeong J.(2007*) Computational Mat. Science* 39: 649–63
5. Tovo R. and Livieri P. (2008) *Eng. Fract. Mech*. 75: 1804–14
6. Papadopoulos I.V. and Panoskaltsis V.P. (1996) *Eng. Fract. Mech* 55: 513-28
7. Kaminski M. (2007) PhD thesis, Ecole des Mines de Paris, France
8. Sen M. and Shan H.S. (2005) *Int. J. Machine Tools & Manufacture* 45: 137–52
9. Dubey A.K. and Yadava V. (2008) *Int. J. Machine Tools & Manufacture* 48: 609-28
10. Zeid A.O.A (1997) *J. Mat. Processing Technology* 68: 27-32
11. Johnson H.H. (1965) *Mat. Research & Standards* 5: 442-45
12. Baudin G. & Policella H. (1978) *La recherche aérospatiale* 4:195-203
13. Gallerneau F., Chaboche J.-L. (1999) *Int. J. Damage Mech.* 8: 405-27
14. Meric L., Poubanne P. & Cailletaud G. (1991) *Eng. Mat. & Technology* 113: 162-70