MACHINING PARAMETERS EFFECTS ON SURFACE AND FATIGUE LIFE OF ALUMINIUM ALLOY AERONAUTICAL PARTS

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ABSTRACT

This study lies within the general scope of design and manufacturing processes improvements of aeronautical machined parts requiring fatigue behaviour guarantees. The surface quality is a dominating factor of the parts fatigue behaviour and must be specified in the dimensioning phase. The proposed approach couple a model connecting the machining parameters with the generated surface and a fatigue model based on the determination of a local stress intensity factor (K_t) by a finite elements model. The presented approach was confronted with the experiment and a maximum error of 15% in terms of fatigue life was obtained in the HSM milling cases studied.

INTRODUCTION

Machining is the most used process in production of components for the mechanical engineering industry. The final characteristics of the surface quality of the machined parts are a dominating element of their fatigue life. As these characteristics are strongly related to the manufacturing process, it appears judicious to optimize the parameters of machining to improve quality of production and also to study the relations between the machining of a surface and its resistance to fatigue. The surface is the central topic of this study : it is generated by machining and the durability of the part in fatigue depends on its qualities. We thus propose to go from surface to fatigue life in the first part and from machining to surface in the second part of this article. These two studies were undertaken on same aluminium alloy in collaboration with Airbus France.

PART 1 : FROM SURFACE TO FATIGUE LIFE

Fatigue life of structures is known to highly depend on the surface quality. Consequently, a great attention is paid to the specification and the realization of surfaces of machined parts when those must be dimensioned in fatigue. Three parameters are usually proposed to describe surface condition: i) a geometrical parameter: surface roughness; ii) a mechanical parameter: residual stress; iii) a metallurgical parameter: microstructure. These parameters can vary separately according to the machining conditions. In engineering design, the effects of these parameters are commonly accounted for by using empirical reduction factors which modify the endurance limit of the material [1]. Reduction factors are defined for each type of machining process. Moreover, within each category of machining process the use of these reduction factors leads to surface specifications (generally in terms of roughness) linked to machining parameters such as tool shape, feed rate… Even if giving satisfactory fatigue life predictions, the use of this empirical method has obviously limitations due to its restricted area of validity. Indeed, changing machining process or machining parameters must then be accompanied by a new definition of reduction factors and/or surface specifications that must be validated by performing new fatigue tests. This constitutes a real problem as machining processes are in constant evolution in order to increase productivity.
In this context, the present study deals with the influence of machined surface quality on the fatigue strength of an aluminium alloy and aims to provide a mean to easily predict fatigue life when changing machining parameters without relying on empirical relations established by time-consuming and expensive fatigue tests. In the case of this alloy, surface roughness appears to be the predominant parameter affecting fatigue life and the present work focuses on the modelling of the effect of this parameter.

In the present paper, surface roughness is considered as generating local stress concentration governing surface crack propagation or non-propagation. This approach requires the calculation of the stress concentration factor K_t . K_t is estimated by the finite element analysis of measured surface topographies. For fatigue limit, this so-calculated stress concentration factor is integrated in a non-propagation threshold approach. For limited fatigue lives, propagation life time (N_p) and initiation life time (N_i) are distinguished: K_t is used in a Basquin type power law [2] for evaluating N_i; an estimation of N_p is obtained integrating K_t in a Paris law and considering the stress concentration only affects surface crack propagation. This model is established based on academic surfaces generated by a shaper and is validated on industrial specimens with surfaces obtained by numerous and various machining processes leading to different surface roughnesses.

Experimentals

The material investigated is a 7010-T7451 aluminium alloy, Al Zn6MgCu as defined by ISO norms. It was provided in the form of a rolled plate of 70mm thickness. The microstructure is composed of grains that are highly elongated in the rolling direction. Grain size is about 350µm in the rolling (L) direction and about 150µm and 60µm in transverse TL and TC directions respectively. Al_7Cu_2Fe and Mg_2Si intermetallic particles of 8-10µm size can be found regularly in the microstructure and are located in recrystallized grains. These grains are smaller than the previous grains: 80, 60 and 40 µm in L, TL and TC directions respectively. Specimens are taken in the plate so that the stress induced by four-point bending is parallel to the TL direction. They have been machined according to different machining conditions in order to obtain different surface conditions in terms of roughness and residual stresses. Residual stresses have been measured using X-ray diffraction technique with ASTX2001 device. The so-obtained values of residual stresses are given within +/-30MPa. Concerning the geometrical characterization of the surfaces, a Mahr (Perthometer PKG-120) contour and roughness measuring system has been used. Surface characteristics are presented in Table I. Whatever the machining process and machining parameters, no change of the surface microstructure has been detected with the means of investigation that were used (microscopic observation and micro-hardness measurements). Four-point bending fatigue tests have been conducted at room temperature in order to explore fatigue lives around 10^5 cycles. Tests were performed with a load ratio R=0.1 and a frequency of 10Hz.

Table I. Surface characteristics of four-point bending specimens

Specimen reference	Machining	Ra* (µm)	Rt*(µm)	Transversal Residual Stress (MPa)	Longitudinal Residual Stress (MPa)
UL11	shaper	0.5	3	-137	-191
UL12	shaper	0.5	3	-45	-78
UL21	shaper	7	30	-54	-157
UL22	shaper	7	30	-21	-147
Fine milled	HSM milling	0.25	1.7	-	-
Slot milled	HSM milling	11.1	40	-	-

* Ra and Rt as defined in ISO 4287

Preliminary results

Experimental SN curves are presented in Figure 1. The influence of surface condition on the fatigue life is more important for high cycle fatigue.

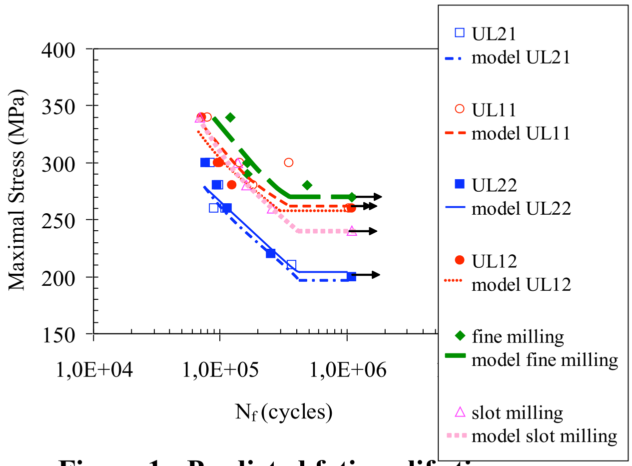


Figure 1 : Predicted fatigue life time compared to experimental SN curves

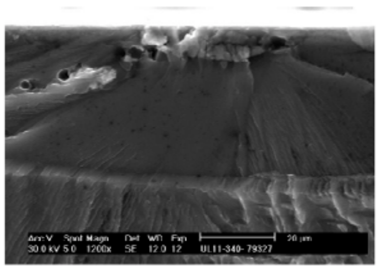


Figure 2 : Fracture surface of UL specimen

Roughness has obviously a predominant influence on the fatigue life. For a given roughness, residual stresses only seem to have a slight influence on the fatigue life: UL11 and UL12 display the same fatigue behaviour for instance. However, the geometric roughness parameter R_a is not able to fully explain the difference in fatigue strength between all the samples: for instance, slot milled specimens exhibit a better fatigue resistance than UL21 and UL22 specimens in spite of a higher value of R_a.

Fracture surfaces observations (Figure 2) show that whatever the specimen and the load level, fatigue cracks initiated on microstuctural defects (essentially intermetallic inclusions and sometimes porosity) located on the flat loaded surface (within 20µm under the surface) and at the bottom of the machining grooves (when grooves are perpendicular to the loading). This is consistent with the observations that can be found in literature [3]. These defects were included in small recrystallized grains.

As seen in these preliminary results and noted also by many authors [4], [5], [6] standard purely geometric surface roughness parameters are not able to correctly describe the effect of roughness on the fatigue life of the investigated aluminium alloy. In the following, surface roughness is supposed to generate local stress concentration. However, this effect is not considered in terms of notch effect through the fatigue stress concentration factor K_f but is integrated in a fracture mechanics modelling.

Finite element analysis of surface topography

In most of the recent approaches presented in the literature [4], [5], [7], the stress concentration factor K_t is calculated from averaged geometrical parameters of the surface. In the present study, the estimate of K_t based on measurements of the surface topography has been preferred. K_t is found by finite element analysis of the measured surface topography and is then supposed to lead to a stress condition which is more representative of what really undergo the samples. This way of characterizing a surface topography from a mechanical point of view without the use of geometrical parameters gave place to a patent [8]. A similar approach has also been proposed by As et al. [6]. 2D profiles that are measured are recorded with a sampling rate of 1µm/point. From the 17000 points that are recorded, only 800 points are regularly extracted and interpolated with a spline function to be used in the finite element modelling.

As seen in Figure 3, this results in a filtered profile where second order roughness (induced by tool edge defects for instance) is not taken into account. This filter has been chosen because stress concentration generated by second order roughness is supposed to be not significant, from a fatigue point of view, compared to stress concentration generated by first order roughness (due to tool shape and machining parameters). This profile is then used as surface model to generate the finite element geometry. Material behaviour is linear elastic. Plane strain hypothesis is supposed for this 2D calculation. Triangular elements with quadratic interpolation are used for the mesh. Elements size is roughly 30µm. For this filtered profile, it has been shown this mesh size leads to convergence of the numerical results [9]. Problems of validity of continuum mechanics and of the hypothesis of isotropic and homogeneous material induced by extremely refined mesh, such as pointed out by As et al.[6], are so avoided. Uniform load is applied as boundary conditions. The maximal Von

Mises equivalent stress obtained by the calculation is then divided by the nominal Von Mises equivalent stress due to the applied load to classically determine the stress concentration factor K_t. Due to regularity of grooves, this K_t value is generally found in most of the valleys of the measured surface topography. An example of finite element calculation performed to determine K_t is shown in Figure 4.

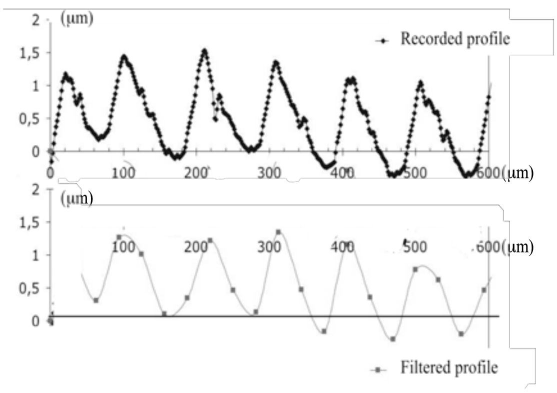


Figure 3 : Example of recorded and filtered profile of surface specimen

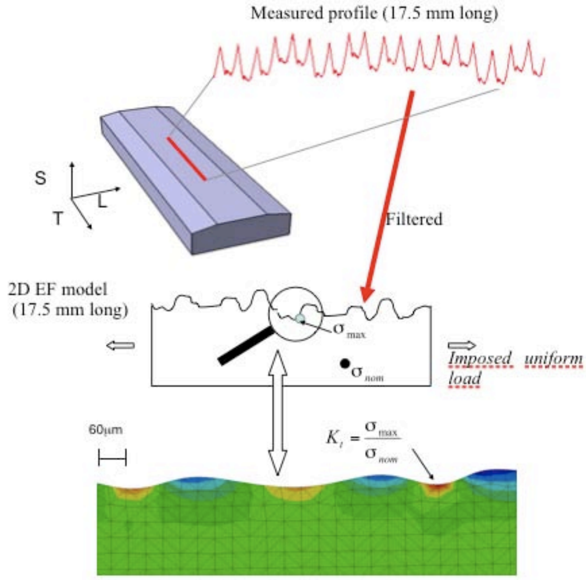


Figure 4 : Principle of finite element calculation to determine local stress concentration factor

Effect of local stress concentration on fatigue life

As noticed in the section presenting the preliminary results, the effect of surface roughness is different according to fatigue life time. Therefore, different modelling is proposed to predict fatigue. For fatigue limit the chosen model relies on the non propagation of an initial crack (or defect). According to linear elastic fracture mechanics the fatigue crack propagation threshold can be expressed with the following equation:

$$\Delta K_{th} = F\Delta\sigma_{th}\sqrt{\pi a} \qquad (1)$$

where a is the crack length, F is a shape factor and $\Delta\sigma_{th}$ is the minimum stress range required to propagate such a crack. Supposing the initial crack is located at the bottom of a machining groove and is very small, the stress concentration effect affecting the stress at the crack tip leads to

$$\Delta K_{th} = FK_t\Delta\sigma_{app}\sqrt{\pi a} \qquad (2)$$

The fatigue limit can then be derived by considering it as the minimum stress range that can be applied without involving any propagation of an initial defect:

$$\Delta\sigma_D = \frac{\Delta K_{th}}{FK_t\sqrt{\pi a}} \qquad (3)$$

With the following hypotheses, the fatigue limit is then quite easy to evaluate and only depends on the stress concentration factor:

1. the threshold stress intensity factor range ΔK_{th} does not depend on the surface condition as whatever the machining parameters, metallurgical evolution has not been detected for the investigated alloy. Its value can be found in data base (ΔK_{th}=3.5MPa m$^{1/2}$) [10].
2. Initial crack or defect does not depend on the surface condition. Indeed, as noted in the preliminary results, failure initiation always occurred on intermetallic inclusion within a re-crystallized grain, whatever the surface conditions. According to these observations, initial crack (defect) length a is

considered to be the re-crystallized grain size in S direction, that is to say 40μm. In the same way, the shape factor *F* is supposed to be identical whatever the surface condition and is roughly 1.12 for small cracks [11].

For limited fatigue lives, the roughness effect is different than for fatigue limit. This is attributed to crack propagation which constitutes the main part of fatigue life time. Machining process and subsequent roughness only have influence on the crack propagation in surface. Therefore, crack propagation in surface (along L direction) and in depth (along TC direction) are treated separately. In the case of a semi elliptical crack the stress intensity factor can be expressed according to Newman and Raju [11]:

$$K_{I\phi} = f(a, c, \phi, W, t)\sigma\sqrt{\pi a} \quad (4)$$

where *a* and *c* are respectively the half short axis length and half long axis length of the crack, Φ is the angle (compared to the long axis) for which *K* is calculated, *W* is the specimen width and *t* the specimen thickness. The detailed expression of *f* function can be found in [11]. It is supposed that a crack propagates in surface (increasing *c*) and in depth (increasing *a*) according to Paris law:

$$\frac{da}{dN} = C(\Delta K_{90°})^m \qquad \frac{dc}{dN} = C(\Delta K_{0°})^m \quad (5)$$

with *C* and *m* material constants that can be found in database (m=3.41, C=3.17 10^{-11} (m/cycle)/(MPa√m)^m in the present case). The main hypothesis is then that surface roughness generates stress concentration that only alters the surface crack propagation and the Paris law becomes:

$$\frac{da}{dN} = C(\Delta K_{90°})^m \qquad \frac{dc}{dN} = C(K_t \Delta K_{0°})^m \quad (6)$$

An iterative calculation is then performed and, for each cycle, *a* and *c* are calculated and their new values are used to evaluate $\Delta K_{90°}$ and $\Delta K_{0°}$. Initial crack size is re-crystallized grain size with an elliptical shape ratio a/c=0.5 according to fracture surfaces observations. This grain size is considered as an long initial crack size (as required by Paris law) because fracture surfaces exhibit homogeneous features after the first grain fracture. Calculation is stopped when either $a=t$, $c=W$ or $K_{1\Phi}=K_{IC}$ that is to say when crack either propagates through the thickness, through the width or is unstable. The number of iterations (cycles) is then considered as the crack propagation life (N_p). Therefore, (N_p) can be evaluated if the stress concentration factor associated with surface roughness is known. Afterwards an estimate of the crack initiation life (N_i) can be obtained using a reference SN curve. This reference SN curve has been provided by the industrial partner (specimen shape and loading similar to those used in this paper) and has been chosen because the roughness-induced stress concentration factor of the specimens was equal to one. For each load level, crack propagation life time (N_p) is then calculated according to the method previously presented with the appropriate stress concentration factor (K_t =1). Considering total life time is the sum of crack propagation life time and crack initiation life time, N_i is estimated for each load level by subtracting N_p from the experimental total life time given by the reference SN curve. Assuming the crack initiation life time can be expressed according to a Basquin type power law [2] :

$$N_i = \beta(K_t\sigma)^\alpha \quad (7)$$

β and α are easily determined by plotting N_i as a function of the load level σ. These values of β and α (β=8.08 and α=9.02E24) are then used to determine N_i by Eq.(7) whatever the specimen and the load level.

In Figure 4, it can be seen the depth of the surface layer affected by the stress concentration is of the same order of magnitude as the recrystallized grain size considered as the initial crack size used in the previous model calculating (N_p). This supports the hypothesis that crack propagation in depth is not affected by the stress concentration (Eq.6). On the contrary, considering propagation in surface (along L direction), K_t calculated by the 2D finite element analysis is supposed to affect all the sample width in a similar way, supporting hypothesis of Eq. 6. For laboratory specimens (where grooves are parallel), it is obviously close to reality. For milled specimen, the previous conditions are locally relevant for initiation step and beginning of crack propagation (high groove radius compared to grain size). When crack propagates from a macroscopic point of view, the crack follows the envelope of the grooves that can be assimilated to a straight line.

Results

For each specimen, the stress concentration factor K_t characterising the surface conditions is calculated according to the previous presented process. The so-obtained values are then used in Eq. (3) to determine the fatigue limit of each type of specimen. For limited fatigue lives, the total number of cycles to failure is calculated with

$$N_f = N_i + N_p \quad (8)$$

where N_i is determined via Eq. (7) and N_p is estimated by the iterative calculation using Eq. (6). The so-obtained results are compared with experimental data in the SN curves presented in Figure 1. Fatigue limits are also included to get a global assessment of the complete modeling. Experimental results and predicted fatigue life time are in good agreement for all types of specimens. In particular, even the SN curve of slot milled specimens is well modeled, confirming than more than Ra, the local stress concentration determined in the present study is a relevant parameter to describe the influence of machined surface texture on fatigue behavior. Moreover, the whole approach has been validated with other high speed machined specimens. These specimens were machined according to many different milling processes: face milling, shoulder milling, slot milling, finish plain milling, finish end milling, each with an up or down milling strategy. For each category, tool geometry and machining parameters (such as cutting speed or feed rate for instance) varied. Figure 5 presents the experimental and predicted fatigue life time as a function of K_t respectively for tests with a maximal stress of 320 and 300MPa. Obviously, the model gives good results for the various samples. The scatter observed for low K_t values can result either from the scatter of fatigue data or from the fact that K_t has not been evaluated for each specimen but only for one specimen of each category. Therefore, changes of the surface topography due to possible wear of tools is not taken into account.

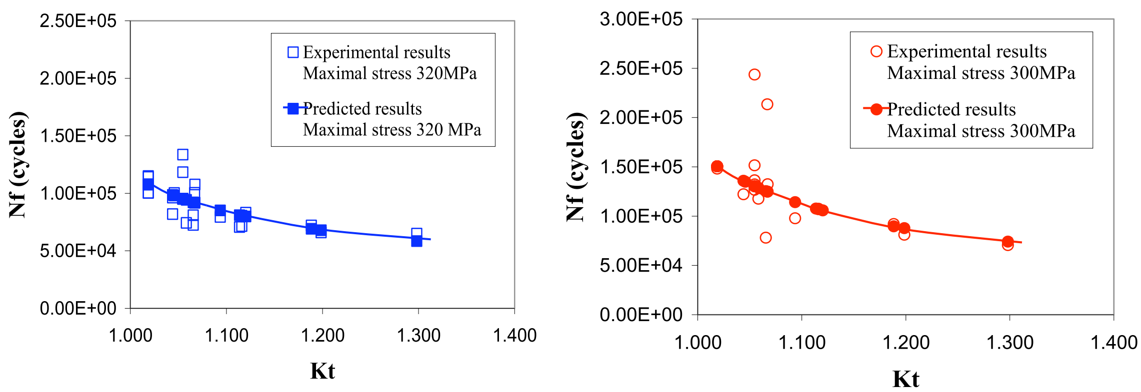


Figure 5 : Predicted and experimental fatigue life time versus Kt for high speed machined specimens with various machining conditions – Maximal stress 320MPa (left) and 300MPa (right)

Conclusion

For the present Al alloy and for the machining processes that have been investigated, the influence of machined surface condition on the fatigue behaviour is due to a predominant effect of roughness. In order to model this effect, surface topography is characterized from a mechanical point of view without the use of geometrical parameters: stress concentration factor K_t is calculated by finite element analysis from surface measurements. This so-calculated stress concentration factor is integrated in two different modelling to predict limited fatigue lives and fatigue limit. In addition to this calculated K_t, these two modelling only require basic fatigue crack propagation data (fatigue threshold and Paris law parameters). The whole approach (measurement of surface topography, determination of K_t, fatigue life prediction) provides a reliable mean to predict fatigue life of components machined in the present alloy when changing machining parameters and processes in an industrial frame without time-consuming and expensive tests. Further investigation is necessary to define the validity area of this global modelling. In particular, it could be interesting to test this method with a larger range of machining processes. Changing the material could also lead to adapt this approach in terms of K_t calculation or fatigue model and to extend it to combined effects of roughness, microstructure and residual stress.

PART 2 : FROM MACHINING TO SURFACE

The development of models of cut received a considerable attention from researchers as well as from industrial engineers. Most of these studies concentrated on the orthogonal cut (edge of the tool perpendicular to the flow of the chip) [12]. Indeed, this framework allows a 2D plane strain modeling and a better comprehension of the basic mechanisms of the chip formation. For fifteen years, many models of calculation by finite elements have been developed for this purpose, but their extension to the industrial cases 3D (milling for example) remains very complex and very expensive in term of CPU time [12].
To mitigate this problem, the approach that we propose here is based on a mechanistic model 3D developed by Altintas et al [13]. In a simplified way, this model connects a depth of cut to a cutting force via coefficients of cut which are given by a series of experimental tests of orthogonal cut. In our approach, the coefficients of cut are determined by a numerical model of cut 2D. Moreover, the local thickness of not deformed chip is calculated starting from an algorithm of intersection tool/matter of the type Z-Map [14] which allows the modeling of complex cases of millings (hemispherical milling 5 axes for example) as well as the rebuilding of the machined surface. topography. Besides, in the present study, the interaction between cutting forces calculation and surface building is introduced. Tool bending which may highly influence surface topography is therefore taken into account.

Construction of the model 3D starting from the model 2D

The mechanistic model of Altintas et al., [13] proposes to discretize the cutting edge in a series of elementary edges. The total cutting force is then the sum of all the cutting forces of these elementary edges. These efforts are obtained by multiplying the elementary chip thickness by cutting coefficients which are determined from results of numerical simulations SPH 2D.
The numerical simulations were carried out using the hydrodynamic code of nonlinear calculation LS-DYNA [15] by using the method Smoothed Particle Hydrodynamics (SPH) within the framework of the orthogonal cut 2D. Let us recall that it is a Lagrangian method without grid, which proposes a new space discretization: the points or particles are affected of a mass and a sphere of influence in which their interactions are balanced by functions of interpolation. The use of this method for modeling of the cut offers many advantages: the great deformations are easily represented (no remeshing necessary); the separation chip/part is modeled in a natural way and friction is taken into account by the interaction between the particles. It is not necessary to introduce a numerical parameter to fit the experimental cutting forces into this model. The validation of this approach was carried out by comparison with experimental results in term of cutting forces and morphology of chips [16].

Determination of the cutting coefficients

In order to determine the coefficients of cut necessary to the mechanistic model, the influence of feed on the cutting forces (FC) and on feed forces (FF) is studied using developed model SPH. Figure 6 illustrates a case of application on a 7075 aluminium alloy. The four coefficients of orthogonal cut are then deduced from these curves (two slopes + two ordinates in the beginning).It can be noticed that, in the case of milling, the cutting conditions are not orthogonal but oblique. A traditional empirical transformation [12] transforms the 4 coefficients of orthogonal cut into 6 coefficients of oblique cut. They are function of the angle between the speed of the tool and the edge of the tool and then make it possible to calculate efforts according to the local conditions 3D of cut.

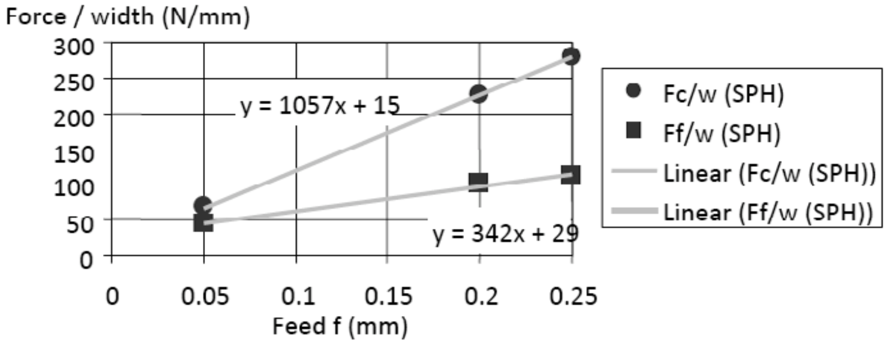
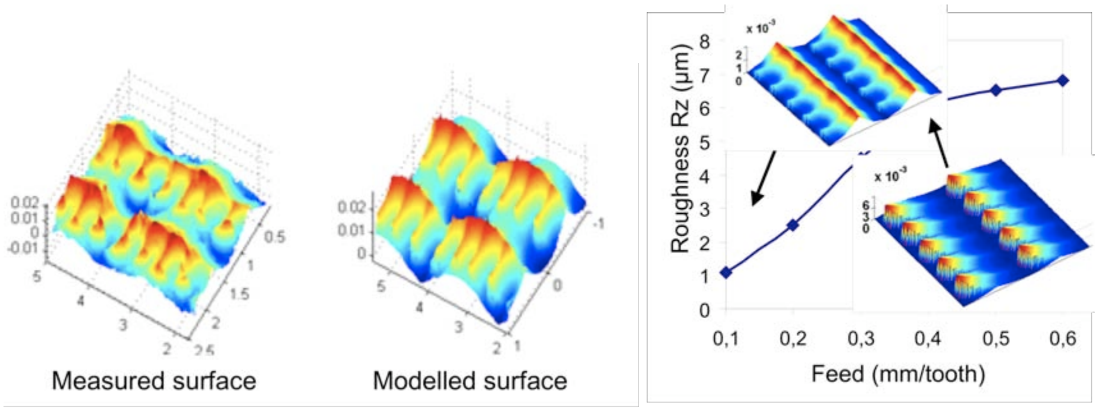


Figure 6 . Résultats SPH : *Cutting forces predicted by SPH 2 D model, α=0° r=20µm AA7075-T6*

Model of intersection tool/part.



The essential data that it remains to determine in order to use the mechanistic model is the local thickness of the not deformed chip. Analytical models exist but are limited to simple cases of machining. An approach of the Z-Map type was selected because it applies to a large variety of the types of milling. This method is based on a vectorial representation of the part: the passage of the edge cuts a certain number of vectors to a certain height and this, at each step of rotation. It is thus possible to determine 3D texture of the machined surface as well as the local cutting conditions. The path of the cutting edge is discretized for each step of rotation. An algorithm of intersection determine the quantity of removed matter. This phase is illustrated by the intersection of an increment of rotation with a vector of Z-map. The 3D texture of the part is also deduced. Figure 7 shows the good agreement between numerical surface and measured surface. The influence of feed per tooth on the geometrical roughness parameter R_z is also presented in this figure. With this model it is also possible to build surfaces generated by parallel ends cutter, torus cutter, ball cutter, and insert cutter.

Cutting forces.

The cutting coefficients necessary to the evaluation of the 3D efforts of cut are obtained starting from model SPH 2D. The local thickness of the not deformed chip determined by the model of intersection tool/part as well as the coefficients of cut obtained starting from model SPH 2D are integrated in the mechanistic model. The results of the developed model are compared with experimental data resulting from the literature [12]. Figure 8 shows that this model is able to reproduce cutting forces for 3D applications like hemispherical milling with a very good precision.

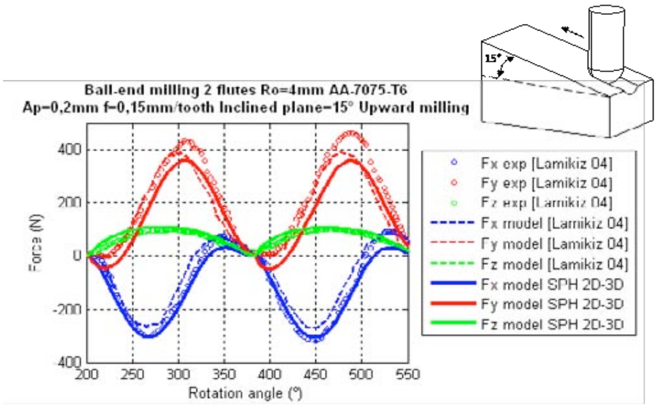


Figure 8 : developed model compared to Lamikiz work [17]

GENERAL CONCLUSION :

Determination of the fatigue life starting from the manufacturing range.

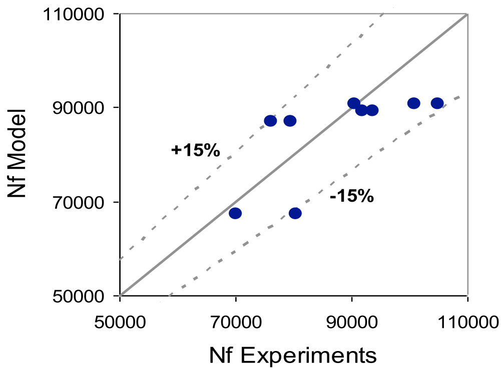


Figure 9. Predicted fatigue life versus experimental results

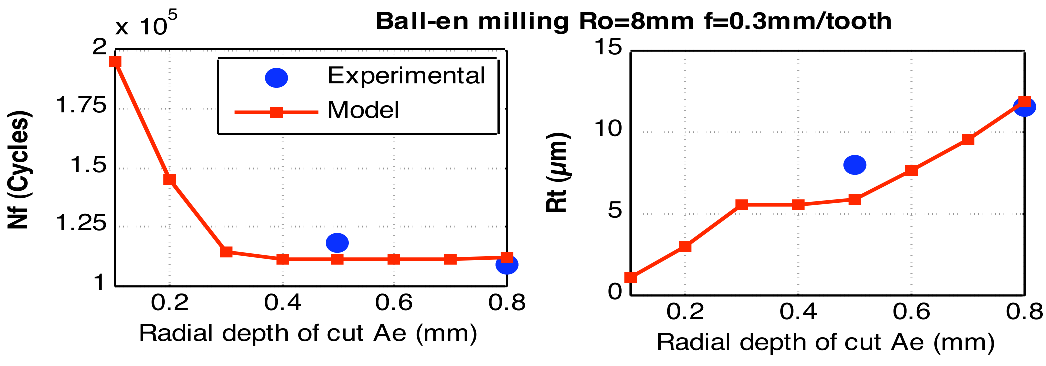


Figure 10 : predicted and experimental fatigue life and roughness versus radial depth of cut for a ball-end milling tool

The model 3D described in the previous chapter is able to predict 3D surface machined from machining parameters. This model takes into account the axial, radial, and eccentricity defects of a milling tool and can also integrate bending of the tool because the cutting forces are also calculated. As it was presented in first part of this paper, roughness was identified as the dominating parameter on this aluminium 7010 alloy [9]. The implementation of our model connecting the machining parameters to generated surface coupled with the

Kt→Nf approach thus makes it possible to consider a predictive approach of the relationship machining parameters - fatigue life. The Kt→Nf approach requires as input datum a profile of roughness. We propose here to use the theoretical profile of roughness determined by the model of surface developed. The objective here is to give tendencies on the influence of the of machining parameters on the fatigue life.This approach was validated on cases tests of 4 points bending-test specimens carried out in milling high speed using of a toric milling tool . Figure 9 compares the fatigue life calculated by the suggested approach and experimental results. The maximum error is approximately 15% out of 9 cases of studied millings with a strong concentration of the predicted fatigue life around 90000 cycles. That is due to the weak variations of the machining parameters for these various cases. Nevertheless, a marked evolution of predicted fatigue life is noticed when considering a large variation of machining parameters. Some experimental results presented in figure 10 confirm the validity of these predictions.

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