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Influence of surface integrity of 15-5PH on the fatigue life

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Abstract

The effect of surface integrity parameters on fatigue life has been investigated. Various surfaces have been manufactured with a controlled surface integrity in order to achieve fatigue test and to compare the influence of each parameters independently (residual stresses, surface roughness, and microstructure). The difficulty to reproduce the same surface integrity on each sample had been pointed out. It is necessary to characterize the surface of all the samples before testing and take it into account in the fatigue test procedure. Staircase tests have been carried out to determine the average fatigue strength at 2.10^6 cycles for each case of surface integrity. First results show that very good surface finish conditions combined with compressive residual stresses are beneficial.

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Keywords: Surface integrity; residual stresses; fatigue life; rotating bending; surface roughness

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Nomenclature

Ra	Surface average roughness (µm)
Rz_{max}	Maximum height/depth of the roughness profile (µm)
Rt	Maximum height of the roughness profile (µm)
σ_{xx}	Longitudinal surface residual stress (MPa)
S_f	Fatigue strength (MPa)
SEM	Scanning Electron Microscopy
EBSD	Electron Back-Scattered Diffraction

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1. Introduction

15-5PH is a martensitic stainless steel widely used in aeronautic and nuclear industry for high valued and critical parts. The machining sequence of these parts is often locked and is responsible of their surface integrity [1,2] (surface roughness, residual stresses distribution near the surface and microstructure).

However, some unexpected events can occur, such as tool and/or cutting conditions changes, leading to modifications on the machining sequence which can have strong consequences on the resulting surface integrity. Several studies on this subject area were conducted by the CIRP[†] [3,4]. Furthermore, it is well known that the surface integrity affects the fatigue strength [5,6]. So it is really important to understand how these modifications will influence the fatigue behavior.

The aim of this work is to study the fatigue strength of various surface integrity cases. First, a large work of surface engineering by applying different manufacturing operations has been done to obtain samples with controlled surface characteristics. These surfaces have been fully characterized using surface topography measurements, SEM observation, and residual stresses analysis. Then, rotating bending fatigue tests had been performed on the produced samples to determine the average fatigue life at 2.10^6 cycles for each surface integrity case.

Finally, fatigue test results and surface characterization have been analyzed in order to identify which parameter of surface integrity has the largest influence on the fatigue resistance of the material.

2. Surface engineering

Various cases of surface integrity were defined in order to be able to study the influence of a single parameter – roughness or residual stresses – at a time on fatigue properties. Case 1 is corresponding to the machining sequence currently used on real parts. For this industrial case, it has been found tensile axial residual stresses on the surface ($\sigma_{xx} = 200 \pm 50$MPa) and an average roughness Ra≈0,9µm [7]. Based on these observations, other cases are defined in order to modify the values of these two parameters as following (Fig. 1a):

Tensile residual stresses equivalent to case 1 with a lower roughness (Ra≈0.35µm) are searched for the case 2. Cases 3 and 4 derived from previous cases by keeping the same level of Ra but by introducing compressive residual stresses. Very low surface roughness associated with large compressive residual stresses is targeted for case 5.

Machining conditions have been optimized to approach at best these ideal cases directly on fatigue test samples which have a toroidal geometry in order to localize the maximum stress in the smallest section with a diameter of 10mm (Fig. 1b).

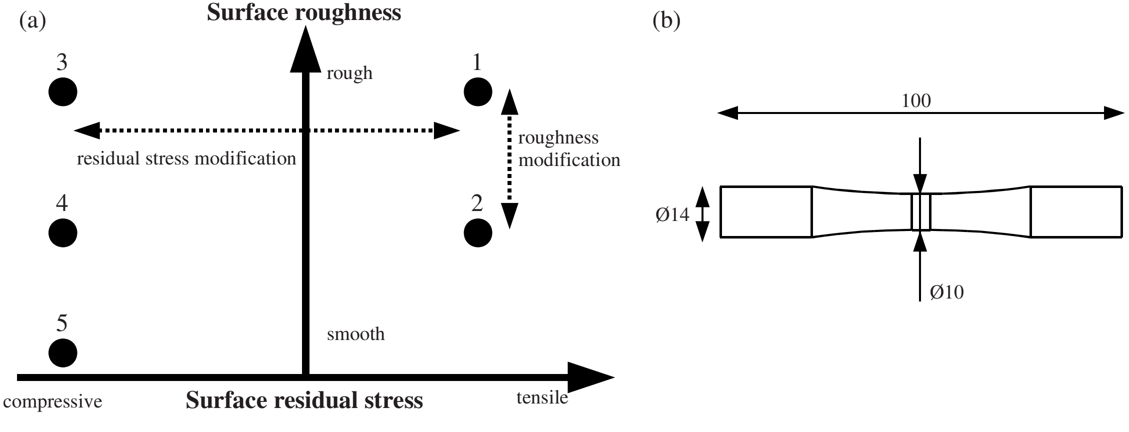

Fig. 1. Description of surface integrity cases studied (a) and schematic of a test sample (b).

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[1] International Academy for Production Engineering

2.1. Sample production

All the manufacturing operations conducted in this work were performed on a CNC Lathe Transmab T450 with real time force measurements thanks to a piezoelectric dynamometer plate or an instrumented tool holder. Processes involved in this study are: turning and roller burnishing applied after turning (Fig. 2).

The operation of turning and its consequences on 15-5PH surface integrity have been studied by A. Mondelin during his thesis [7]. Concerning roller burnishing, this operation leads to various publications [11,12]. As opposite to turning which involved material removal, roller burnishing consist in applying a pressure through a ceramic ball and make this ball moving on the surface. The consequences of this process are the modification of the surface topography due to small plastic deformations and the generation of compressive residual stresses under the surface. Based on these studies, an experimental work was performed to find the best set of process parameters. This leads for each case to the definition of a preparation sequence:

- Case 1 is obtained by turning with industrial cutting conditions and is the reference (Ra≈0,9µm and σ xx=200± 50MPa). Case 1' is identical to the case 1 but the tool holder on the lathe has a lower stiffness.
- Case 2 is a variation of case 1. The cutting conditions are almost the same; the feed of the tool has just been reduced to decrease the roughness.
- Case 3 is obtained by applying roller burnishing in such a way that the roughness is equivalent to case 1.
- Case 4 is a variation of case 3. The burnishing feed has been reduced to reduce the roughness.
- Case 5 is obtained by applying roller-burnishing with a very low feed

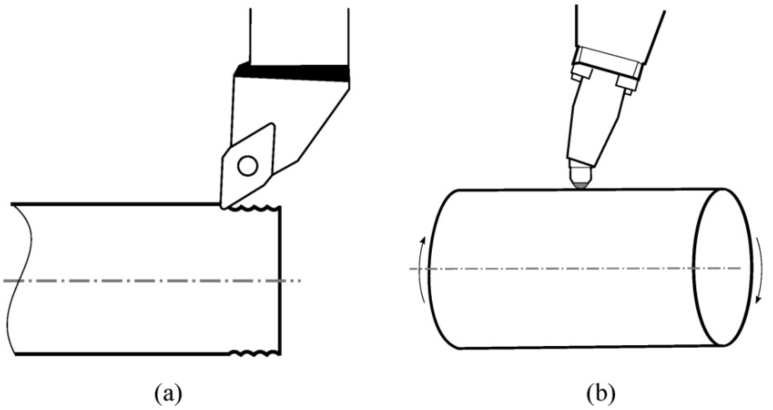


Fig. 2. Schematic representation of the turning (a) and burnishing (b)

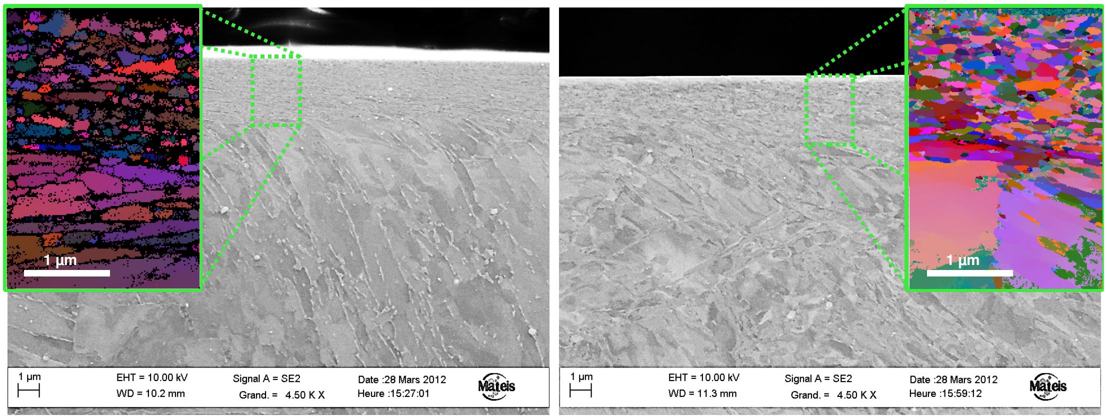
2.2. Surface characterization

Non-destructive methods have been used in order to characterize the surface integrity of all samples to check if the expected surface integrity was obtained. Several 2D roughness profiles have been measured according to the international standard [8]. Standard roughness parameters such as Ra, Rt or Rz were calculated. On this subject, the literature suggests that amplitude height parameters are the much relevant to connect roughness with fatigue life [5,9]. Residual stresses analysis has been carried out using X-ray diffraction and $\sin^2\Psi$ method. In order to keep samples intact, only surface measurements have been performed. Evaluation of stress distribution under the surface is found to be relevant with the numerical model developed by [7,10] in terms of profile, affected depth, and order of magnitude of residual stresses. Some samples were cut and polished in order to observe the microstructure in each case studied. A particular attention was given to the extreme surface layer of approximately 2µm which is found to be the most affected area. This layer was characterized with SEM and EBSD.

2.3. Results of surface analysis

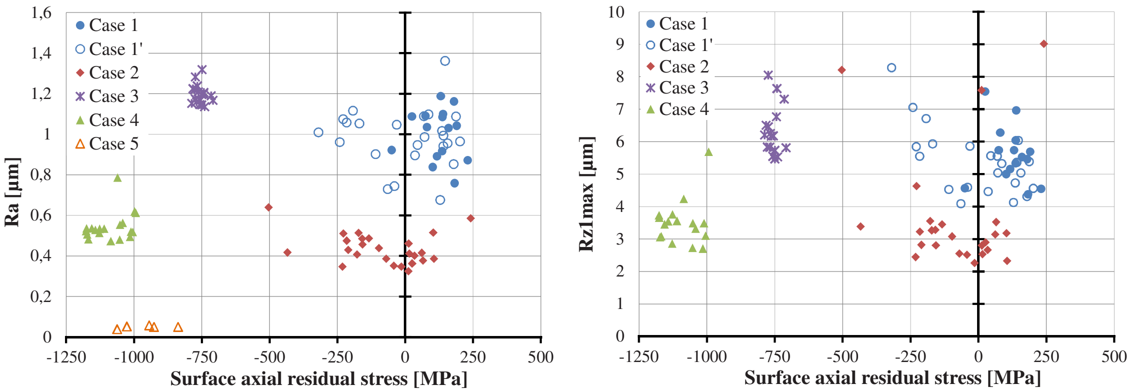
For each case, many samples were manufactured and controlled thanks to the methodology described above. First, it can be noticed that there is no significant difference on the extreme surface layer between the microstructure of a machined surface and a burnished surface (Fig. 3). This thin layer of approximately 2µm depth is composed by very small equiaxed grains under 300nm of diameter in both cases. Under the machined surface (Fig. 3a), the microstructure under the surface looks unaltered excepted a small transition zone where the microstructure seems to follow the material flow under the tool. For the case 5 surface (Fig. 3b), the surface layer is followed by plastically deformed martensite, consequence of the roller burnishing.

Non-negligible variations have been found on surface residual stresses and on roughness on the case 1 and 2 despite the fact that the cutting conditions were the same in each case (Fig. 4). However, tendencies are the same between Ra (Fig. 4a) and Rz_{max} (Fig. 4b). Large surface defects, detrimental for fatigue testing, can be detected thanks to the Rz_{max} parameter. No relationship has been found between this surface residual stress and the surface roughness on cases 1 and 2. It means that the phenomenon responsible for this variation does not occur at the same scale than roughness generation.



(a) (b)

Fig. 3. Microstructure observation under the surface and EBSD map of the surface layer for a machined surface case 1 (a) and a roller-burnished surface case 5 (b)

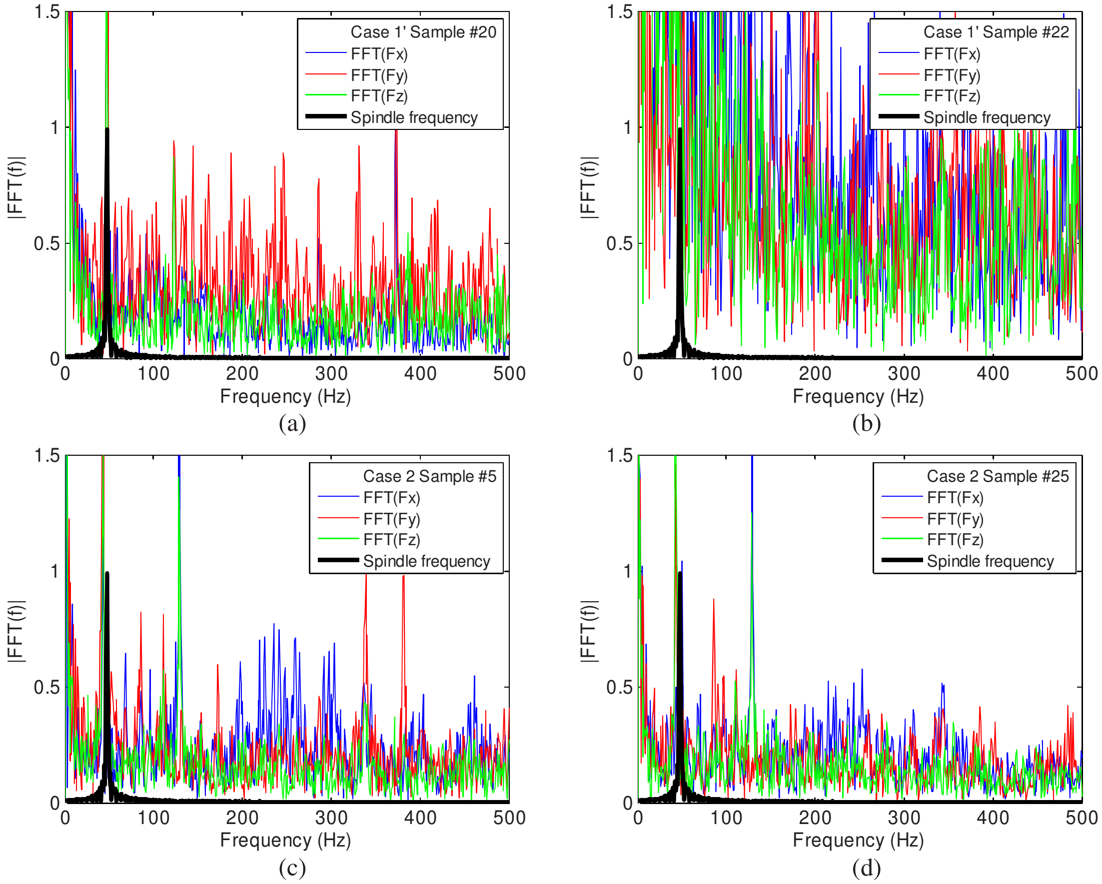


(a) (b)

Fig. 4. Surface axial residual stress versus (a) average roughness Ra or, (b) maximum height/depth of the roughness profile Rz_{max}.

A frequency analysis on the machining forces had shown that case 1’ residual stresses seem to be correlated to the noise on the force signal. Noisier is the signal, more compressive are the residual stresses (Fig. 5a and 5b). This effect has been explained by the low stiffness of the instrumented tool holder. Indeed, case 1 samples were machined with a standard tool holder mounted on a stiffer piezoelectric dynamometer plate and residual stresses produced are almost always tensile. However, there are still unexplained variations, especially on the case 2: samples were machined with the stiffer tool-holder but huge variations on surface residual stresses are observed without noticeable increase of the noise on the forces signal (Fig. 5c and 5d). It means that vibrations are not the only ones responsible for residual stresses generation in this case. SEM observations on these surfaces has shown strong variations which indicate that in some cases the tool do not cut the material, but literally plough the surface, leading to compressive residual stresses generation (Fig. 6).

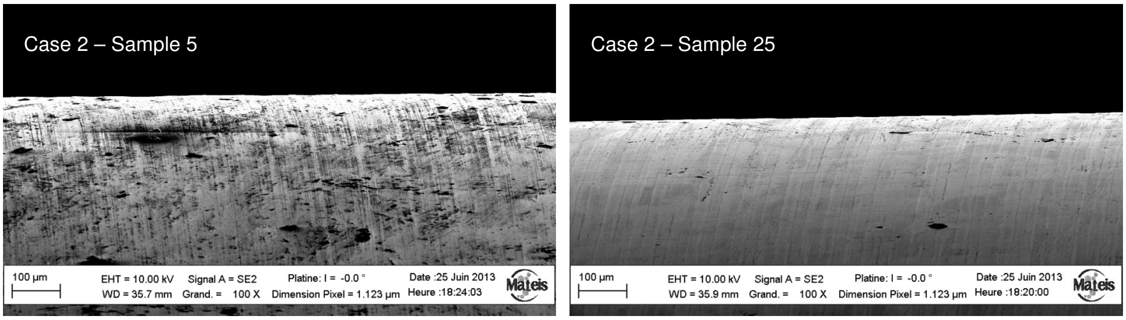
For cases 3 and 4, the reproductibility of the process is obvious. It has been possible to produce samples with the wanted surface integrity. The difference on the average residual stresses is due to the burnishing feed rate modification between case 3 and 4 which leads to a diminution of the surface work hardening when the feed is increased.



(a) (b)

(c) (d)

Fig. 5. FFT on machining forces for case 1’ sample with compliant surface integrity (a), and non-compliant (b); and for case 2 sample with (c) compressive (σ_{xx}=-215MPa) and (d) tensile surface residual stresses (σ_{xx}=100MPa)



(a) (b)

Fig. 6. SEM observations of machined surfaces (case 2) where residula stresses are (a) compressive (σ_{xx}=-215MPa) and (b) tensile (σ_{xx}=100MPa).

These first characterization results have shown that direct transposition of industrial sequences on small samples lead to very different surface characteristics. Even if cutting conditions are the same, variation are still observed, especially on residual stresses [13]. To take this dispersion into account in this study, it is necessary to perform surface analysis on all the samples before fatigue tests to sort the samples and select some of them in order to fit as much as possible with the description.

3. Fatigue tests

3.1. Method

Fatigue tests have been performed on a four point bending rotating machine with a fatigue stress ratio R=-1. This machine allows a constant bending moment in the sample's cross section up to 200 Nm, which means that for a Ø10mm sample, the maximum stress is 2000 MPa.

In order to minimize the number of samples of each case necessary for the fatigue strength determination, a test procedure has been set-up. First, a Locati test was conducted in order to evaluate the fatigue strength of the studied case. This method, based on Miner hypothesis [14] on cumulative damages gives an approximation of the fatigue strength with only one test sample. The purpose of this test is to define the starting point for the staircase. Then, in order to determine a more reliable value, a Staircase test is performed [15]. It gives the fatigue strength with a 50% failure probability at the number of cycle considered (here 2.10^6 cycles). This method requires ten sample minimum to get the average fatigue strength.

3.2. Staircase test

From surface analysis developed in the previous section, samples were classified according to their surface integrity in order to match with the specifications. Results of these tests are summed-up in the table 2 and on figure 7. Some results are only projections because the number of specimens is found sometimes insufficient to determine the fatigue strength according to the staircase method.

For the reference surface (case 1) the calculated fatigue strength of 642MPa has been found to be in good agreement with the value of 650MPa found in the literature [16].

These results confirm that compressive residual stresses, associated with a very low surface roughness, improve the fatigue life. It can be observed an increase of more than 25% of the fatigue strength, from 642MPa to 825MPa, which can be directly compared with the observations recently made by Avilés *& al.* on an AISI 1045 [17].

Surprisingly, by observing case 5 and 4, the surface roughness appears to play a non-negligible role even if there are deep compressive residual stresses on the surface. Case 3 tendencies seem to confirm this observation. The comparison of the Sf calculated for case 1 and estimated for case 3 tends to show that a large increase of compressive residual stresses (from 150MPa to -750MPa) does not increase a lot the fatigue strength for relatively high roughness whereas for lower roughness, the impact of residual stress seems larger (case 2 and 3).

Table 2 . Staircase results, estimated values of Sf are given in parentheses

Case	Number of specimen tested	S_f (MPa)
1	13	642
2	5	(600-650)
3	10	(650-700)
4	11	754
5	19	825

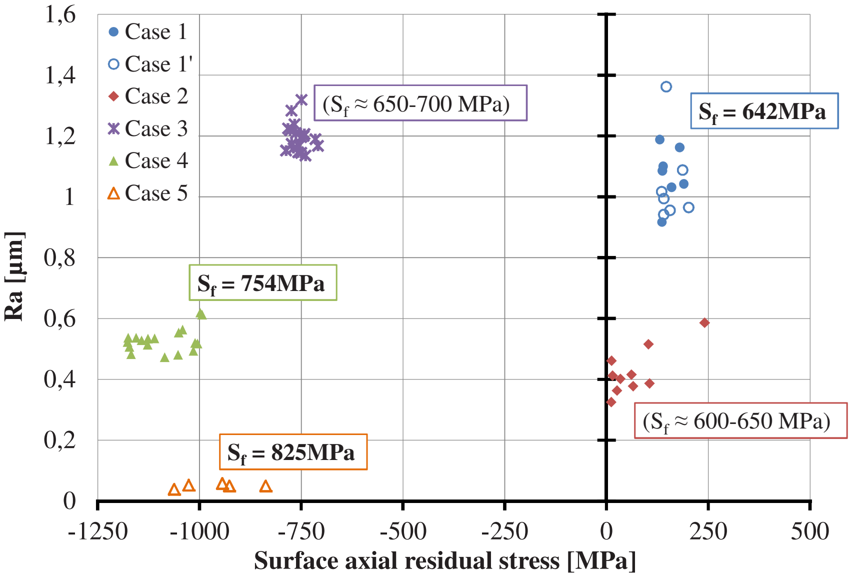


Fig. 7. Surface residual stresses and surface rougness (Ra) with associated fatigue strength.

4. Conclusions

In this paper, a method has been developed to investigate the effects of surface integrity on the fatigue life. Samples are produced in order to fit with the surface integrity of real parts.

Based on the preliminary work conducted in this study, it appears that the manufacturing of samples having the same surface integrity is a critical point. Thus, the importance of characterizing the whole set of sample is necessary to reduce all the bias which can be induced by surface integrity variations. At least, a frequency study of the machining forces could provide good information to eliminate bad samples. It can also be necessary to adapt the tool and/or the conditions to increase the stability during the machining (i.e. due to the scale effect between a real part and a sample, tools and machining condition could vary). This way, it should be possible to reduce the uncertainty in fatigue tests results.

Firsts fatigue results are in good agreement with the literature: it has been found that compressive residual stresses associated with a very low surface roughness increases the fatigue stress. Nevertheless, a higher roughness seems to have a non-negligible effect on the fatigue strength even if there are large compressive residual stresses. In fact it seems that the improvement of fatigue strength due to compressive residual stresses decrease with an increase of surface roughness.

Beyond the fact that this method could provide information on the influence of surface integrity, the fatigue tests results can be extended to real parts having an equivalent surface integrity and solicitation spectrum

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