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Influence of residual stress profile and surface microstructure on fatigue life of a 15-5PH

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Abstract

This works aims at identifying the influence of surface integrity parameters on fatigue life of a 15-5PH. The effect of residual stress profile, surface roughness and microstructure are investigated. Various cutting and superfinishing processes (turning, ball burnishing and belt finishing) are used so as to reach various engineered surface integrities and as a consequence to highlight the influence of each surface integrity parameter. Rotary-bending tests have been carried out on samples to determine the average fatigue strength at 2 million cycles. It is shown that the influence of a deep compressive sublayer is by far more important than the ones of surface roughness or microstructure. The so-called 'white-layer' brings also a slight improvement of fatigue resistance.

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Keywords: Surface intergity, fatigue life, superfinishing processes, white layer

1. Introduction

The 15-5PH is a martensitic stainless steel widely used for critical parts in the aeronautic or energy fields. The table 1 below presents its composition.

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Table 1 : 15-5 PH chemical composition

C	Mn	Si	Cr	Ni	Cu	Nb	S	P	Fe
0.07	1.0	1.0	14 to 15.5	3.5	2.5 to 4.5	0.15 to 0.45	0.03	0.04	BAl

In these sectors the machining sequences are critical and cannot be changed easily by authorities' certifications. The reason for this is that the machining operations modify the surface integrity parameters responsible of the fatigue strength of the steel and the parts and slight changes in the process can have major influences on the performances and lifetime. [1], [2]. [3], [4]

In previous works Chomienne [5] has machined customized parts trying to identify the influence of roughness and surface residual stress on fatigue behavior. The picture below (figure 1) presents the 4 sets of surface characteristics that were tested.

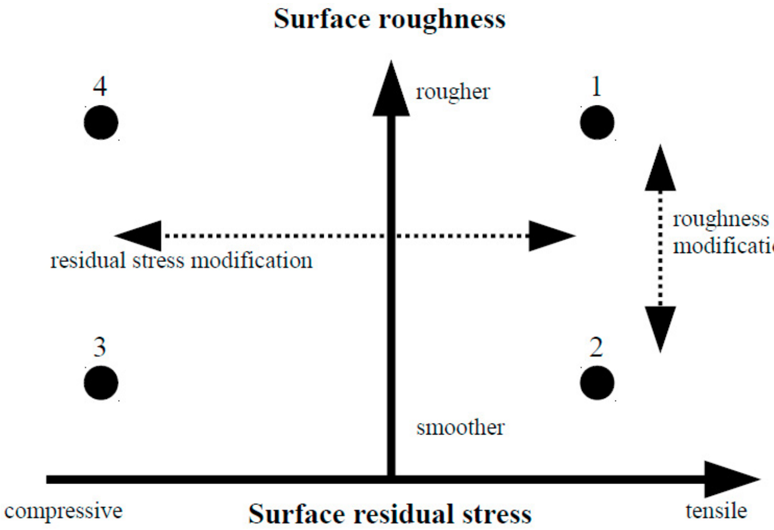

Figure 1: Characteristics of the samples tested by Chomienne [5]

In the article, the conclusions were that surface compressive residual stresses associated with a very low surface roughness increases the fatigue strength. 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.

The main idea of this paper is to complete the previous job by introducing the effects of the so called "white layer" and the shape of the residual stress gradient. To do so, belt grinding process is used to produce new sets of samples in addition to turning and roller burnishing. Then these samples are tested in fatigue by "Locati" method and staircase method in order to identify the role of these two surface integrity parameters in the fatigue behavior .

2. Surface integrity customization

Concerning machining and fatigue life, the surface integrity mainly regroups the surface residual stresses, the microstructure / metallurgical state and the topography. For all the finishing and superfinishing process, all these parameters are varying together and it is very difficult to identify the effect of a single parameter onto the fatigue life of the parts. For this study, it has been proposed to use finish turning, ball burnishing and belt grinding to machine bending test fatigue samples with custom surface integrity (figure 2) and quite low roughness (around Ra 0.6µm).

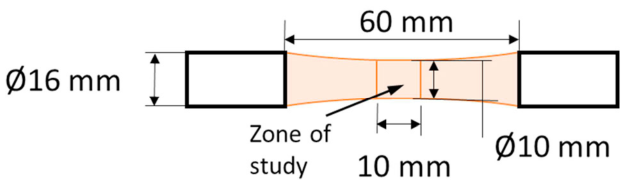

Figure 2: Bending test fatigue samples

2.1. Turning

The turning operation uses cutting tools with a very precise geometry (tool tip, cutting edge) and it is very simple to control the topography of the surface and to modify roughness parameters. Moreover, turning is known to generate tensile residual stress values [6, 7] and this feature will also help us machining the sample. Nevertheless, it is very difficult to control the microstructure changes and most of the time "white layer/nanostructured layer" appears. In this study, the turning will be used to produce samples with more tensile surface residual stresses and white layer at the top surface.
The table below (table 2) presents the parameters used to turn the fatigue samples.

Table 2: Turning conditions

Cutting speed ($m.min^{-1}$)	Feed rate ($mm.rev^{-1}$)	Depth of cut (mm)	Tool tip radius (mm)	Insert reference
90	0.08	0.6	0.4	DNMG 15 06 04 PF 4215

2.2. Ball burnishing

The ball burnishing process uses also a very precise geometry tool (2mm ceramic ball) and topography control is not an issue. In the literature this process is also well known for generating deep compressive surface residual stress [8]. Concerning the microstructure, it also produces white layer. In this article, the ball burnishing process allows producing fatigue samples with compressive surface residual stresses and deep compressive gradient, controlled roughness and top surface microstructure close to the turning one. The table below (table 3) presents the parameters used to roller burnishing on fatigue samples.

Table 3: Ball burnishing conditions

Rolling speed ($m.min^{-1}$)	Normal force (N)	Feed rate ($mm\text{-}rev^{-1}$)	Ball diameter (mm)
50	80	0.11	2

2.3. Belt grinding

The belt grinding process uses abrasive grains with a statistical geometry repartition. It is possible to change force and grain size to control the roughness but the residual stresses generation is not so well mastered. In this paper, the belt finishing will be used to generate fatigue samples with compressive residual stress, controlled roughness but without top surface "white layer".
The table below (table 4) presents the parameters used to belt finish the fatigue samples.

Table 4: Belt grinding conditions

Grain size (µm)	Roller hardness (shore)	Roller axial Displacement (mm)	Roller oscillation frequency (Hz)	Normal force (N)	Belt speed (cm/min)	Operation time (sec)
100	80	0.5	12.82	250	5.5	30

2.4. Generated surface

With the parameters used by the three processes, it is possible to machine 3 sets of samples with surface integrity parameters changing one at a time.

<u>Roughness</u>

Concerning the roughness, the parameters listed in the tables above allows to obtain Ra between 0.62µm to 0.7µm for all the three processes. This parameter has been considered representative of the surface roughness for the previous fatigue investigations [5]

<u>Residual stresses</u>

Residual stresses have been estimated with the X-ray diffraction technique and the $\sin^2\Psi$ method following the EN15305 standard. The in-depth values were obtained using electrolytic polishing. Figure 3 illustrates the different residual stress gradients. As we can see, the roller burnished samples and the belt ground ones have quite the same surface residual stress but the profile is much more compressive in the depth of the part for the Roller burnished ones. The turned samples have a very big difference concerning the top surface residual stress compared to the two others but the in depth gradient is closed to the belt ground ones.

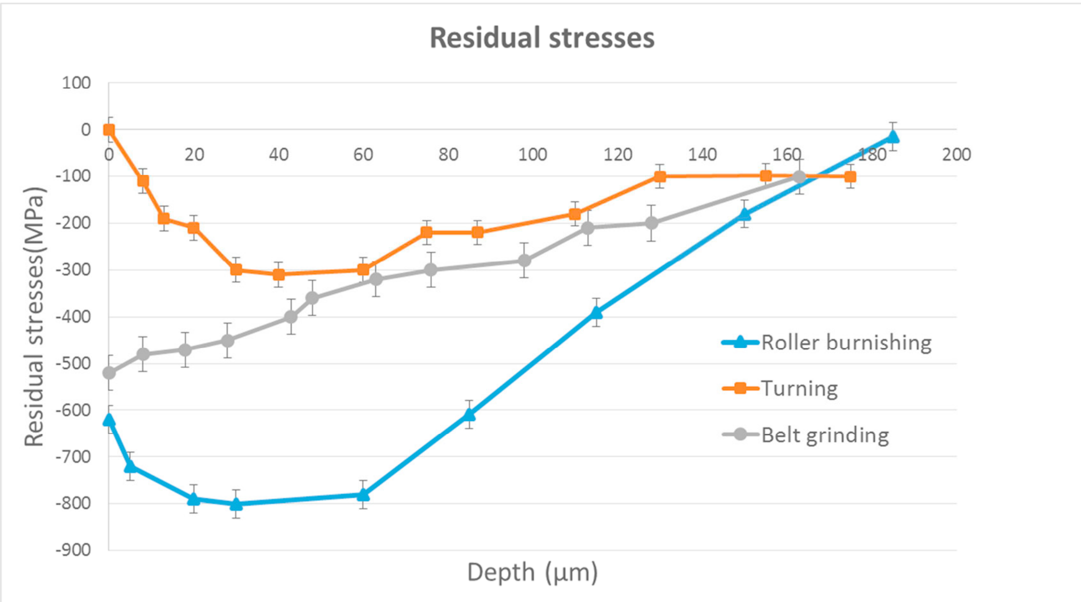

Figure 3: Residual stress gradients for the 3 sets of samples

<u>Surface layer</u>

The top surface microstructure was investigated with SEM. The picture below (figure 4) presents the “white layer” obtained with the turning and the ball burnishing process. They are assumed to be quite close in term of thickness and grain size for the rest of the study.

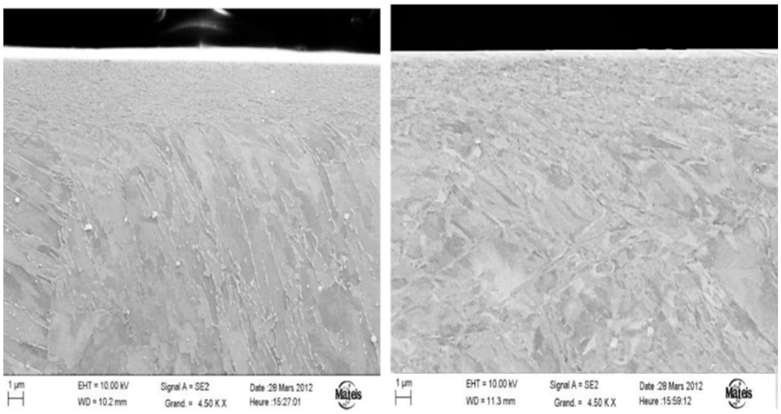

Figure 4: Surface layer generated by turning (left) and ball burnishing (right) [5]

Concerning belt finishing, it is supposed to remove the surface layer, leaving the microstructure close to the bulk one. The figure 5 presents the difference from a turned top surface to a belt finished one.

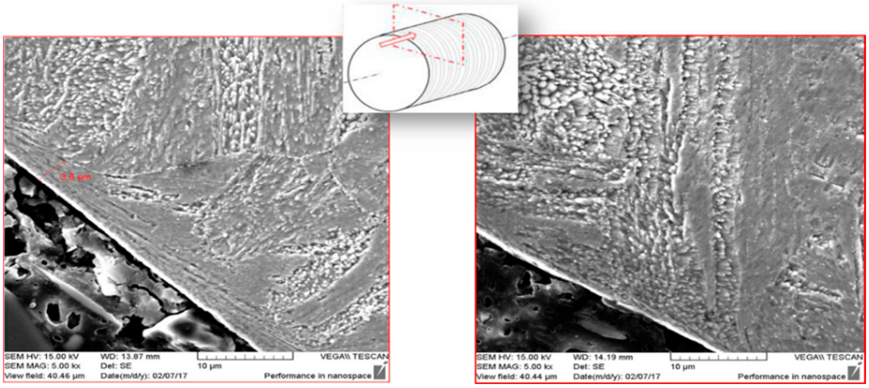

Figure 5: SEM observation of the surface layer after turning (left) and belt grinding (right)

After all these observations it is possible to summarize all the surface integrity parameters values in the following table (Table 5).

Table 5: Summary of the Surface properties

	Roughness Ra (µm)	**Surface residual stress (MPa)**	**Residual stress gradient profile**	**Nanostructured surface layer**
Set 1: **Turning**	0.62±0.13	0	Little Compressive	With
Set 2: **Roller burnishing**	0.7±0.05	-620	Deep compressive	With
Set 3: **Belt grinding**	0.7 ±0.14	-520	Compressive	without

3. Rotary bending fatigue tests

3.1. Protocol

The rotary bending fatigue tests are performed on a Walter bay® machine. The bending moment is generated by different weights P and the fatigue stress ratio R is equal to -1 (figure 6).

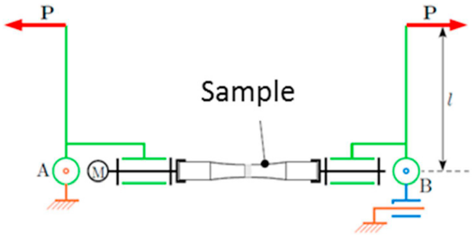

Figure 6: Rotary bending fatigue system

The fatigue tests were performed in two steps.

First Locati protocol was used based on Miner hypothesis [9] and cumulated damages. It uses only one sample to estimate the endurance limit. It is loaded step by step (20 MPa) until its failure and in this study the number of revolutions for each step is set to 200 000. Starting stress is set to 580MPa. The "Basquin" slope is fixed to 11.24.

Then, in order to determine a more reliable value, a Staircase method test is performed [10]. It gives the fatigue strength with a 50% failure probability at the number of cycle considered (here 2.10^6 cycles). This method requires a dozen of sample. The beginning level for the stress is set to 560 MPa and the increasing steps are 15 MPa.

3.2. Results

The table below presents the fatigue life of the samples after the fatigue test, depending on the process used to machine them. (First : Locati - Second : staircase)

Table 6: Fatigue life results (σ_s)

	Number of samples tested	σ_D (MPa)
Turning	1+10	590 - 612
Belt Grinding	1+10	568 - 592
Roller Burnishing	1+10	700 - 754

4. Discussion

Comparisons can be made between the 3 machining process in order to identify the most important parameters on the fatigue life of the sample.

Turning Vs. Roller burnishing
Both samples have the "white layer" but the fatigue life of the roller burnished samples is 20% higher (average values) than the turned samples. This result confirms that negative surface residual stresses and deep compressive gradient are increasing fatigue life.

Turning Vs. Belt grinding
The turned samples have the "white layer" nor the belt ground and the major difference is on the surface residual stress value. In this case, the turned samples have a fatigue life 3.6% higher than the belt ground ones (average values). This means that even if the surface residual stress value is negative for belt finishing, the presence of white layer seems to slightly increase the fatigue strength.

Belt grinding Vs. Roller burnishing
The previous comparison shows a soft influence of the white layer to improve the fatigue life but here the main difference is the depth of the compression gradient in the samples. As the white layer produces a few percent of increase the addition of the deep compressive gradients increases the fatigue life of 25%.

5. Conclusions

Previous study concerning surface integrity influence on fatigue life of the parts has shown the importance of a low roughness and compressive surface residual stress. The investigations performed in this article enhance the conclusions concerning the effect of the white layer and the residual stress gradient profile for surface with low roughness. It is shown that a deep compressive residual stress gradient leads to a significant increase of the fatigue life. This may be due to its role to slow the crack propagation. Moreover the “white layer” presence also seems to have a small effect on the fatigue stress augmentation. It may play a role in the crack generation at the top surface.
The results and the tendencies highlighted by the study need to be reinforced but the dissociation of the surface integrity parameters performed here is the key to better understand the phenomena.

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