Shot peening for surface topography optimization to avoid micro pitting

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Abstract

Mechanical components suchas gears or bearings are highly affected by contact fatigue phenomenon. It is well known that the micro pitting mechanism is responsible for components fracture/failure by contact fatigue, and there are a lot of details in the literature describing its morphology, apparition, etc. [1-3]. Despite the trivial predominant impact of the surface roughness on micro pitting apparition, there are several attempts in literature to establish a relationship between surface roughness and micro pitting.

In this paper, it is shown that an appropriate/controlled shot peening, could reduce the micro pitting phenomenon. A specific image analysis methodology applied to quantify the micro pitting, is described. This methodology allows the comparison between the reference and the shot peened specimen by means of interrupted tests.

Relationship between surface topography and micro pitting is also established using surface characteristics (Rku or Rsk) and functional parameters (specific film thickness (λ) and sliding ratios). EBSD analyses have pointed out surface accommodation by plastic deformation at the beginning of contact fatigue tests.

Introduction

The micro pitting is a minimal degradation that is generally encountered at the surface hardened components. The process of micro pitting degrades progressively the geometries of the contact surfaces which can result in the fatigue failure in the form of macro-pitting [1].

Previous studies [2] aimed on optimization of combined surface treatments (case hardening and shot peening) for gear applications, showed that the bending fatigue strength is greatly improved when carburising is combined with shot peening. Nevertheless, the literature provides little guidance on the relationship between the shot peening treatment and the contact fatigue failure related to the micro pitting however the important influence of the surface topography is denoted [1-3].From these results and considering that micro-pitting is a first responsible to initiate fracture/failure of components by a subsurface contact fatigue (pitting) [4], the main objective of this study is to find the best shot peening conditions leading to surface topography optimization as well as roughness parameters optimization, in order to eliminate or at least postpone micro pitting apparition.

Material and treatments

The material considered in this study is a carburized 18CrNiMo7-6 steel, which is subjected or no (depending on the case study), after grinding, to different shot peening conditions. These treatments have been performed on specimens used on rolling contact fatigue machine (see Figure 1).

The carburizing characteristics in terms of micro-hardness profile and case hardening depth are given in

Figure **2**. It may be seen that the case depth which means the depth where micro-hardness is equal to 550HV is of the order of 2mm for both cylindrical (A) and crowned (B) specimens.

From among all shot peening conditions applied, three of them have been selected on the basis of Rku and Rsk roughness values. They are named SP1, SP2 and SP3.

We have to remind that Rku describes the peaks shape, and Rsk the presence of peaks or valleys (see

Figure 3). Rku<3 and Rsk<0 give logically an optimal surface topography to avoid micro pitting. The residual stress profiles obtained with these conditions are presented in Figure 4. They present a typical residual stress profile of shot-peening treatment. Surface analyses have also been performed using optical photography and 3D interferometry. Results are summarized in Figure 5.

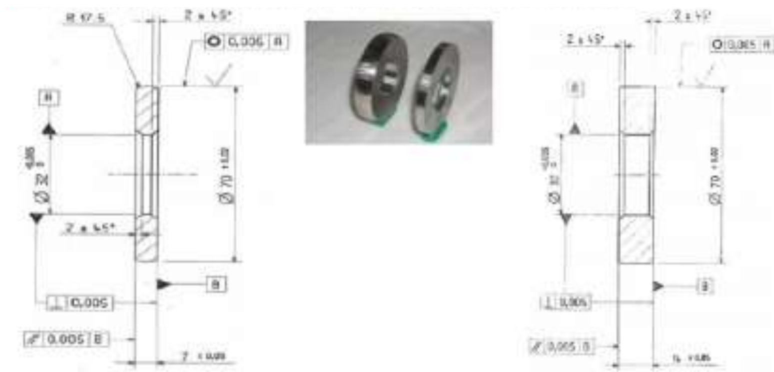
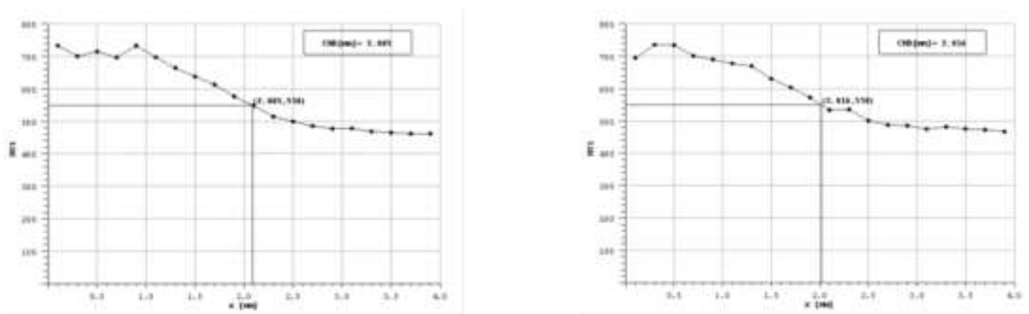


Figure 1 : Geometry of fatigue contact specimen



a) **b)**

Figure 2 : Micro-hardness curves: a) Cylindrical specimen, b) Crowned specimen. The case depth is 2mm.

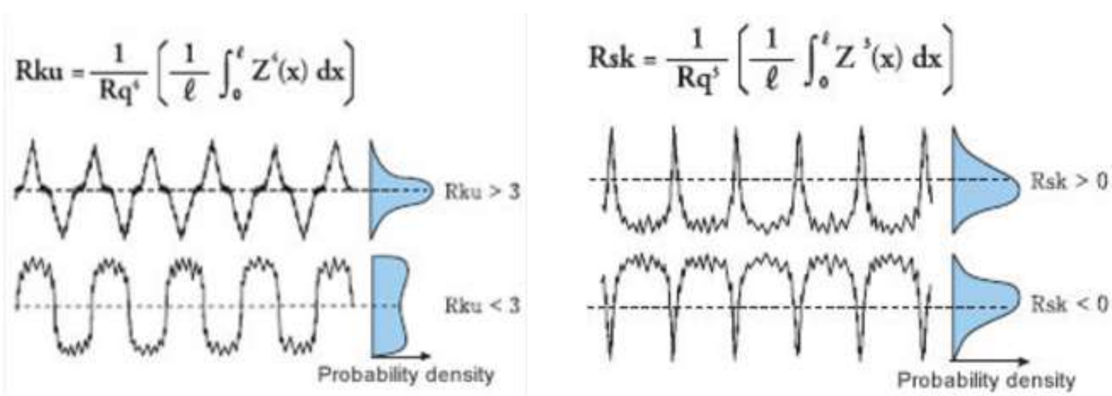


Figure 3 : Definition of roughness profile parameters: Kurtosis (Rku) and Skewness (Rsk)

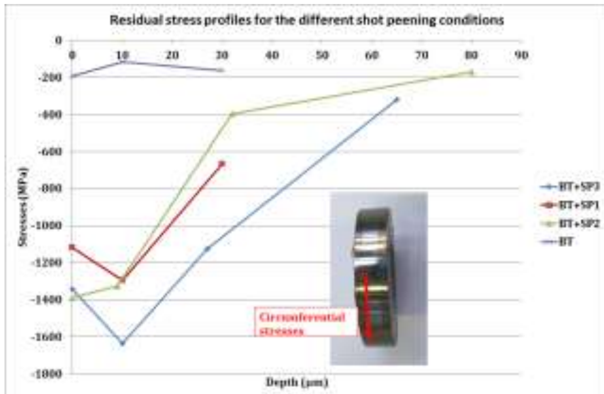


Figure 4 : Residual stress profiles after shot peening

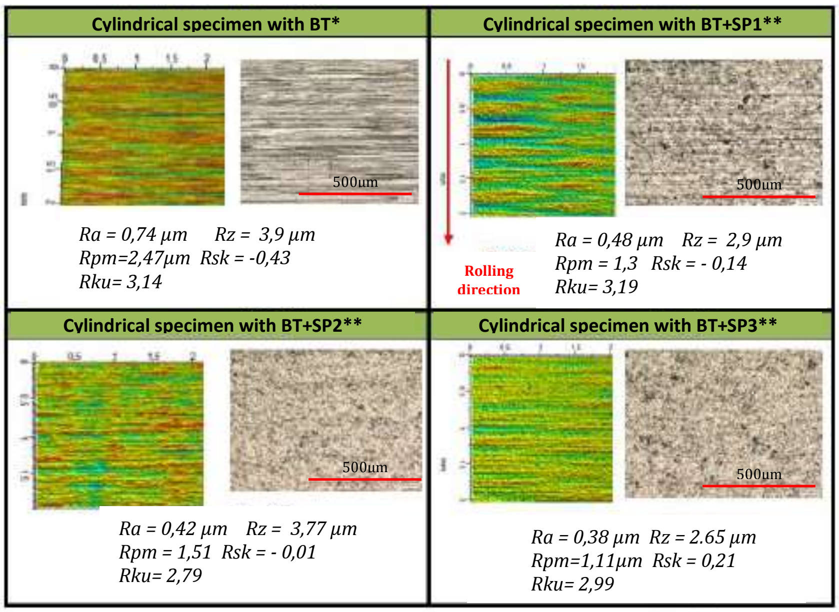


Figure 5 : Surface topography characteristics for the different treatments

***** Basic treatment (BT): Case-hardening, quenching, tempering and grinding
****** Basic treatment with a specific Shot Peening (BT + SP (1, 2 or 3)): Case-hardening, quenching tempering, grinding and Shot peening.

Experimental procedure

Contact fatigue test

The test carried out is a standard rolling test in which the two test specimens (shown in Figure 1) roll over each other, at a given pressure and a given slip rate.
The tests are performed under the following conditions:

- ✓ Contact pressure : 2500MPa,
- ✓ F=20Hz (cylindrical specimen speed: 1074 rev/min et crowned specimen speed : 1341 rev/min),
- ✓ Sliding ratio rate : 20 %,
- ✓ Lubricant: ISO VG 150,
- ✓ Inlet temperature: 70°C,
- ✓ Tests are interrupted after 36mn, 72mn, 96mn, 156mn, 240mn and 326mn.

To be as close as possible to the real contact conditions in gears, as shown in Figure 5, specimen have been machined with grinding direction normal to the rolling one.

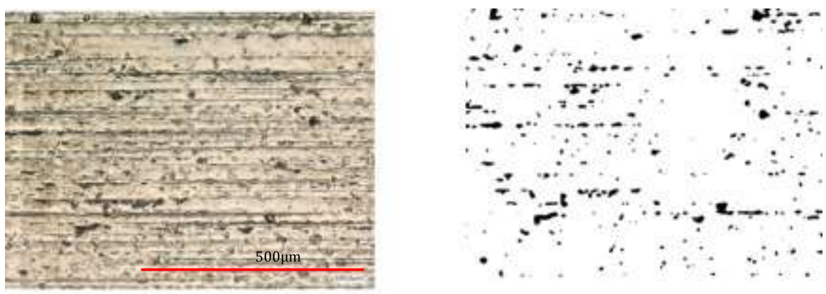
Image analysis

Before tests, a specific area is identified and photographed on the specimens. After each interruption, the same area is photographed again and analysed with a specific image analysis methodology providing the surface rate affected by micro pitting. An example is given in Figure 6.

Results

Micro pitting evolution

Figure 7 shows the surface's evolution during rolling test for several surface treatments.
A first qualitative analysis indicates that, after 156mn of contact fatigue test, the micro pitting affects more or less all the specimen's surface. When shot peening is applied (SP1, SP2, SP3) the surface affected by micro pitting decreases. We can also note a difference between the three shot peening conditions.
To get more quantitative results, all these photos have been treated by image analysis. The curves in Figure 8 present the evolution of micro pitting affected area along the fatigue test.



Slice	Count	Total Area	Average Size	%Area	Mean
Image 5.0	318	84652	266.201	4.409	255

Figure 6 : Example of micro pitting identification and quantification

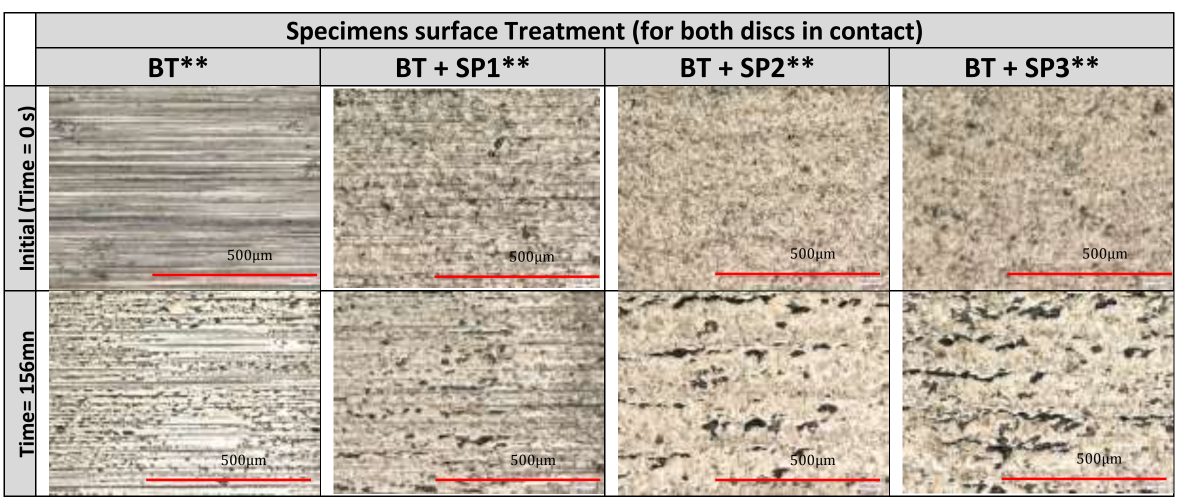


Figure 7 : Micro pitting evolution on cylindrical specimen during rolling, for the different treatments

It is clear on these curves that micro pitting is more important on grinding specimen, and it occurs very quickly.
By ading the shot peening (SP1, SP2 and SP3), it appears that the micro pitting is reduced, compared to the carburized-grinded sepcimens. One of these solutions, SP2, seems to be more efficient to reduce micro pitting. Moreover, for all the micro pitting increases continuously during the first 156mn of test.

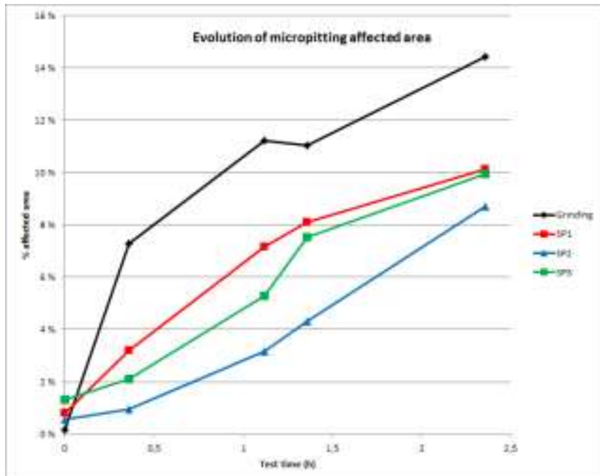


Figure 8 : Micro pitting quantitative evolution for specimen with and without shot peening

On the rolling contact fatigue, the specific film thickness parameter (λ), firstly defined by Tallian [5], is often used to predict the apparition of micro pitting. It is known, that the smaller λ is (<<1), the higher is the risk of micro pitting. This parameter is defined as follow:

$$\lambda = h_{min}/\sigma$$

Where, h_{min} is the minimal oil thickness and σ is the root mean square (RMS) depending on roughness parameters (σ_i = Ra, Rpm or Rq, i=1, 2) associated to both conjugated surfaces:

$$\sigma = \sqrt{\sigma_{i=1}^2 + \sigma_{i=2}^2}$$

Then, three specific film thickness specific are adopted in this study (see Table 1).

Table 1: Specific film thickness parameter (λ) values

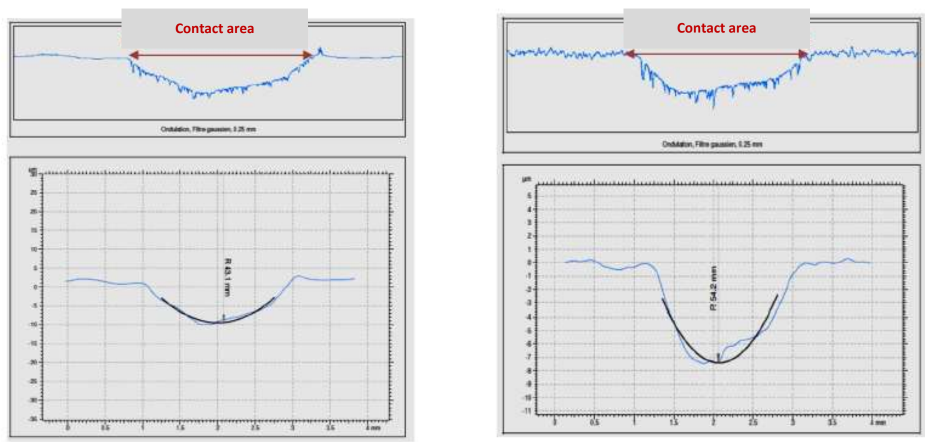
	Specimen's surface Treatment (for both discs in contact)			
	BT**	BT + SP1**	BT + SP2**	SP3**
$\boldsymbol{\lambda_{Ra}} = {h_{min}}/{\sqrt{Ra_1^2 + Ra_2^2}}$	0,38	0,46	0,65	0,58
$\boldsymbol{\lambda_{Rq}} = {h_{min}}/{\sqrt{Rq_1^2 + Rq_2^2}}$	0,3	0,37	0,52	0,46
$\boldsymbol{\lambda_{Rpm}} = {h_{min}}/{\sqrt{Rpm_1^2 + Rpm_2^2}}$	0,11	0,14	0,2	0,22

It can be noticed that for all cases λ<1; that confirms the apparition of micro pitting whatever the surface topography is. Nevertheless, the SP2 shot peening solution, leads in most of cases to higher λ values. That indicates that the risk of micro pitting apparition is lower. This is in accordance with the previous result on the percentage of micro pitting affected area (Figure 8).
Likewise, SP2 is also the solution for which Rku value (peaks shape) is <3 and Rsk value (valleys) is < 0. Let us remind that these conditions give a favorable surface topography for reducing micro pitting.

Pitting

The last step conducted in this study consists on the verification if the SP2 solution can also postpone pitting. To achieve this goal, tests have been performed on carburized, grinded and SP2 shotpeened specimen during 50h ($3*10^6$ load cycles). Unfortunately, pitting never appears, even on grinded specimen. Calculations using ISO 6336 standard [7] predict that an initial pitting marks should occur after 5 hours under the test conditions.

In order to explain these deviations, complementary measurements of the surface profile of the cylindrical specimens are carried out. A relatively large surface deformation is thus observed (see Figure 9). This deformation has to be taken into account to determine the effective contact pressure, which is finally 20% lower than the theoretical one. The contact pressure decreased from 2500 to 2000 MPa for which the time of appearance pitting is greater than 100 h ($>\approx 10^7$ load cycles), according to the ISO 6336 [6].



(a) **(b)**

Figure 9 : Surface deformation on grinded (a) and SP2 (b) cylindrical specimen after 50h rolling contact fatigue

EBSD analysis

In order to understand and explain the surface deformation, EBSD (Electron BackScatter Diffraction) analysis [7] has been performed on grinded specimen, on and out of rolling contact area (Figure 10), after 2,5hrs of rolling fatigue contact under 2500MPa theoretical pressure.

The picture on the right side shows the presence of very small sized grains on the surface layer (until a depth of 15µm). This is the consequence of plastic deformation [8] which occurs during the early cycles.

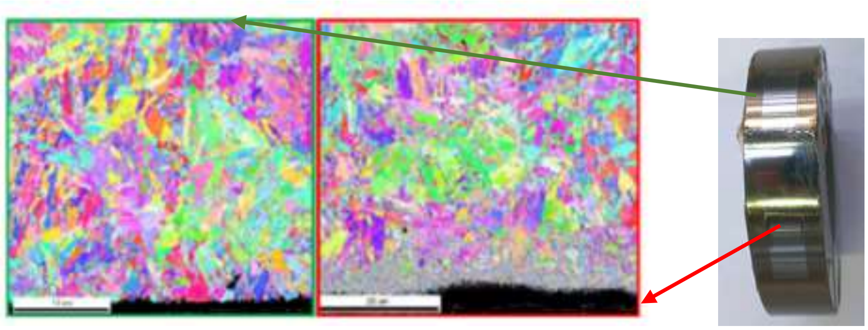
This plastic deformation is also confirmed considering the KAM (Kernel Average Misorientation) parameter. Figure 11 shows evolution of this parameter out of and in the rolling contact area, with respect to the normal depth. It can be seen that after rolling, almost 50% of grains present a disorientation of about 30° reflecting the introduction of certain plasticity.

This plastic deformation explains the shape modification on the specimen contact area.

Conclusions

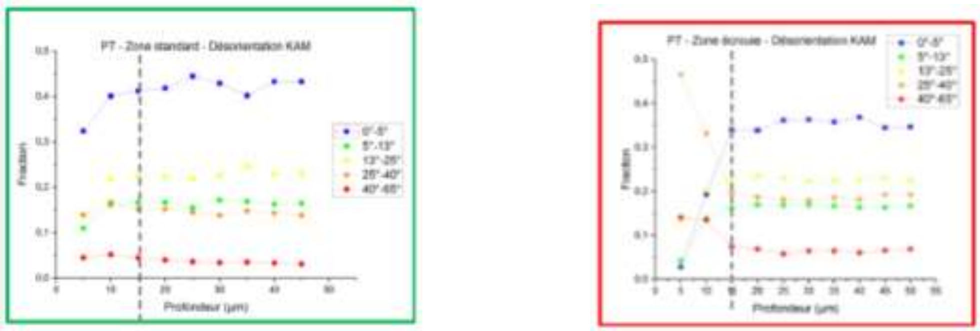
The work carried out in this study allowed the development of an interrupted test method to monitor the micro pitting progression with the development of a specific image analysis method for quantification of this flank damage through the percentage of the affected area. A detailed analysis was conducted to follow, during testing, the evolution of the parameters characterizing the surface topography conditions. By examining the obtained results, a particular type of shot peening has been identified as enough promoter to improve the contact fatigue strength of gear teeth. These main conclusions are also deduced:

- It is possible to obtain, by shot peening, a surface topography optimized to avoid or postpone micro pitting.



a) Analysis out of contact area b) Analysis on contact area

Figure 10 : EBSD analysis on grinded specimen after 2,5 hrs rolling contact fatigue



a) b)

Figure 11 : Evolution of KAM parameter a) out of rolling area, b) on rolling area

- The optimal surface topography shall comply Rku<3 and Rsk<0,
- Specific film thickness (λ) calculation is also a good indicator for micro pitting prediction.

The obtained results also point out that plastic deformation occurs at the beginning of the test, resulting in 20% decrease of the contact pressure. Consequently, it was not possible to check if the SP2 solution postpones also pitting. Some tests on gears are in progress to validate this shot peening solution (SP2) on components.

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