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# SURFACE DEFECTS: PROPOSITION OF AN EVALUATION MODEL – TECHNOLOGY AND METHODOLOGY

**Enivaldo Amaral de Souza**
Instituto Tecnológico de Aeronáutica – ITA/CCM, Marechal Eduardo Gomes, 50 - Vila das Acácias – São José dos Campos – SP, Brasil
enivaldo@ita.br

**Ronnie Rodrigo Rego**
Instituto Tecnológico de Aeronáutica – ITA/CCM, Marechal Eduardo Gomes, 50 - Vila das Acácias – São José dos Campos – SP, Brasil
ronnie@ita.br

**Anderson Vicente Borille**
Instituto Tecnológico de Aeronáutica – ITA/CCM, Marechal Eduardo Gomes, 50 - Vila das Acácias – São José dos Campos – SP, Brasil
borille@ita.br

**Carlos Yuji Sakuramoto**
GMB, General Motors do Brasil - Av. Goiás 1805 – São Caetano do Sul – SP
**carlos.sakuramoto@gm.com**

**Abstract.** *Surface defects are usually detected in the final product, resulting in damage and loss of quality. Measurements on stamped plates, gears and worn areas of mechanical components indicate that defects can be mechanical or aesthetic. Based on wavelength, wave amplitude and roughness, both micro and macro defect characteristics can be identified, enabling distinguishes between mechanical and aesthetic. The aim of this study is to evaluate the technique and the most appropriate measurement parameters for different surface failure modes. To the development of this study, a conventional confocal microscope and a confocal microscope of chromatic aberration were used. Different parameters of acquisition and materials with different reflectivity characteristics were studied. The techniques were evaluated by capacity and functions of their respective equipment, both for measurement and analysis. The analysis of the results showed that the wavelength of the defect is the most relevant factor when characterizing the proper measurement technique. Equipment shall be especially assessed by resolution, measuring time and quality of image stitching tools. For failure modes with nanometer wavelength, it is appropriate to use conventional confocal microscopy. The technique using confocal microscopy of chromatic aberration was best suited to millimeter wavelength defects.*

***Keywords: Confocal Microscopy, Surface failure modes, Surface defects.***

## 1. INTRODUCTION

Surface defects are defined as geometric deviations from the real surface when compared to the designed geometry. Their origin is a function of the manufacturing processes, which create deformation incompatibility due to different material phases coexistence, different internal stress levels or temperature gradient occurrence. (WANG, GONG, 2002).

Failure can be defined as the inability of the component to correspond to the demand required. In For stamped sheet metals, surface defects are usually detected in the final product, resulting in damage and loss of quality. Defects can also be represented by wear and induce loss of function in case of components submitted to friction and contact forces. In addition, noise and vibration can be resultant from surface low quality. These failure modes are associated to sliding forces applied to uneven surfaces of rotating components (WANG, GONG, 2002; BRUSHAN, 2002; LECHNER; NAUNHEIMER, 1999).

In general, defects are represented by three main concepts: Form error, waviness and roughness. Each concept is classified regardless defect wavelength. Form error is characterized by very large wavelengths, typically above 50mm. Waviness components are millimetresized (1–10 mm). And roughness is indicated when high-frequent features of the profile with spatial deviations below 1 mm are measured (CLARYSSE; VERMEULEN, 2004; ANDERSSON, 2009).

There are several techniques for surface quantitative assessment. They are classified into the concepts of mechanical contact and optical models. Some of the techniques are atomic force microscopy, interferometry, confocal microscopy, and digital microscopy. Their concepts' difference also induces to distinct characteristics like resolution and accuracy. Each one has also its own restrictions as field dimensions, magnification and measurement time (BRUSHAN, 2002; BLAIS, 2004).

In the industry, the role of measurement strategy is crucial, and mistakes can result in inappropriate design of acquisition and measurement systems and misinterpretation of data. The study of Weckenmann, Knauer and Killmaier (2001) has provided a detailed list of all the factors that may induce error in measurement of parts.

Considering all potential surface failure modes and available measurement techniques, defining the suitable equipment and developing an optimized procedure is a hard and time consuming activity. Furthermore, if this step in not properly performed, two dangerous scenarios can take place. They are the incorrect technical conclusions and financial loss by a wrong equipment selection.

This work aims to assess and provide a proposal of parameters and measurement techniques most appropriate for different failure modes in various metal surfaces by confocal microscopy. The study will present a comparative approach for two confocal techniques: conventional and chromatic aberration. Sensitivity analyses will be conducted to optimize measurements parameters to a specific failure mode. The main expectative is to support researchers who need a literature review on measurement techniques for new confocal microscopes. The development of modern and accurate equipment is essential for industrial growth and economic development, although the technical use and parameters of these devices for new research lines are unknown.

## 2. LITERATURE REVIEW

### 2.1 Conventional confocal microscopy

Conventional confocal microscopy focuses the object along the beam direction and visualizes only the volume around the focal area. In general, a confocal microscope is constituted by a laser which corresponds to the light source projected on the sample. A scanner is a digitizer unit that moves the laser in order to focus the sample line by line. The Z focus control the specimen and acquire the image in sections in the plane XY. The photomultiplier, detects the photons emitted and / or reflected by the sample (HELL, 1992).

In the confocal microscopy technology, all the structures out of focus are eliminated in the image formation. It improves image definition and increase field depth in comparison to optical microscopy. Another advantage over conventional optical microscopy is that the confocal technique has the ability to divide optical images into sections for samples with wide depth range. It enables the subsequent overlapping of images to form a 3D image (MINSKY, 1961; FELLERS; DAVIDSON, 2005). Figure 1 shows the operating principle of confocal.

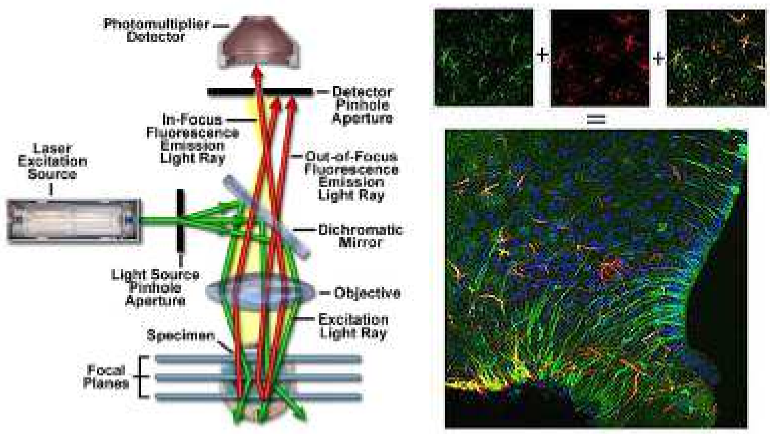


Figure 1 - Conventional confocal microscopy concepts (FELLERS; DAVIDSON, 2005).

### 2.2 Chromatic aberration confocal microscopy

This technique is based on the principle of colors' different wavelength for determining the depth under analysis. The confocal microlenses are responsible for creating the chromatic aberration over the light bean generated by the system. The light is spread in a full spectrum lighting and, thus, different wavelength rays. These incident lighting rays are reflected in the surface to several different directions, including back to the system detector. Depending on the sample topography on the analyzed region, there will be higher detection intensity for one specific color Figure 2. This color information is used for determining the wavelength to be input in the real depth calculation (TIZIANE et al, 2000; SHI et al, 2004).

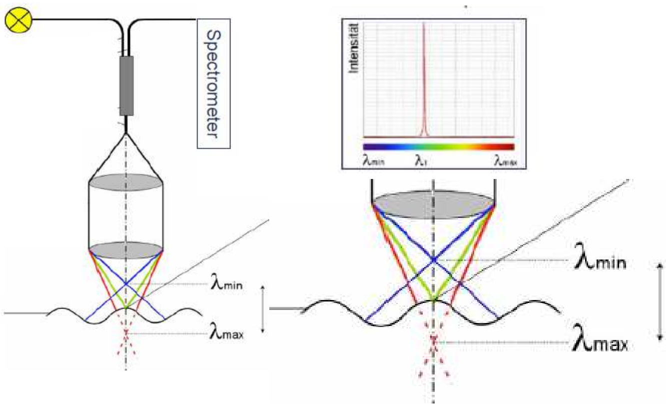


Figure 2 - Working principle of confocal microscope chromatic aberration (SHI et al 2004)

The main advantage of this technique is its high light efficiency and the possibility of measuring larger fields without reducing the numerical aperture. It presents different configuration variations for different applications. The topography of the sample can be determined by a color image, which leads to a reduction in measurement time. To reduce measurement time on curved surfaces, for example, it is useful to adjust the focal lengths of micro lenses to the individual shape of the object. Therefore, only the difference between the focal distribution and the actual shape is determined. (TIZIANE et al, 2000).

### 2.3 Optics

The image of the surface is formed by a set of pixels, each pixel receives a given intensity of light scattered by the amount corresponding point at the surface. A bright surface is the result of the scattered light concentrated around the specular direction. In surface characterized as mat, the scattered light is spread into a larger cone and the image received by human eye is less sensitive to the geometrical configuration (SANDOZ et al, 1996).

The human eye is very sensitive to discontinuities in the surface shape, especially with respect to buckle. The analysis of defects of form and curling is precisely related to the change of the gradient of the curvature. The higher the gradient, the higher will be the severity of the defect. The gradient is more sensitive to disturbance of the surface than to the variation in depth of the defect. Therefore, it becomes more relevant to evaluate the surface quality with respect to the curvature (ANDERSSON, 2009).

Despite the relevance of the surface gradient, defect geometry must still be evaluated. Among them, depth, angles and length should be highlighted. Mathematical models like “Raleigh” and “Beckmann-Spizzichino” propose algorithms to quantify the reflected beam lighting intensity. In addition, the defective surface cannot be assessed through one individual deviation analysis. All the defects must be analyzed inside a statistical approach, with the probabilistic distribution of the geometric feature. This approach is proposed in the models of “Torrance-Sparrow” and “Height Distribution” (NAYAR; IKEUCHI; KANADE, 1989; SHEN; CHEN; 2012; SANDOZ et al, 1996).

### 2.4 Profile geometry concepts

The use of filters follows the orientation of standards ISO 4287, ASM, DIN 4760. According to the ASM (1994), the term texture refers to the peaks and valleys in the surface produced by a particular process of manufacture. By convention, texture comprises two components: undulation and roughness. According to DIN 4760, the separation of roughness and waviness can be effected by spacing and depth of the irregularities of relief. Roughness is the set of irregularity, small protrusions and indentations that characterize a surface. The understanding of each concept allows the classification in four groups: Height, Spacing, Hybrid and Functional parameters. As defined by ISO 13565-2, several of the Height parameters can be identified for three-dimensional analysis by replacing “R” prefix by “S”. This means *Sa*, *Sz* and *Sq* have a similar mathematical model when compared to *Ra*, *Rz* and *Rq*, respectively.

Parameters *Rsk* (skewness) and *Rku* are classified as Height parameters. The skewness indicates the symmetry of the amplitude distribution over the midline profile. The negative value of skewness represents a surface condition typically with large valleys. Kurtosis is the measurement of the amplitude distribution slope. Both concepts are represented in Figure 3.

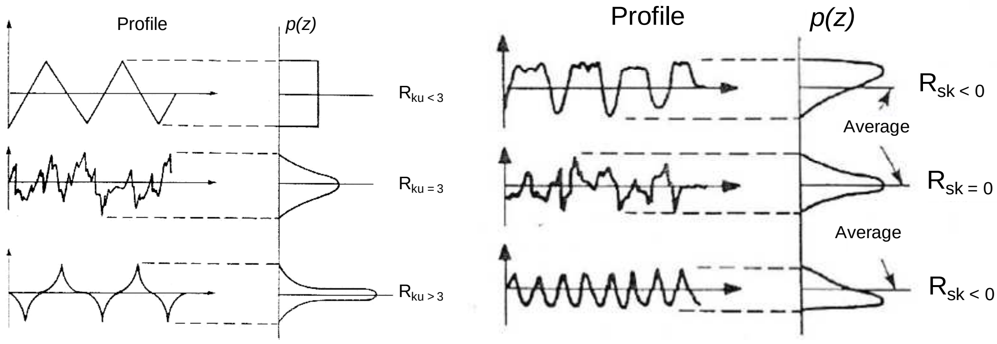


Figure 3 - Asymmetry amplitude distribution curve (ASME 1995).

When roughness analysis is linked to functional understanding, the Abbott-Firestone curve concept is applied. Also named “Bearing Area Curve”, it is used to define parameters *Rpk*, *Rk* and *Rvk* with the specific boundary definition *Mr1* and *Mr2* (DIN 4776 and ISO 13565-2). The definition of parameters and the distribution of the total area of contact are shown in Figure 4. Parameter *Rpk* is the value of the average roughness of the peaks that are above the minimum contact area of the profile, defined by *Mr1*. In the opposite way, *Rvk* is the value of the mean roughness in the valleys region, which is below the contact area as defined by *Mr2*. The parameter set as Rk and the central portion of the band roughness, in between *Mr1* and *Mr2* (SCHMÄHLING; HAMPRECHT, 2007). As defined by ISO 13565-2, the equivalent parameters of *Rk*, *Rvk* and *Rpk* for three-dimensional analysis are *Sk*, *Svk* and *Spk*.

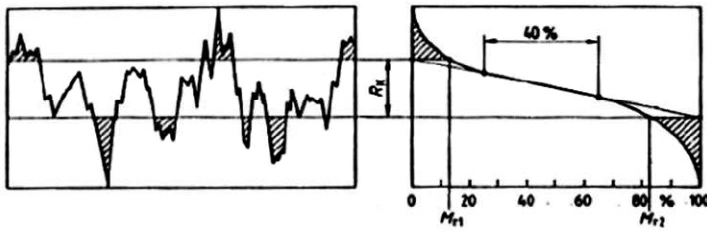


Figure 4 - Abbott-Firestone curve generation (CARVALHO, 2007)

## 3. MATERIALS AND METHODS

The scope of this study is basically composed in three parts:

1. Comparative analysis between both confocal techniques;
2. Sensitivity analysis on the equipment selected for a specific analysis;
3. Parameters definition for representing roughness defects.

The comparative study will be based on the analysis of image quality and measurement time. The measurements were performed with two equipment. Conventional confocal microscope measurements were performed with a Leica DCM3D. For chromatic aberration confocal microscopy technique, a Cyber CT 100 was applied, as shown in Figure 5.


Figure 5 - Chromatic aberration confocal microscope (left); Conventional confocal microscope (right)

With the selected equipment, the next step is to define the set of parameters to optimize image quality. Some of all the variables available in the equipment will be here explored. It includes option of lighting color and intensity, threshold, speed factor, step, exposure time and magnification.

The conventional confocal microscope has two lighting possibilities, white light and blue light. In addition, each source of light can be adjusted in regard of intensity. This adjustment is necessary for the reflectivity differences in between materials. The threshold is the variable associated to the confidence level of a measurement to be representative of a real point. The discretization step defines the quantity of layers that will compose final image and is directly linked to vertical resolution. The speed factor is responsible for the time of formation of each image layer, and the step influences the acquiring image time. A sophisticated lens system is highlighted on the conventional confocal microscope. The used equipment is composed by six lenses that vary from 2.5X to 100X of magnification.

In the available equipment of chromatic aberration confocal microscopy, it is only offered the option of white light, being only the intensity an adjustable factor. Variables such as step and threshold present analogous concepts for both equipment. Exposure is given in milliseconds. Although it varies inside a small scale, it plays a great influence on the quality of the final image. Different from conventional confocal microscope, it has sensors rather than an objective. The available equipment has two sensors: CHR-600 and CHR-3000. The first one has a resolution of 0.02µm and a measurement range of 600µm. The latest one has a resolution of 1.0µm and a measurement range of 3.000µm.

The criterion to evaluate the adjustment of these variables was the measured area. A poor adjustment results in several “dark” regions. In these points, data were not raised or, at least, with a minimum confidence level. Equipment software allows verifying the measured are with a percentage value, as shown on Figure 6. Acquisitions with less than 90% are not recommended.

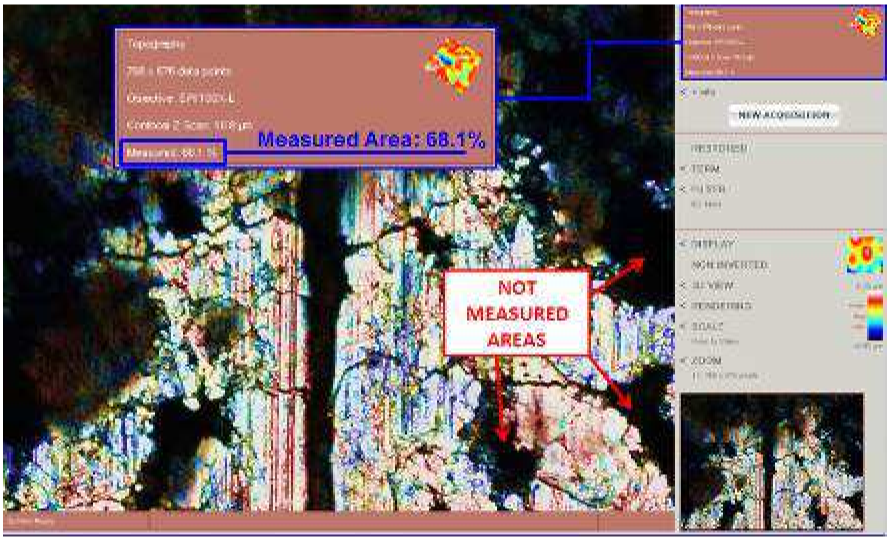


Figure 6 - Image quality verification with measured area criterion

Different samples were evaluated for each part of the scope. The techniques comparison was supported by the analysis of three specimens: an aluminum component with mechanical wear caused by a tribological test; a steel stamped component marked by scratches; and a vehicle panel with distortions caused by local buckling. These last two specimens were also submitted to the sensitivity analysis. The definition of the most suitable roughness parameters were performed with a gear tooth submitted to different shot peening processes. The Figure 7 shows a panel with images exemplifying each sample or failure mode analyzed.

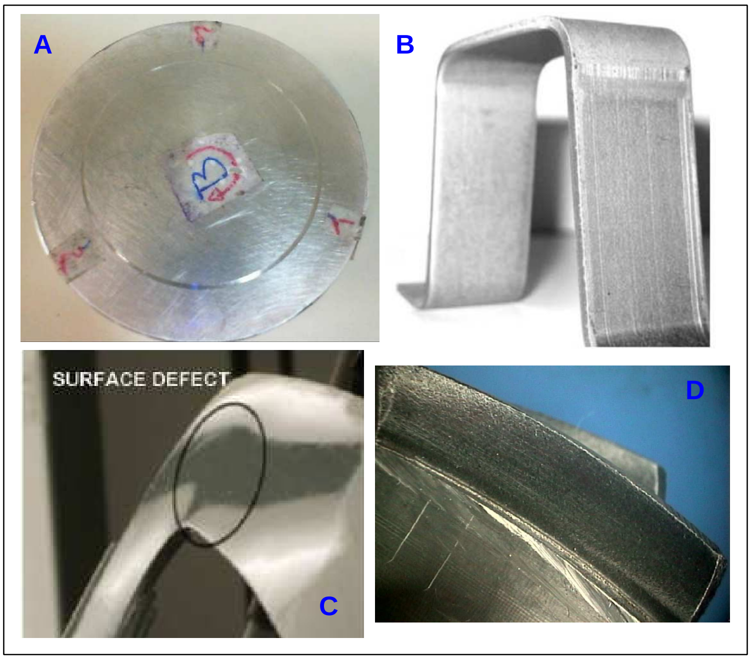


Figure 7 - Specimens and failure modes: (A) Aluminum disk after tribological test; (B) Scratched stamped sheet metal (PEREIRA; YAN; ROLFE, 2012); (C) Local bucking in vehicle component (LE PORT; THUILLIER; MANACHl, 2011); (D) Gear tooth after shot peening process.

## 4. RESULTS AND DISCUSSION

### 4.1 Techniques comparison

The first results presented are regarding the comparative analysis between both confocal techniques. The images acquired in each system and their corresponding profile graphs are shown in Figure 8. For both devices, it was possible to demonstrate the width of wear track due to this present millimeter width. The conventional confocal technique was applied with 20X magnification. For confocal of chromatic aberration, the sensor applied was the CHR 3000.

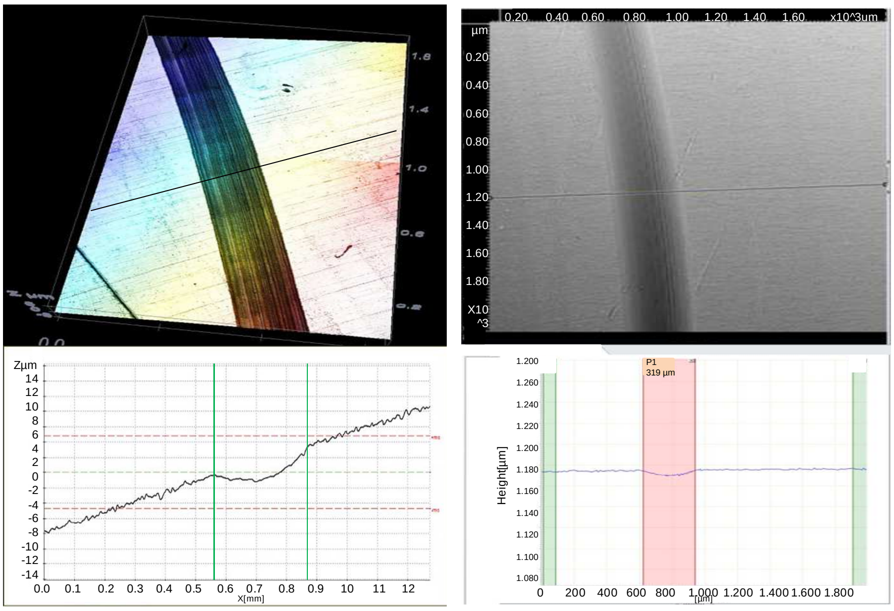


Figure 8 - Conventional confocal microscope image (left); Chromatic aberration confocal microscope image (right).

The analysis of both charts from Figure 8 can meet the analysis objective. The result of wear depth could be taken from both techniques. That was already expected from Leica system, once conventional confocal microscopy reaches higher magnification, being more appropriate to micro defects analysis. However, the defect depth in this case is in the order of 3 µm. This intensity is large enough to be measured by the chromatic aberration technique. The advantage of this last technique was the time employed, consuming approximately 50% less time. Going further, the quick performance allows the measurement of whole wear groove, so the wear profile could be analyzed.

In the following case, the scratches of stamped sheet metal are under analysis. The Figure 9 shows conventional confocal microscope image at the left side and chromatic aberration confocal microscope image at the right. Only the visual inspection would be enough to indicate the difference between the resolutions of the equipment. This study required extra attention to exposure criteria for being nanometer defects. For this study it was used lens with 100x magnification (higher precision equipment under study) in conventional confocal microscope. The confocal chromatic aberration was used with the higher precision sensor CHR 600.

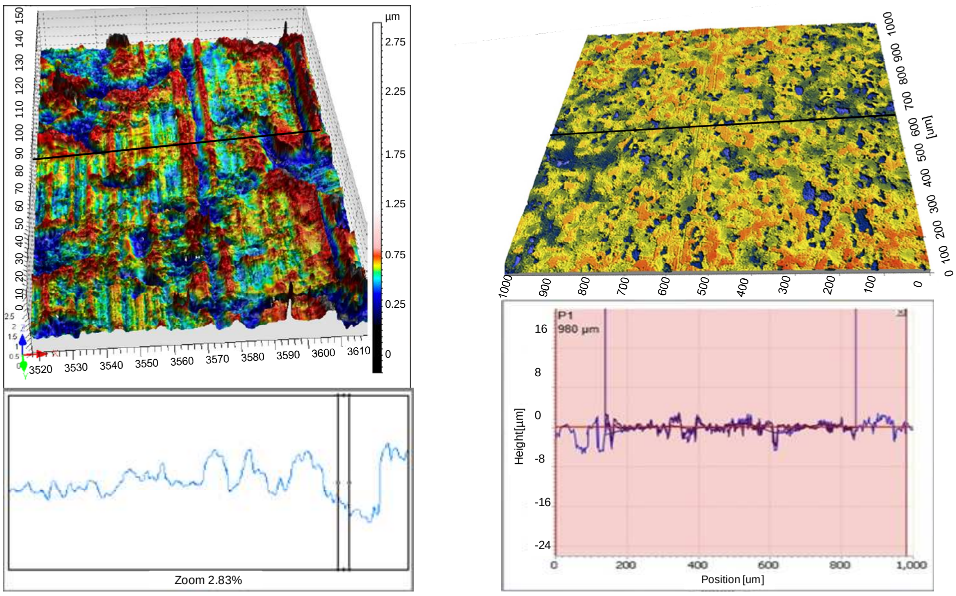


Figure 9 - Conventional confocal microscope image (left); Confocal microscope image chromatic aberration (right).

Besides roughness results, the study required the analysis of individual scratches in regard of width, depth and slope of the defect walls. The results in conventional confocal microscope allowed clear scratch identification and quantification. The same analysis was not possible with the aberration chromatic confocal microscope, once the technique was not sufficiently precise. This happened once the defect under analysis can now reach much lower intensities. The scratch depth varied in the range between 20 nm and 500nm, with median of 125 nm. And this intensity was not compatible with equipment resolution.

The last comparison analysis was performed over buckling defects in sheet metal samples. The defect is usual in large panels and the specimen investigated is much similar to the image of Figure 7(c). The measuring area is now increased from few millimeters to a quadratic area with edges of 100 mm. It required larger analysis fields and, in case of the conventional confocal microscope, the consequent usage of low magnification lens. Several images were acquired and joined with the stitching tool. Even though, it was not enough to allow complete image acquisition.

The defect is not any more a roughness feature but a waviness failure mode. The defects are characterized by a depth in the order of 50 µm with a wavelength around 40 mm. Not only the large area was an issue but the defect depth demanded constant focus adjustment from one image to the next one. And even automatically controlled, the focus was lost several times along the measurement. Another disadvantage was the time consuming. If the measurements would be completed, there was a system prediction of almost two hours.

The same sample was submitted to chromatic aberration confocal microscope. The image was completely formed and, after a sensitivity analysis, the measurement time was of about 2 min. Its working principle, not demanding to create several images for the same point, enables a quick scanning operation. It is therefore recommended for all waviness and form error failure modes.

### 4.2 Sensitivity analysis

In the timeline of defining the measurement procedure, the next step after selecting the equipment is the sensitivity analysis. The purpose is to optimize the results for the specific specimen particularities. The first analysis performed was with the Leica equipment for the scratched sheet metal specimen.

Based on the graphic correlation between the intensity of light per area measured, it was possible to observe with Figure 10 the existence of an optimal point in adjusting the light emission. The variation is due to the material reflectivity and specularity. The later developed expertise with this parameter enabled further optimization. But it depended on other factors to reach a maximum level of utilization (100%).

In the threshold evaluation (also Fig. 10 it was possible to observe that it should be selected taking into account mainly the evaluation regions of interest. It was noted that with the variation of this parameter in the sense of approximation to zero results in maximizing the image. However, this analysis cannot be taken just by looking the area measurement percentage. As much as it gets close to zero, the higher is the possibility of appearing peaks that does not represent the actual surface. It is therefore recommended a coupled analysis between the measured area (%) and a visual inspection of the three-dimensional graph.

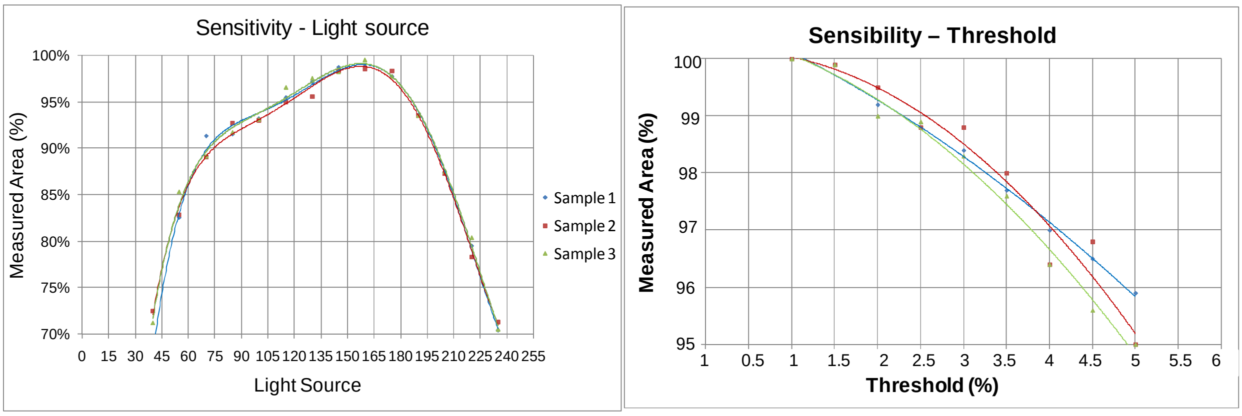


Figure 10 - Correlation between light intensity and measured area (left); Correlation between threshold and measured area (right).

In the graphs of Figure 11, it is possible to see the influence of acquisition speed and light color. The speed is related to the vertical step. In consequence to an excessive increase in speed, the step also increases also and therefore the final image quality decreases. The usage of different light colors, despite of both having achieved a good level acquisition, shows a percentage of wide variability in image quality. For this study the white light stood out and resulted in better definition.

The observation that can be made about blue light is that it arrives in the surface with less intensity, because it induces lower reflectivity. As described previously, confocal microscopy works focusing and capturing light imaging. In this case the white light causes a higher reflectivity for both reflexive and opaque surfaces, bringing better results.

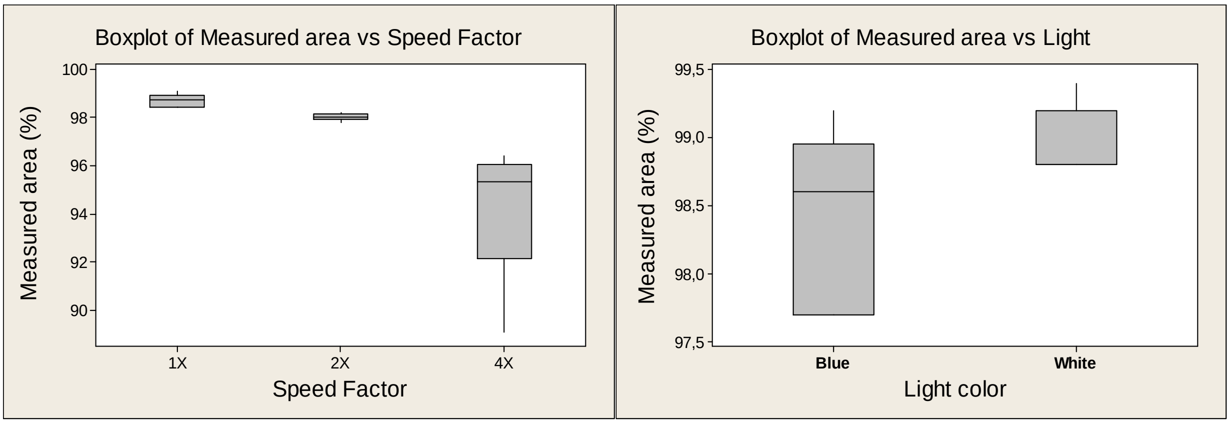


Figure 11 - Correlation between speed factor per measured area (lefty); Correlation between light color per measured area (right).

When it comes to the correlation of parameters for the chromatic aberration confocal microscope, there were applied the same concepts of the previous definition of acquisition parameters. Making an analogy between the related parameters, and applying in specimens from stamped sheet metal, it was possible to draw up Table 1. For this equipment the exposure behaves as the light intensity in conventional confocal microscope. For less reflective surfaces it is essential that the exposure is increased.

Table 1 - Interactive method for the definition the parameters of confocal microscope chromatic aberration.

| Parameter | | | | |
|---|---|---|---|---|
| **Threshold [%]** | **Exposure [ms]** | **step [mm]** | **Light [%]** | **Vertical resolution (nm)** |
| 0 | 0.25 | 0.05 | 15 to 100 | 20 |
| 1 | 0.5 | 0.1 | | 100 |
| 5 | 0.8 | 0.2 | | |
| 10 | 1 | 0.5 | | |

The Figure 12 shows an image with loss of acquired points due to incorrect parameters selection. These not measured areas are indicated with white arrows. All factors must be observed, but in this case two deserve greater attention. This picture had missed resolution due to low exposure and incorrect light selection.

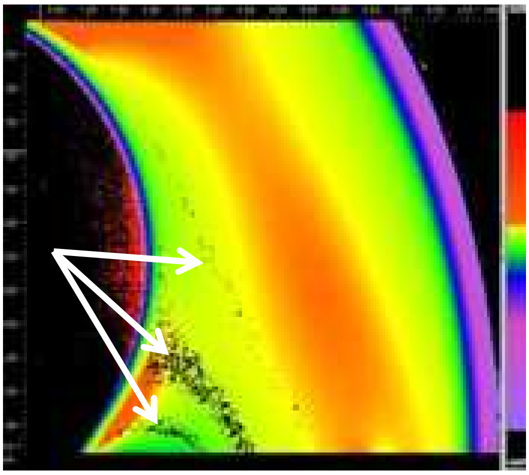

Figure 12 - Image with lost points

The sensitivity analysis confirms that one of the biggest advantages of confocal microscope chromatic aberration was the acquisition speed (Table 2). It is also possible to observe that equipment has greater simplicity in defining the parameters for analysis. Because the confocal microscope chromatic aberration have been shown to be robust and satisfactory, images produced for the study discussed in this table has been addressed only the step factor. Two images in the same region were evaluated with different steps. There was observed no significant difference in order of magnitude and, on the other hand, gain time was paramount surpassing 100% increase.

Table 2 – Sensitivity analysis of lateral step.

| **Indicator** | **Step 0.2mm** | | **Step 0.5mm** | | **Difference** | |
|---|---|---|---|---|---|---|
| Time(Min) | 05:05 | | 02:07 | | **02:58** | |
| Angle(°) | 0.06 | 0.1156 | 0.056 | 0.1248 | **0.004** | **0.0092** |
| Height(mm) | 0.0249 | 0.0487 | 0.0217 | 0.0442 | **0.0032** | **0.0045** |
| Reference | x | y | x | y | | |
| Length(mm) | 79 | 52 | 79 | 52 | - | |

## 4.3 Roughness parameters selection

The analysis of the parameters for defining roughness quality was performed with the shot peened gears. In this study, there were applied four different process sets, each one with a media size. From Set#1 to Set#4, the media size was reduced. The media diameters are very small, in the order of 0.5 mm. The indentation is directly associated with the diameter, creating surface irregularities of few microns. Therefore, the surface measurements were conducted with a conventional confocal microscope. This study aims at objectively evaluating the surface homogeneity produced by each peening treatment. The images, made with 20X lens, are represented as contour charts on Figure 13. At the right side, a color scale defines the height amplitude of surface defects.

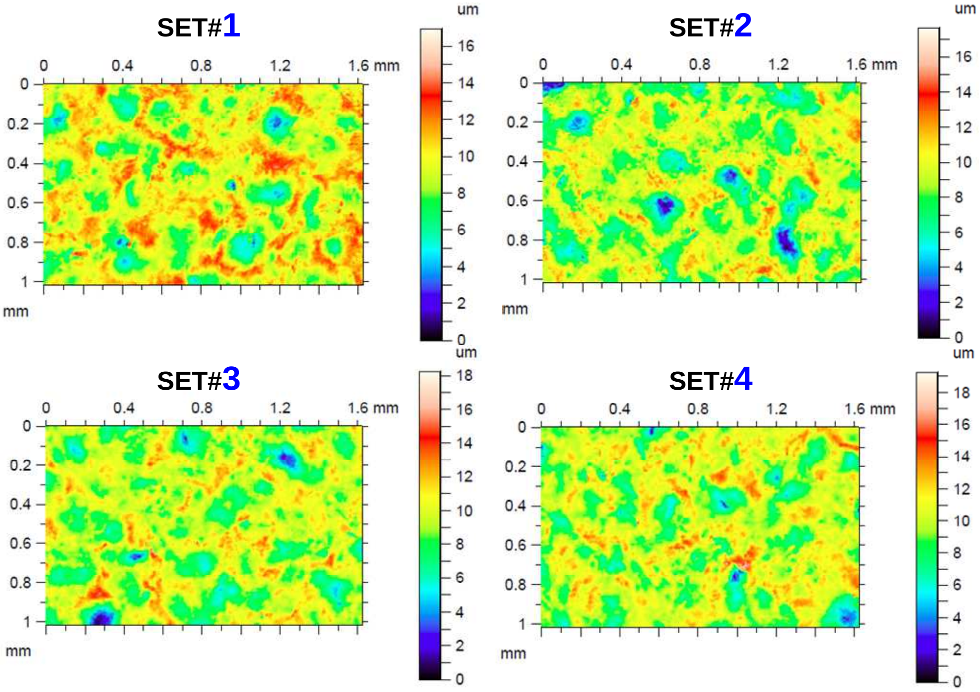


Figure 13 - Confocal microscopy images of shot peened gears

A comparative look into the charts allows the conclusion that the Set#1 has the less regular surface. The colored scale map shows higher amplitude points and less homogeneity on this first treatment. In the same image, the indentation circular shape is clearly defined by the high amplitudes surrounding the lower points. Both the higher amplitudes and the indentation shapes gradually disappear from Set#1 to Set#4. This is reflecting the media size reduction, which finds the lowest value at Set#4. In the objective of quantitatively representing this observation, both height and functional roughness parameters were analyzed. They were respectively calculated with Sa (spatial average roughness) and Sk (spatial core roughness of a bearing area curve) parameters. Their results, with error bars, are shown in Figure 14. The Sk boundary limits Mr1 and Mr2 were defined as 10% and 80%, according to ISO 13565.

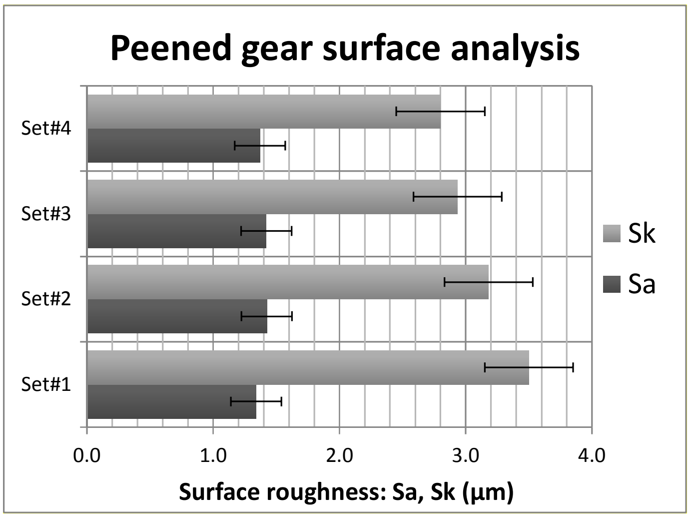


Figure 14 - Height and functional roughness parameters for analyzing peened gear

The observation from the contour chats is not reproduced by Sa results. In this height roughness analysis, all of the treatments are not statistically differentiated. In the other hand, the functional parameters analysis goes in agreement with subjective evaluation. The value of Sk is gradually reduced from Set#1 to Set#4. The understanding of this difference is based on the concept of each parameter. The Sa values calculates the mean deviation of data collected and Sk computed this data only in the core region, between Mr1 and Mr2 boundary limits. With the height restriction, Sk results avoid sampling the unevenness of large peaks and deep valleys, potentially coming from insufficiently prepared samples measurement issues. In this case, where the defect shape is previously known (round indentations), the functional parameter works as an advanced filter and enables better results than height roughness parameters.

## 5. CONCLUSIONS

With the present study, it was concluded that it is extremely important for the researcher to watch out for the purposes of the project at the equipment selection time.

The conventional confocal microscopy showed better performance with micro defects. Small surface geometries, as scratches with depth as low as 20 nm, can be clearly identified and quantified in regard of width and wall slope. However, this performance is not repeated with large wavelength defects. Due to its operating principle, focus adjustment during stitching operations may not properly follow profile variation and image loss is the immediate consequence.

The chromatic aberration confocal microscopy is considered to be the best alternative for milimetric surface defects. Large panels buckling defects in regions of 1000 m² can be evaluated in only 2 min. Its working principle, not demanding to create several images for the same point, enables a quick scanning operation. Analogically, its resolution limits the analysis for defects of not less than few microns of depth. In this case, as experimented with wear profiles, both techniques were precise enough. Chromatic aberration confocal microscopy would be defined by the time saving provided.

The results from the sensitivity analysis performed shows how underutilized would be the equipment if not properly set. This conclusion is clearly perceptible with the light intensity adjustment. A slight adjustment can increase the measured area from 70% to almost 100%. As a concrete contribution, this article suggests in the end of this topic, through table 3 and table 4, some parameters set for both techniques. It must be obviously adjusted for each specific specimen, but it can be seen as an initial proposal by a surface researcher.

Finally, the article discusses the importance of defining the correct surface analysis parameter. There is a traditional concept that roughness must be measured by height parameters as *Ra*, *Rz* or *Rq*. The shot peened gears analysis showed that the function of the surface must be understood in order to propose the parameters that will properly quantify the subjective assessment.

Table 3 – Techniques for conventional confocal microscope

| Parameter | Zones worn mechanical components | Sheets stamped for verification of scratches |
|---|---|---|
| Lens | 20 x | 100 x |
| Light | White | White |
| Light intensity | 100 to 150 (Observe reflectivity of the material) | 115 to 145 (Observe reflectivity of the material) |
| Threshold | 1.5% | 1.5% |
| Resolution | 1µm | 1µm |
| Measurement | Extend Topography (use only if need more than one field) | Extend Topography (use only if need more than one field) |
| Z scan | Symmetric(whenever possible) | Symmetric (whenever possible) |
| Speed factor | 1x | 1x |

The Table 4 lists the recommended techniques for confocal microscope chromatic aberration.

Table 4 - Techniques for confocal microscope chromatic aberration

| Parameter | Zones worn mechanical components | Sheets stamped for verification of scratches |
|---|---|---|
| Acquisition mode | Scan | For this kind component could not identify the standard techniques of sufficiently satisfying |
| Sensor | Higher speed lower resolution | |
| Light intensity | 62 to 80% (vary according to the reflectivity of the material) | |
| Threshold | 0% | |
| Step | 100µm | |
| exposure rate | 0.8ms | |

## 6. ACKNOWLEDGMENTS

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