ISSN 1516-392X

STATISTICAL ANALYSIS OF FUNCTIONAL ROUGHNESS PARAMETERS OBTAINED FOR GROUND SURFACES OF STEELS[1]

Giuseppe Pintaúde[2]
Gustavo Takehara[3]
Pedro Luiz Fiad do Amaral[4]

Abstract
This paper analyzed the variation of functional roughness parameters, useful to calculate the real contact area, for nineteen specimens divided in two groups of materials, where nine of them were of SAE 1010 steel and the remainder of SAE 1045 steel. All specimens were subject to plane grinding, using the same process parameters for both materials. The ground surfaces were analyzed in a white light interferometer. The functional roughness parameters were used to calculate the bandwidth parameter, using a routine previously tested for a bearing steel. Based on the statistical variation observed for Sq parameter, the specimens were reclassified in four groups only, which allowed discussing some care required in order to prepare specimens for tribological tests.
Key words: Functional roughness parameters; Contact area; Grinding.

[1] *Technical contribution to 68th ABM International Congress, July, 30th to August 2nd, 2012, Belo Horizonte, MG, Brazil.*
[2] *Metalurgical engeneer. Prof. Dr., Post-Graduation Programme in Mechanical and Materials Science Engineering, UTFPR, Câmpus Curitiba. Curitiba, PR, Brazil.*
[3] *Undergratuated student of Mechanical Engineering at UTFPR, Câmpus Curitiba. Curitiba, PR, Brazil Eng. Mecânico, Prof., Departamento Acadêmico de Mecânica, UTFPR, Curitiba. Curitiba, PR, Brazil.*
[4] *Metalurgical engeneer. Prof. Academic Departament of Mechanics, UTFPR, Curitiba, PR, Brazil.*

ISSN 1516-392X

1 INTRODUCTION

Characterizing metallic surfaces is an important step after manufacturing processes, because most of the mechanical applications depend on the surface design. In Tribology, some roughness parameters are defined as functional, because they can be related directly to the contact area.(1). The product among the summits radius with the density of summits and the standard-deviation of summits height is usually considered as constant for each manufacturing process.(2)

Nonetheless, for a same process, different variables can cause fluctuations on roughness parameters, and consequently, the contact area can change when the resulted surfaces are put in service. In the case of plane grinding, largely employed to reach surface flatness, there are lot of variables that can disturb the final roughness, such as the lubricant flow and the wear of grinder.

This work aims to describe the variations of 3-D functional surface roughness of ground steels, prepared with the same parameters. As a result, careful on specimens' preparation for tribological tests using grinding can be indicated.

1.1 Definitions

There are 14 main 3-D parameters belong to a group known as S. They can be classified in five types: amplitude, spacing, hybrid, fractal and others, as described in Table 1.

Table 1: Family of S parameters

FAMILY OF 'S' PARAMETERS				
AMPLITUDE PARAMETERS	**SPACING PARAMETERS**	**HYBRID PARAMETERS**	**OTHER PARAMETERS**	**FRACTAL PARAMETER**
Root-mean square deviation - Sq	Density of summits- Sds	Arithmetic mean peak curvature - Ssc	Texture direction - Std	Fractal dimension – Sfd
Skewness - Ssk	Fastets decay auto -correlation lenght - Sal	Root-mean square slope - Sdq	Ten points height of surface– S5z	
Kurtosis - Sku	Texture aspect ratio - Str	Developed interfacial área ratio - Sdr		
Maximum peak/valley - Sp, Sv				
Maximum height – Sz				

Here, we will especially mention three parameters – Sq, Sdq and Sds – because they are directly related to the contact area definition. First of them, the Sq parameter, or the root-mean-square deviation of the surface, can be defined as a dispersion parameter defined as the root mean square value of the surface departures within the sampling area.(3) Formally, Sq is given by:

$$Sq = \sqrt{\frac{1}{MN}\sum_{j=1}^{N}\sum_{i=1}^{M}\eta^2(x_i,y_j)} \quad (1)$$

ISSN 1516-392X

Where,
M is the number of points of per profile;
N is the the number of profiles; and
η (x_i,y_j) is the the data set of the rough surface or the wavy surface or the primary surface texture, depending on a requirement of the surface analysis.

Another functional parameter is the Sds, defined as the number of summits contained in a unit sampling area:[4]

$$\text{Sds} = \frac{\text{Number of summits}}{(M-1)(N-1)\Delta x\,\Delta y} \tag{2}$$

Where the product ΔxΔy corresponds to the dimensions of the measured area.

It is very important to point out that the number of summits to be considered is the already established by EUR 15178 N report,[5] which defines that a point will be a summit if it higher that its 8 neighbors. Here, this definition will be obeyed.

Finally, the Sdq parameter is described as the root-mean-square slope of the surface [3] and it can be calculated using the Lagrange's polynomial for seven points along orthogonal directions, as follows:

$$\text{Sdq} = \sqrt{\frac{1}{(M-6)(N-6)}\sum_{j=4}^{N-3}\sum_{i=4}^{M-3}\rho_{ij}^2} \tag{3}$$

where:

$$\rho_{i,j} = \left(\left\{\frac{1}{60\Delta x}\left[-\eta(x_{i-3},y_j)+9\eta(x_{i-2},y_j)-45\eta(x_{i-1},y_j)+45\eta(x_{i+1},y_j)-9\eta(x_{i+2},y_j)+\eta(x_{i+3},y_j)\right]\right\}^2 + \left\{\frac{1}{60\Delta x}\left[-\eta(x_i,y_{j-3})+9\eta(x_i,y_{j-2})-45\eta(x_i,y_{j-1})+45\eta(x_i,y_{j+1})-9\eta(x_i,y_{j+2})+\eta(x_i,y_{j+3})\right]\right\}^2\right)^{1/2}$$

unctional roughness parameters can be expressed using only one variable, defined as bandwidth parameter (α),[6] given by:

$$\alpha = \frac{m_0 m_4}{m_2^2} \tag{4}$$

In equation (4) m_0, m_2 and m_4 are known as the spectral moments of zero, second and fourth order, respectively, and they are represented by equations 5, 6 and 7. Profiles are described by height z and spacing x, and function E is the corresponding expectation.

$$m_0 = E(z^2) \tag{5}$$

$$m_2 = E\left\{\left(\frac{dz}{dx}\right)^2\right\} \tag{6}$$

ISSN 1516-392X

$$m_4 = E\left\{\left(\frac{d^2z}{dx^2}\right)^2\right\} \tag{7}$$

It is possible to assume that the spectral moment of zero-order is equivalent to the square deviation of surface height. In the same way, m_2 can be associated to the average slope. Thus, the following equations can be defined:

$$m_0 = (Sq)^2 \tag{8}$$

$$m_2 = (Sdq)^2 \tag{9}$$

On the other hand, the density of summits is a function of m_2 and m_4 simultaneously:

$$Sds = \frac{m_4}{m_2}\frac{1}{6\pi\sqrt{3}} \tag{10}$$

Isolating m_4 in equation (7) and substituting m_2

$$m_4 = Sds.(Sdq)^2.6\pi\sqrt{3} \tag{11}$$

Putting the equations (8), (9) and (11) into equation (4), α can be calculated from 3-D parameters as follows:

$$\alpha = \frac{Sq^2 Sds.Sdq^2 6\pi\sqrt{3}}{(Sdq^2)^2} = \frac{Sq^2 Sds.6\pi\sqrt{3}}{Sdq^2} \tag{12}$$

2 EXPERIMENTAL

The specimens were divided in two groups, depending on their geometry and material. The first one (group A) was manufactured in 1010 steel, prepared from a rolled bar with 3" diameter. The Vickers hardness of steel is 194 ± 7. The bar was initially machined to obtain the following diameters: 70, 65, 60, 55, 50, 45, 40, 35 and 30 mm. Afterwards, they were cut to 50 mm length. Figure 1 illustrates the final dimensions of specimens.

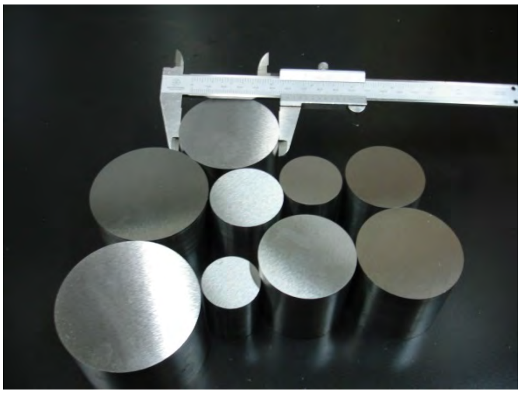


Figure 1: Specimens manufactured in 1010 steel.

ISSN 1516-392X

The other group of specimens was prepared in 1045 steel (Group B). The Vickers hardness of this material is 223 ± 4. The raw bar had 3” diameter, and in this case, all specimens were firstly machined to obtain the same diameter of 56 mm and 20 mm length. Their final dimensions are illustrated in Figure 2.

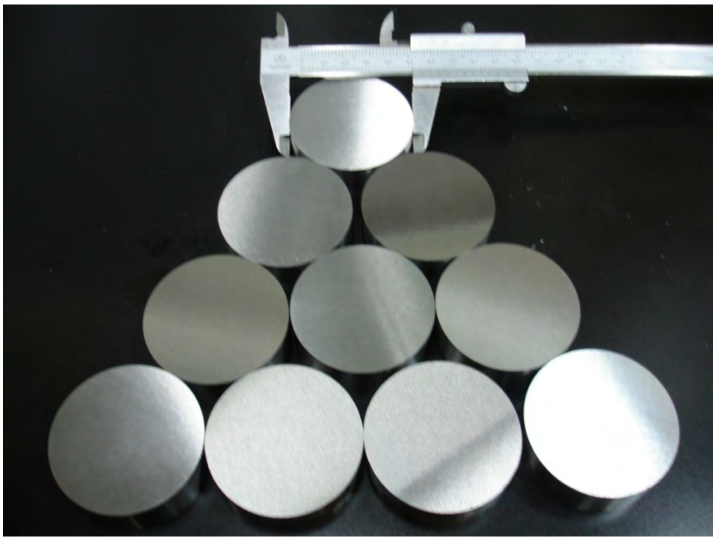


Figure 2: Specimens manufactured in 1045 steel.

All specimens of were fixed at the same time on the magnetic table belong to tangential plane grinder, as illustrated in Figure 3. Table 2 presents the grinding parameters used to machine all specimens.

Figure 3: Illustration of specimens’ disposal before grinding.

Table 2 – Grinding parameters used to prepare the specimens

Longitudinal velocity of plane	Transversal velocity of plane	Cutting velocity	Work depth	Grinder	Lubricant
32.5 mm/s	10 mm/min	32.5 m/s	0.030 mm	AA80K60V2	Emulsion at 2%

The roughness measurements were performed using a Taylor-Hobson CCI Lite non-contact 3D optical profiler, which works based on the white light interferometry. For each image, a magnitude of twenty times was applied, giving rise to areas of approximately 3.25 mm^2. Each average value was a result of three measurements, made in the positions indicated in Figure 4.

ISSN 1516-392X

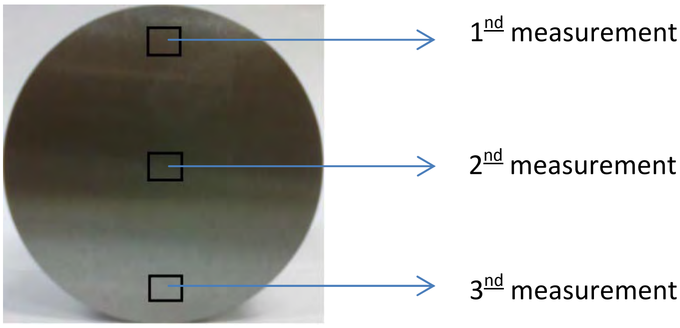


Figure 4: Approximated areas used to measure 3-D surface roughness.

To validate the procedure, a sample was extracted from an inner bearing rolling (FAG code 6204). This sample was prepared using conventional metallographic procedures, such that the final surface quality was polished. Three measurements of surface roughness parameters were made, resulting in an average value of 14 ± 2 for the bandwidth parameter.

Comparing this value with those reported by Zavarise, Borri-Brunetto e Paggi(7) for a stainless steel and for zirconia, and those described by Pintaude et al.(8) for 52100 steel, it is possible to consider the applied routine as valid.

3 RESULTS AND DISCUSSIONS

In order to help the reading, the specimens of group A are numerated from 1 to 9, while those of group B receive numbers from 10 to 19.

Table 3 shows the average results for Sa, Sq, Sdq and Sds of specimens belong to group A.

Table 3 – Average values of roughness parameters for specimens belong to group A

C.P.	Sa (μm)	Sq (μm)	Sdq	Sds (μm^{-2})	Alfa
1	1.8 ± 0.2	2.2 ± 0.2	0.26 ± 0.002	13300 ± 200	32
2	3 ± 1	4 ± 1	0.27 ± 0.005	13920 ± 70	93
3	2.2 ± 0.3	2.7 ± 0.4	0.27 ± 0.003	15200 ± 200	50
4	2 ± 0.3	2.4 ± 0.3	0.22 ± 0.05	13000 ± 4000	49
5	4 ± 2	5 ± 3	0.25 ± 0.004	12200 ± 200	164
6	2.5 ± 0.1	3.1 ± 0.1	0.31 ± 0.03	15000 ± 400	49
7	2.7 ± 0.5	3.3 ± 0.6	0.31 ± 0.04	13800 ± 600	51
8	5 ± 2	6 ± 3	0.28 ± 0.002	12800 ± 200	190
9	3.2 ± 0.4	4 ± 0.5	0.29 ± 0.04	12700 ± 300	80

Within the specimens, a little variation could be observed for Sdq and Sds parameters. Unlike, in some cases the variation in Sq could be considered high, especially for specimens 2, 5 and 8, where the coefficient of variation reached 50%. This aspect will be analyzed comparing the results obtained for group B, presented in Table 4.

ISSN 1516-392X

Table 4 – Average values of roughness parameters of ground specimens belong to group B

C.P.	Sa (μm)	Sq (μm)	Sdq	Sds (μm^{-2})	Alfa
10	1.2 ± 0.1	1.5 ± 0.1	0.23 ± 0.004	14000 ± 200	19
11	1.8 ± 0.4	2.2 ± 0.4	0.25 ± 0.005	14000 ± 400	34
12	2.1 ± 0.8	3 ± 1	0.24 ± 0.002	13670 ± 40	50
13	1.7 ± 0.2	2.1 ± 0.3	0.24 ± 0.001	13400 ± 500	34
14	1.3 ± 0.5	1.7 ± 0.6	0.27 ± 0.05	14700 ± 600	20
15	1.2 ± 0.2	1.5 ± 0.3	0.24 ± 0.009	15790 ± 60	21
16	1.2 ± 0.1	1.3 ± 0.1	0.24 ± 0.003	16020 ± 70	16
17	2 ± 0.9	2 ± 1	0.25 ± 0.003	13900 ± 300	45
18	1.2 ± 0.1	1.5 ± 0.1	0.24 ± 0.001	14700 ± 400	19
19	1.9 ± 0.4	2.4 ± 0.1	0.26 ± 0.001	14800 ± 100	43

In the same way to that observed for group A, within the studied parameters, Sq (and also Sa) presented the highest variation in specimens of group B. It is notable the high stability of parameters Sdq and Sds. Moreover, in general, one can be considered that the Sq values of group B were smaller than those described for group A, although the same parameters of grinding were used for both group of specimens. The result of this is that the bandwidth parameter had less variation for group B (16 until 50), while for group A, a very large range of values can be perceived (32 until 190).

A way to check if the surfaces have a Gaussian distribution of heights is to compare the Sa and Sq values. Plotting nineteen average values of Sa and Sq, we found a linear relationship (Figure 5), with a coefficient of determination equal to 1.2356, a quite similar value found by Krundak, Gyani e Bana[9] for ground surfaces notably Gaussian.

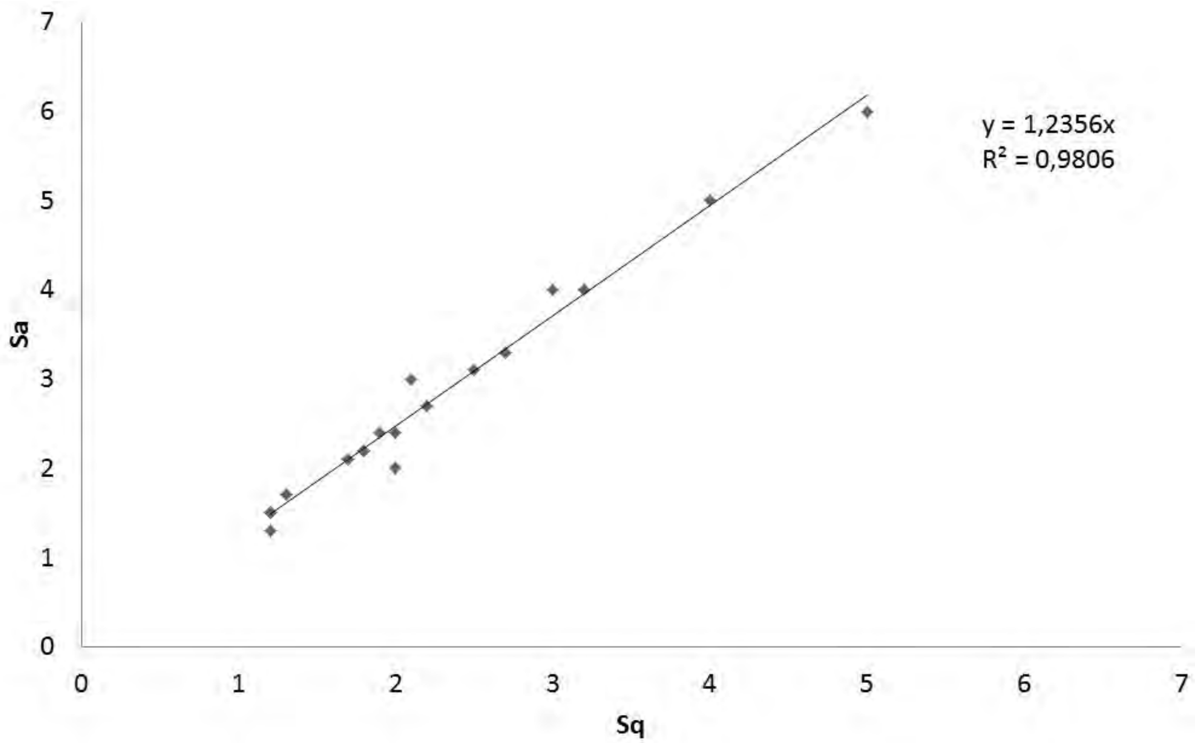


Figure 5: Relationship between Sa and Sq, considering nineteen average values.

ISSN 1516-392X

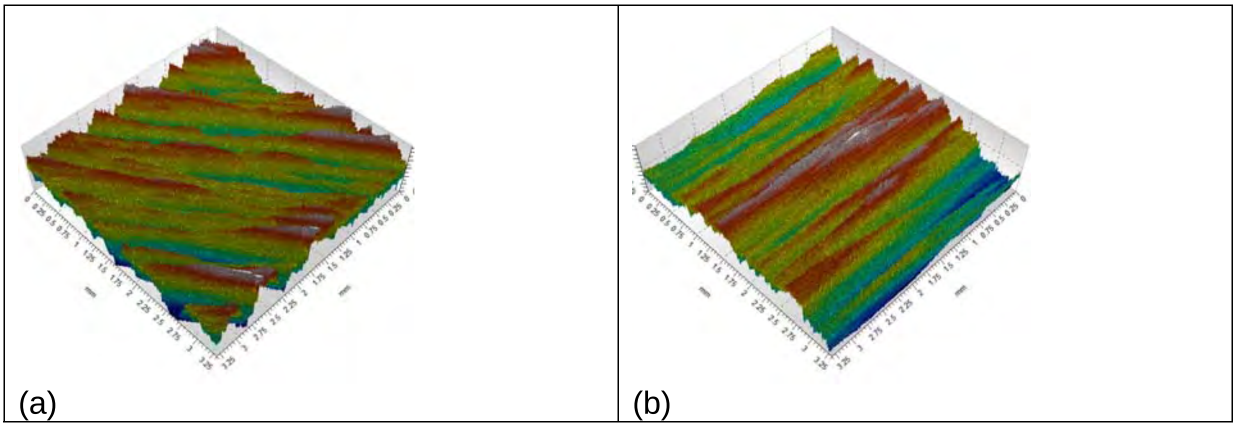
Considering now the high variation observed in Sq values, this parameter was used to separate the specimens in different groups (G1 to G4), according to the one-way analysis of variance (ANOVA), applied with significance level of 5%. The specimens associated to each rearranged group are presented in Table 5. Also, it shows the average values of Sq, Sdq and Sds parameters for these groups of specimens, and the correspondent bandwidth parameter.

Table 5 – Average values of Sq, Sdq, Sds parameters and alfa value of rearranged groups after ANOVA

GROUP	Specimens	Sq (μm)	Sdq	Sds (μm^{-2})	Alfa
G1	10, 14, 15, 16, 18	1.5 ± 0.3	0.24 ± 0.02	15000 ± 800	19
G2	1, 4, 11, 12, 13, 17, 19	2.3 ± 0.6	0.25 ± 0.02	14000 ± 700	41
G3	3, 6, 7	3.1 ± 0.5	0.30 ± 0.03	14700 ± 800	51
G4	2, 5, 8, 9	5 ± 2	0.27 ± 0.02	12900 ± 700	144

The variation of bandwidth parameter can be considered as huge for specimens manufactured in a same process. Specimens of G1 show an alfa value close to that obtained for polishing, while the bandwidth parameter of G4 group is one order of magnitude high. For tribological purposes, although all specimens of 1010 steel were ground at the same time and using the same processing parameters, they could not be design for the same application.

The rearranging of groups led the specimens of 1010 steel (1 and 4) to stay together with those of 1045 (11, 12, 13, 17 and 19), regardless their differences in properties and heights. This is a surprisingly result, because the grinding operations for each steel was not performed at the same time. Figure 6 illustrates the surface similarity found for specimens 1 (1010 steel) and 11 (1045 steel). It is possible to see the anisotropic character of surfaces.



(a) (b)

Figure 6: Surface images of ground specimens: a) Specimen 1, first measurement; and b) Specimen 11, 2nd measurement.

Therefore, other variables were more important than the difference of materials to the resulted surface roughness. Machining at the same time specimens of different diameters certainly affect the mechanical efforts, changing the mechanical contact between the grinder and each specimen. When specimens with the same diameter were ground, a smaller average roughness values were obtained, showing the importance of the configuration of specimens during the machining. Figure 7 shows the differences in surface characteristics found for specimens 15 (G1), 7 (G3) and 8 (G4).

ISSN 1516-392X

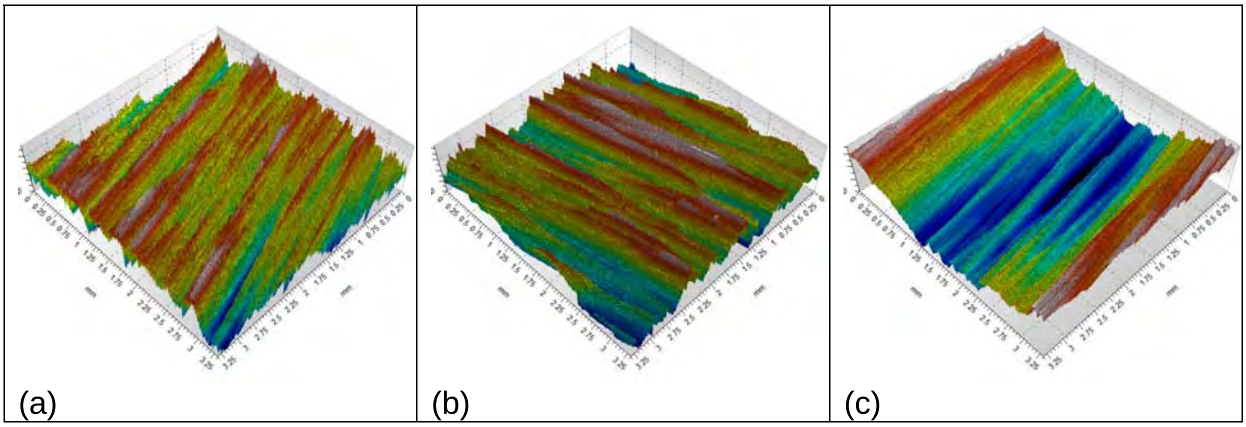


Figure 7: Surface images of ground specimens: a) Specimen 15, 3rd measurement; b) Specimen 7, first measurement; and c) Specimen 8, first measurement.

Figure 7 (c) shows, besides the very high value of average roughness, a notable difference in flatness, which can be a result of the interaction of grinder and the edge of specimen, a region where the mechanical efforts may have presented significant variations.

4 CONCLUSIONS

A 3-D surface characterization of ground steels was presented. Functional roughness parameters were analyzed, and within them the Sq parameter presented the largest deviations. As the identical grinding parameters were used in all experiments, it is recommended to check the variation in the bandwidth parameter when the specimens will be submitted to the systems involving contact problems and tribological applications. In this study, this parameter varied up to one order of magnitude, even using the same grinding parameters.

REFERENCES

1 McCool, J.I. Relating profile instrument measurements to the functional performance of rough surfaces. Journal of Tribology, 1987, p. 264-270.
2 D. J. Whitehouse, DJ; Archard, JF. The Properties of Random Surfaces of Significance in their Contact, Proc. R. Soc. Lond. A, 1970 vol. 316, p. 97-121.
3 Blunt, L.; Jiang, X. Advanced Techniques for Assessment Surface Topography. Butterworth Heinemann, 2003, p. 17-41.
4 Dong, W.P.; Sullivan, P.J.; Stout, K.J. Comprehensive study of parameters for characterising three dimensional surface topography: 3 - Parameters for characterising amplitude and some functional properties. Wear, v.174, 1994, p.29-43.
5 Stout KJ, Matthia T, Sullivan P J, Dong W P, Mainsah E, Luo N and Zahouani H, The Development of Methods for the Characterisation of Roughness in Three Dimensions, Report EUR 15178 EN, EC Brussels, 1993.
6 McCool, J.I. Comparison of models for the contact of rough surfaces. Wear, v. 107, 1986, p. 37-60.
7 Zavarise G., Borri-Brunetto M., Paggi M., On the resolution dependence of micromechanical contact models, Wear, 262, 2007, p. 42-54.
8 Pintaude, G.; Brunetti, C.; Leite, M. V.; Montanez-Calao, L. F. Effect of surface finishing on the elastic contact area evaluation of austempered ductile iron. Lubrication Science, v. 25, 2013, p. 101-109.
9 Krundrak, J.; Gyani, K.; Bana, V. Roughness of ground and hard-turned surfaces on the basis of 3D parameters. Int. J. Adv. Manuf. Technol., v. 38, 2008, p. 110–119.