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REMOVING DEEP VALLEYS IN ROUGHNESS MEASUREMENT OF SOFT AND NATURAL MATERIALS WITH MATHEMATICAL FILTERING

REMOÇÃO DE VALES PROFUNDOS NA MEDIÇÃO DA RUGOSIDADE SUPERFICIAL DE MATERIAIS MOLES E MATERIAIS NATURAIS COM APLICAÇÃO DE FILTROS MATEMÁTICOS

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ABSTRACT

This work presents a methodology used to filter the roughness profile of soft metals and natural materials. This methodology is based on polynomial regression, Robust Gaussian Regression filter (RGRF) and Abbot filter. The advantages of this method come from the possibility of elimination the deep valleys introduced by scratches after manufacturing or associated with anatomy of materials like wood. The method involves three steps: i) fitting roughness raw data with polynomial regression to remove profile form errors; ii) using the RGRF to filter the profile waviness; iii) applying the Abbot curve method to remove the remained deep valleys. The resulting profile was used to determine roughness parameters Ra and Rmax. Samples of wood Eucalyptus Camaldulensis and aluminium were prepared to carry out the measurements and the calculations where performed with algorithms developed using MatLab software. The results proved that the proposed approach is robust against modifications introduced after processing of soft materials surface and suitable to apply to materials having particular anatomic components.
Keywords: roughness, filtering, polynomial regression, RGRF, Abbot curve.

RESUMO

Este trabalho apresenta uma metodologia para filtrar o perfil efetivo na medição da rugosidade superficial de metais moles e materiais naturais, baseado na aplicação de regressão polinomial, regressão gaussiana robusta (RGRF) e curva de filtragem de Abbot. A vantagem deste método reside na possibilidade de remover os vales profundos introduzidos após a fabricação ou associados à anatomia de materiais como madeiras. O método deve ser aplicado em três etapas sequenciais: ajustar os dados do perfil efetivo a uma regressão polinomial para remover o erro de forma; ajustar este novo perfil a uma regressão RGRF para filtrar a ondulação; aplicar a curva de filtragem Abbot para remover os vales profundos remanescentes. O perfil resultante foi usado para determinar os parâmetros de rugosidade Ra e Rmax. Amostras de madeira *Eucalyptus Camaldulensis* e alumínio foram preparadas para executar as medições e os cálculos foram feitos através de algorítmos desenvolvidos no programa MatLab. Os resultados mostraram que a abordagem proposta foi robusta em relação às modificações introduzidas após o processamente de materiais moles e adequada para aplicação em materiais com componentes anatômicos destacados.
Palavras-chave: rugosidade, filtros, regressão polinomial, RGRF, curva de Abbot.

1 – INTRODUCTION

The search for improved performance has been promoting the use of alternative materials to build mechanical parts. Soft metals like aluminium and natural materials like wood are growing in use and are suitable to applications were ease of manufacturing is demanded. Soft metals like aluminium and copper are used in applications involving corrosion resistance and formability. Wood is of great importance in the furniture industry and aesthetics is an important property.

The quality of the manufactured surfaces can be assessed by the surface roughness as characteristics of slip, wear resistance, adhesion of protective coatings, corrosion resistance and fatigue resistance, among others, can be related to roughness parameters. While soft metals are subject to scratches during and after manufacturing, the wood products are typically processed by machining and appear difficult to characterize because of the remained voids and porosity on the surface.

Wood is a porous and heterogeneous material. Their anatomical aspects and physicochemical properties are directly linked to the process of mechanical transformation, since the direction of the fibers, the presence of vessels and the concentration of resin affects the machining processes. These characteristics vary significantly within and between existing species and provide further difficulty when measuring roughness. Reports on measurement of the surface roughness of some wood species showed that there is still no consensus on what parameter should be used to characterize the roughness of this material (Fujiwara *et al.*, 2004).

The analysis of the roughness profile of a sample of wood showed that the peaks depend on the characteristics such as species, density and grain size (Fujiwara *et al.*, 2004). The existing valleys are associated to the anatomical features of the surface or may be consequence of the manufacturing process. These deep valleys in roughness profile are associated to the wood pores which have variable size as a function of the wood species. There are open cavities (pores) on surface that are generated by machining operations during the removal of the wood cells. It is necessary to remove these deep valleys from the profile before determining the roughness parameters (Fujiwara *et al.*, 2004).

Recent studies reported in literature described some specific methods for determining the roughness of wood-based roughness profiles. These methods may be useful to apply to the evaluation of the soft metal roughness since it addresses the problem of deep valleys. Studies regarding the roughness of *Japanese oak* (Fujiwara *et al.*, 2004), *Japanese beech* (Fujiwara *et al.*, 2004), *Carvalho*, *Spruce* and *Beech* (Gurau *et al.*, 2005), all processed by grinding, were reported by some authors. A common point observed by these authors is the need of an appropriate filtering method to remove the imperfections related to the anatomy of wood so that the real state of the machined surface can be evaluated (Gurau *et al.*, 2005).

Raja *et al.* (2002) and Muralikrishnan and Raja (2008) presented an overview of the main filters used to characterize the surface roughness. Filters like the 2RC, Gaussian, Rk, Spline Robust Regression Robust Gaussian and Gaussian regression were presented. Gurau *et al.* (2006) and Hendarto *et al.* (2006) dealt with the investigation of methods used to determine the surface roughness of wood processed by grinding. The effect of sampling length (cut-off) and the Robust Gaussian Regression filter (RGRF) were investigated with two species of sanded wood, the *European oak* and the *Norway spruce*. It was used a polynomial regression to remove the form errors and then the Robust Gaussian Regression Filter (RGRF) was applied (Gurau *et al.*, 2006).

The effect of Robust Gaussian Regression filter (RGRF) was studied in samples of the *Messmate* (*Eucalyptus obliqua*) after removing the form error by applying polynomial regression, with and without removal of the profile deep valleys (Hendarto *et al.*, 2006). These studies indicated that the Robust Gaussian Regression filter (RGRF) was more effective than the Gaussian filter to evaluate the roughness of sanded wood. A method based on Abbott curve was used to remove the deep valleys of roughness profile and to determine the parameters of the surface (Hendarto *et al.*, 2006). The literature does not address the problem of filtering the post-processing scratches in soft metal roughness measurement.

This work presents a filtering methodology to determine roughness parameters of soft metals and natural materials based on polynomial regression, Robust Gaussian Regression Filter (RGRF) and Abbot filter. The advantages of the proposed method is related to the possibility of elimination the deep valleys introduced by scratches after manufacturing of soft metals. The method involves three steps: fitting roughness measured data with polynomial regression to remove the profile form errors, using the RGRF to remove the waviness and applying the Abbot filter method to remove the remained deep valleys on profile.

2 – ROUGHNESS FILTERS

According to Raja *et al.* (2002), a roughness profile determined with a profilometer is a composition of roughness, waviness and form errors, as showed in Figure 1. The deviations of form and waviness must be eliminated before determining the roughness parameters and filtering techniques are required to perform this task. The most used filters reported by literature are the 2RC, the Gaussian, the Rk, the Spline, the Robust Spline, the Gaussian Regression and the Robust Gaussian Regression Filter (RGRF) (Raja *et al.*, 2002).

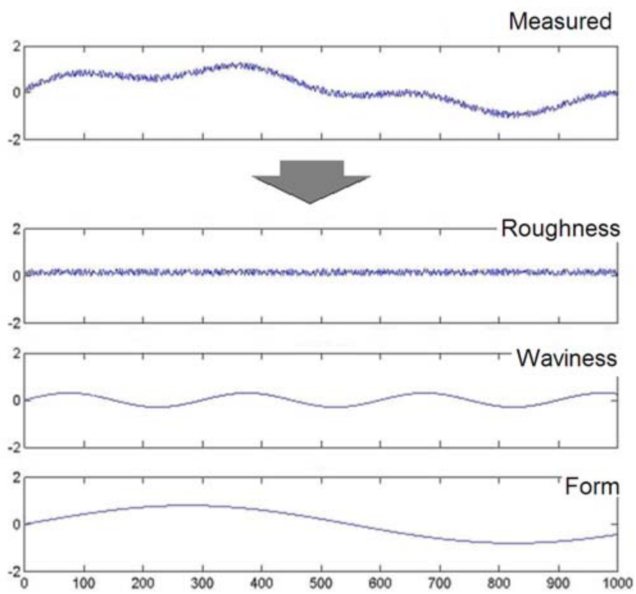

Figure 1 – Decomposition of the measured profile in roughness, waviness and form error

The 2RC filter is the earliest filter used and it is equivalent to a high pass filter. The mean line is determined by convolving the profile with an appropriated weighing function. The roughness profile is obtained by subtracting the the mean line from the measured profile. This filter has the disadvantage of having a nonlinear phase and there is a phase offset that increases with the cutoff. Besides, there is the need for complimentary waviness filter to remove the waviness of the resulting profile (Raja *et al.*, 2002).

The Gaussian filter is one of the most used filters and it was implemented to address the drawbacks of the 2RC filter. The standards ANSI/ASME B46.1 (2009) and ISO 16610-21 (2011) describe its application and the Equation 1 presents its characteristic function. In this expression, the parameters are α = 0.4697 (constant), x is the position in a longitudinal scale beginning at zero (origin) and λ_c is the biggest wavelength of the roughness to a given cutoff.

$$S(x) = \frac{1}{\alpha \cdot \lambda_c} \cdot \exp\left(-\pi \cdot \left(\frac{x}{\alpha \cdot \lambda_c} \right)^2 \right) \quad (1)$$

An important property of the Gaussian filter is its linear phase. This filter may be projected to have 50% cutoff transmission, e.g., with attenuation of 50% to the equivalent wavelength λ_c that is different from the 75% of the 2Rc. The waviness is determined by simply subtracting the roughness profile from the primary profile. The Gaussian filter is not robust against the outliers produced by scratches in soft metals or by the anatomy of wood. Problems associated to end effects must be addressed to avoid loss of information (Raja *et al.*, 2002). Data from raw roughness profile can be analyzed using internet through the site of the National Institute of Standards and Technology, NIST (2007).

Other filters were implemented to address the problem of the end effects as the Rk filter that was recommended by the ISO 13565-3 (1998) Standard. The Rk filter is a two-step filtering approach in which the first step is carried out by applying a low pass Gaussian filter and substituting all profile points that are below the fitted mean line (deep valleys) by the mean line values. The second step involves the calculation of a new mean line with these data using the same low pass Gaussian filter (final mean line). The determination of roughness profile is carried out by subtracting this mean line from the primary profile. This filter has problems associated to the end effects and it is not always robust against very deep valleys (Raja *et al.*, 2002).

Advanced filters as Spline and Robust Gaussian Regression (RGRF) were developed to address these issues. The Spline filter overcome the problem of form and end effects resulting after filtering with RF or Gaussian methods. A derivative of this filter is the Robust Spline filter (Raja *et al.*, 2002). Recent works presented a comparison of some methods used to filter the roughness profile and the Spline filter was described by some authors in literature (Dobrzanski and Pawlus, 2010; Numada *et al.*, 2007).

The Robust Gaussian Regression filter (RGRF) was developed as a modification of the Gaussian filter and its implementation allows the evaluation of the entire roughness profile. Equation 2 shows the mathematical model of this filter, where *z* is the profile, *w* is the mean line, *n* is the number of points, *k* is the function localization index, *l* is the profile point index, *i* is the iteration number, δ is the additional vertical weight and *s* is the regression function. The function *S* is calculated by Equation 3, where λ_c is the maximum cutoff (Raja *et al.*, 2002; Dobrzansky and Pawlus[a], 2010). The first iteration takes place considering $\delta_{i,l} = 0$, but this variable shall be determined as showed in Equation 4 in the following iterations. In this expression, the variables that appears are $c_b = 4.4$ (constant) and $r_{i,l} = z_l - w_l$.

$$E(k) = \sum_{l=1}^{n} (z_l - w_k)^2 \cdot \delta_{il} \cdot S_{kl} \cdot \Delta x \quad (2)$$

$$S_{kl} = \frac{1}{\lambda_c \cdot \sqrt{\ln(2)}} \cdot \exp\left(-\frac{\pi^2}{\ln(2)} \cdot \frac{((k-l)\cdot \Delta x)^2}{\lambda_c^2} \right) \quad (3)$$

$$\delta_{i+1,l} = \left(1 - \left({r_{il}}/{c_b} \right)^2 \right)^2 \quad when \left| {r_{il}}/{c_b} \right| < 1 \quad (4)$$
$$\delta_{i+1,l} = 0 \qquad otherwise$$

The approximation by regression analysis is carried out and the function may be determined to all points of the profile. The objective function (Equation 2) is minimized to organize the data on the mean line (*w*). A first order regression fits a mathematical model that minimizes the deviations in relation to the given equation, a second order regression minimizes the squared deviations and so on for third and fourth order regressions.

The RGRF is progressively growing in application and the literature reported that it is used to fit data from wood roughness measurement in spite of 2RF and Gaussian filter. Nevertheless, the complexity associated to the calculations involved and to the algorithm development has limited the intensive use as a tool to evaluate roughness in these materials (Raja *et al.*, 2002).

Some authors investigated the application of filters to analysis of wood roughness data. Fujiwara et al (2004) proposed the use the RGRF to filter the raw data profile of wood samples measured with different cutoff lengths. Gurau *et al.* (2006) applied the RGRF to evaluate roughness of wood samples and the effect of the cutoff was investigated. Hendarto *et al.* (2006) proposed an approach that requires removing the form error by fitting a polynomial to raw data and applying the RGRF to the resulting profile.

After application of these filters, the problem becomes removing the deep valleys to finally perform the calculations of the roughness parameters. One method commonly used to remove these valleys is the lower valley limit described in the standard ISO 13565-3 (1998). Its application involves the use of the Abbot curve by classifying the roughness profile values in decreasing order and determining the first abrupt change in the value of the second derivative. The lower valley limit is determined and all profile values smaller than the limit must be substituted by zeros, by the lower valley limit value or simply removed of the profile (Hendarto *et al.*, 2006; Dobrzansky and Pawlus[b], 2010).

3 – EXPERIMENTAL

The roughness measurements were carried out using a calibrated Mitutoyo Surftest SJ-301 Roughness tester from IBAMA-DF. A cutoff of 2.5 mm was select in the instrument to capture the data points, using a diamond stylus having tip diameter of 2 μm. The sample surfaces were measured five times and the data was stored in an Excel files (extension xls). Data from raw profile was exported as txt format files. Figure 2 shows the roughness tester used.

Figure 2 – Roughness tester used to carry out measurements

The measurements were carried out in samples of wood, prepared by sanding process. Some wood samples of the *Eucalyptus Camaldulensis* were prepared by sanding using sand paper with grading 120, 220, 320, 400, 800 and 1200, in a row. The samples were cut in plates about 30 x 10 cm in directions longitudinal and tangential to the wood fiber. Figure 3 shows the samples prepared to carry out measurements of the upper surfaces.

Figure 3 – *Eucalyptus Camaldulensis* samples used to roughness measurements

The filtering methodology was applied using algorithms developed with MatLab Software. The filters used were Polynomial, Gaussian, RGRF and Abbot curve, built in separated files. The validation of the algorithms was performed in two ways. The first verification was performed using data from files generated in MatLab software having a predefined simulated profile with known roughness parameters. The second was performed using the measured data files that were uploaded to the NIST internet site (NIST, 2007) to analysis. The results were compared with ones from the developed algorithms. Figure 4 shows the sequence of steps to execute analysis of the measured samples.

The profile and the roughness parameters were determined to data samples after application of the filters Polynomial, Gaussian, RGRF and Abbot filter, in a sequence to eliminate form errors, waviness and sharp valleys of the profiles. Form errors were addressed by Polynomial regression filter, with an equation established to minimize the residuals. Filtered profile was obtained by subtracting the Polynomial data points from raw data. Waviness was filtered by Gaussian and RGRF filters, separately, applied over resulting profiles filtered by Polynomial regression. Deep valleys were removed by application of the Abbot curve, searching for a lower limit valley in the profiles. It was adopted a critical ratio between 3 and 4 to stop the algorithm iterations. The filters were also applied individually to verify their capability of filter form, waviness and deep valleys starting from raw data profile.

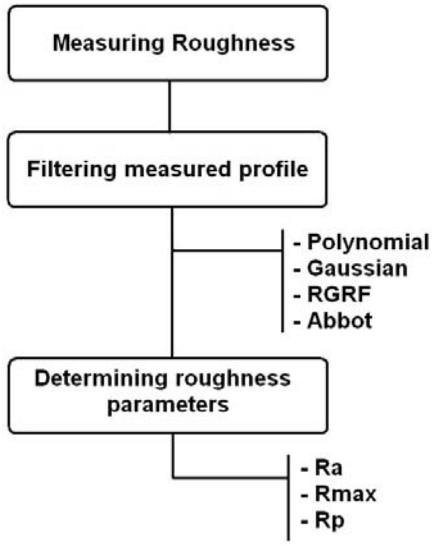

Figure 4 – Steps established to analyze the data samples.

Another algorithm was developed with Matlab software to determine the roughness parameters Ra, Rmax and Rp. The data files stored in txt format were opened and the roughness parameters Ra and Rmax were determined after each step of filtering. Graphs were plotted showing the evolution of the profiles throughout the application of the filters. A graphical comparison of the roughness parameters was performed using a bar graph built in MatLab.

4 – RESULTS AND DISCUSSION

The analysis of the simulated data produced the expected results with all algorithms built to filter roughness raw data, considering the profile form and the roughness parameters Ra, Rmax and Rp. An additional verification was applied at NIST internet site and the Gaussian filter was selected to verify the raw data profile. This analysis confirmed the adequacy of the algorithms.

The raw data obtained from measurement of the *Eucalyptus Camaldulensis* with the Roughness tester is showed in Figure 5. It may be observed the form error and waviness superimposed plus the deep valleys that were associated to the wood anatomy. Next challenge was to separate these sources of variation to obtain the roughness profile and parameters.

The algorithm related to the Polynomial filter was built with MatLab software and the steps established are presented in Figure 6. The filter was built in modules, importing data from text files, calculating the polynomial coefficients, determining the polynomial curve and subtracting the raw data profile. This approach was applied to build the Gauss, RGRF and Abbot filter to obtain a new data file filtered against form, waviness and deep valleys deviations.

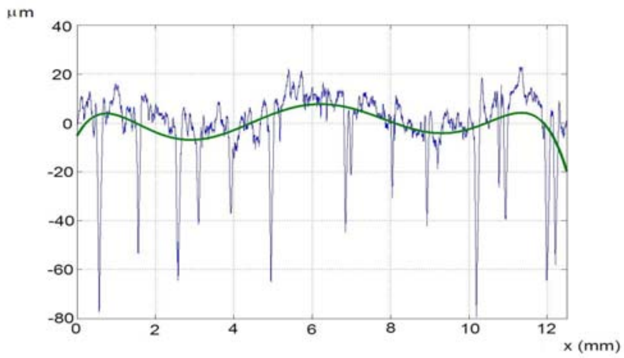

Figure 5 – Roughness profile and line fitted by 6th degree polynomial regression

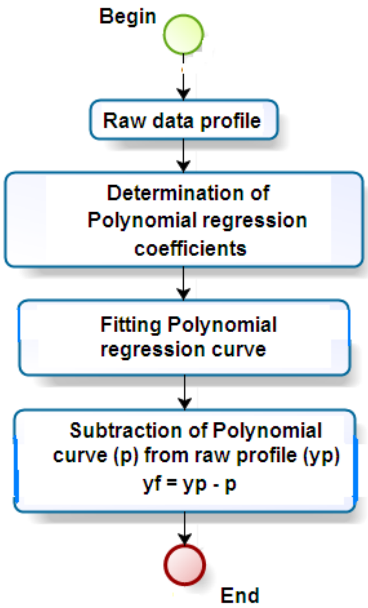

Figure 6 – Steps in Polynomial regression filter construction and application

A least squares polynomial regression with degree 6 was fitted to raw data and the determined curve is showed as the line over the data profile in Figure 5. The regression parameters were determined as b_0, b_1, ... , b_6 in Equation 5, and the results were -5.21, 28.87, -29.46, 10.61, -1.70, 0.12 and -0.0034, respectively. The variables x (mm) and y (µm) are the length and height along the roughness profile. The determination coefficient R^2 was 0.98 and the residuals presented a normal-like probability distribution. The application of this filter reduced the deviations attributed to waviness and form of the profile. The Gaussian and RGRF filters were also applied individually and produced similar results in respect to the polynomial one. The application of Abbot filter separately has allowed the reduction of the deep valleys of the profile but the waviness and form were not addressed.

$$y = b_0 + b_1 \cdot x + b_2 \cdot x^2 + b_3 \cdot x^3 + b_4 \cdot x^4 + b_5 \cdot x^5 + b_6 \cdot x^6 \quad (5)$$

The strategy was then to apply filters in sequence. Both the 6th degree polynomial and the RGRF filters were applied in sequence and Figure 7 shows the results. It was observed that there was a small reduction in waviness and form deviations of the profile attributed to these filters. Nevertheless, it is shown that the deep valleys still remain in the profile. The same analysis was carried out with the polynomial and Gaussian with the analogous results. The application of Abbot and Gauss or Abbot and RGRF reduced the range of the profile as the deep valleys were extracted from the profile, but it was observed that residual variation attributed to waviness was present.

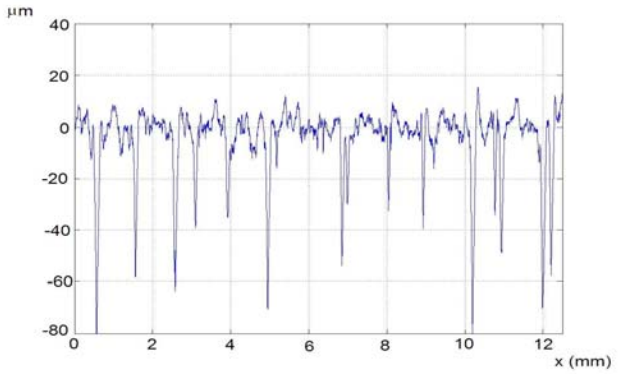

Figure 7 – Roughness profile after application of 6th degree polynomial and RGRF filters

The next step was to apply three filters in a row. Figure 8 shows the results after application of Polynomial regression, RGRF and Abbot filter in sequence. The Polynomial and RGRF addressed and reduced the variation attributed to the form and waviness. A lower limit valley LLV = -3.84 µm was determined with the Abbot filter and it was applied to extract the deepest valleys in the profile. The same analysis was carried out with Polynomial regression, Gaussian and Abbot filters in sequence and there was a small variation in the filtered profile.
The valleys were removed of the profile and the roughness parameters were determined.

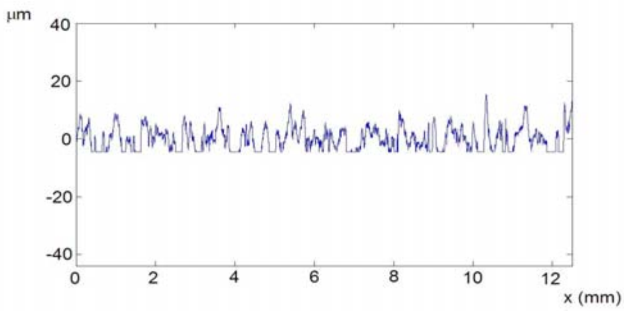

Figure 8 – Roughness profile filtered by 6th degree polynomial, RGRF and Abbot filter

The roughness parameters were calculated for each combination of the filters as described. Figure 9 presents the values of the parameters Ra, Rmax and Rp determined. It was observed that combination of filters or filters alone, with exception of Abbot filter, produced similar results of these parameters, with Ra ranging from 5 to 10 µm, Rmax presenting values between 98 and 102 µm and Rp between 17 and 22 µm. A sharp reduction in Rmax was verified when Abbot filter was applied because this filter removed the deep valleys from the profile. Values of Ra ranging from 4 to 7 µm, Rmax of 20 to 40 µm and Rp of 17 to 20 µm were obtained with previous filtering with two or more filters. The application of Abbot filter alone produced Ra equals to 5 µm, Rmax of 27 µm and Rp equals to 19 µm, but previous application of Polynomial, Gaussian or RGRF, alone or combined, was required to extract waviness and form and reduce these values.

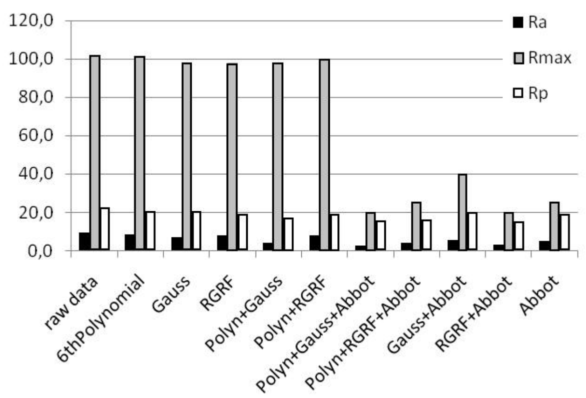

Figure 9 – Roughness parameters determined after filtering data

5 – CONCLUSIONS

The results showed that the proposed approach is robust against modifications like deep valleys introduced after processing of soft materials surface. The application involving the use of filters Polynomial Regression, RGRF and Abbot in samples of wood extracted the form, waviness and deep valleys as showed by roughness parameter values reduction.

The Abbot filter was of paramount importance in extracting the deep valleys of the profile, but it was necessary to apply others like Polynomial, Gaussian and RGRF previously to address the variation attributed to the form and waviness.

Future research may be carried out to investigate the effect of filters like spline filter and applications in soft materials with scratches on surfaces.

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