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Published in:
4. International Swedish Production Symposium

Publication date:
2011

Characterisation of multifunctional surfaces with robust filters

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ABSTRACT

Research has shown that engineered surfaces containing lubrication pockets and directional surface texture can decrease wear and friction in sliding or rolling contacts. A new generation of multifunctional (MUFU) surfaces is achieved by hard machining followed by robot assisted polishing (RAP). The novel production method allows for a large degree of freedom in specifying surface characteristics such as frequency, depth and volume of the lubricant retention valleys, as well as the amount of load bearing area and the surface roughness. The surfaces cannot readily be characterized by means of conventional roughness parameters due to the multi-process production method involved. A series of MUFU surfaces were characterized by using the ISO 13565 standard for stratified surfaces and it is shown that the standard in some cases is inadequate for characterisation of a MUFU surface. To improve the filtering of MUFU surfaces the robust Gaussian regression filtering technique described in ISO 16610-31 is analysed and discussed. It is shown how the robust Gaussian regression filter can be used to remove the form and find a suitable reference surface for further characterisation of the MUFU surfaces.

KEYWORDS

Stratified surfaces, surface characterisation, robust filtering, Gaussian regression, robot assisted polishing

1. INTRODUCTION

This work is a part of a project concerning the development of a new type of multifunctional surface designed for improving the tribological performance of lubricated sliding surfaces. The surfaces are manufactured through a two-step manufacturing process comprising hard turning (the material is hardened before turning) followed by precise robot-assisted polishing [1]. By optimising the process parameters in both processes it is possible to create so-called multifunctional (MUFU) surfaces having nano-scale roughness plateaus combined with channels for lubrication retention (see Figure 1).

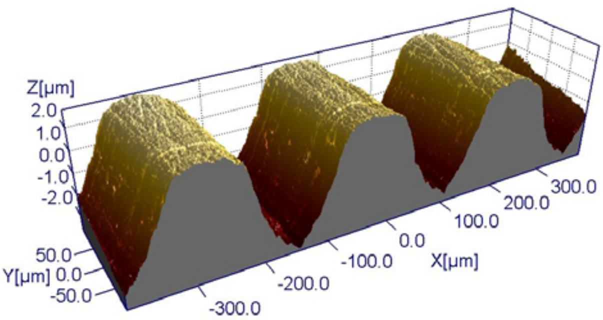

Figure 1: MUFU surface.

Stratified surfaces are especially known to improve the wear characteristics in cylinder liners where plateau honing is used to create the functional properties of the surfaces. The phenomena known as Micro Plasto Hydrodynamic Lubrication (MPHL) is caused by the entrapment of lubricant in pockets or channels in the surfaces of the sliding contacts. Compression and eventually escape of trapped lubricant decreases friction and wear in metal forming [2,3]. Studies have shown that texturing of metal forming dies can significantly improve the tribological properties of the surfaces by decreasing friction and wear [4-8].

The applicability of the MUFU surfaces for industrial use relies on the capabilities for precisely controlling the manufacturing process, and the functional properties of the surfaces are highly related to the surface features. Especially the bearing area ratio, the plateau roughness, the texture orientation, the flank angle between the channel wall and plateaus, and the volume of the channels are considered as important surface features for the functional properties of the surfaces [3-6,8]. The plateau bearing area is defined as the ratio of the surface covered by plateaus divided by the total area. In order to have an effective quality control of the manufacturing, as well as being able to relate the functional properties of the surfaces with distinct surface characteristics, the characterisation MUFU surfaces is of high importance.

Surfaces roughness parameters such as Ra or Rz are often being used to characterise the surface texture of industrial surfaces. However, such parameters have been developed for surfaces having a single process texture and not the multi-process texture of MUFU surfaces. The shape and surface roughness of the lubricant channels were created by the hard turning process and has no relation to the roughness of the plateaus obtained by subsequent polishing.

The ISO-13565 standard [9-11] for characterising stratified surfaces can in theory be used to characterise any multi-process surface, however specific requirements have to be meet in order for the parameters to be meaningful. The standard describes two methods for characterising stratified surfaces. Part 2 takes offset in the material ratio curve or the Abbott-Firestone curve and part 3 the material probability plot [10,11]. Both methods are based on the surface valley suppression filtering technique described in part 1 [9]. This filtering technique however has several disadvantages and recent studies have shown that the robust Gaussian filtering techniques described in ISO 16610-31 [12] are superior because they produce much less distortion of the data [13-15].

This paper describes the applicability of the ISO 13565 standard to characterise MUFU surfaces, and it describes how to improve the filtering of the highly stratified MUFU surfaces using the robust Gaussian regression filtering techniques.

2. FABRICATION OF MULTIFUNCTIONAL SURFACES

The manufacturing of MUFU surfaces is based on novel technology in high precision robot-assisted polishing (RAP) developed by the Danish company Strecon A/S [1]. In its current development the RAP technology can be used to polish 2D round and rotational symmetric workpieces. The polishing scheme can be custom programmed by choosing specific values of the rotational speed, the normal force, and the tool pulsation frequency. Furthermore, the polishing time can be controlled very accurately by specifying the number of identical *passes* of the polishing tool.

In this study the RAP technology has been used to create the special MUFU surfaces resulting in high repeatability and accurate process control, which would not have been possible with ordinary manual polishing. The procedure comprise turning of hardened tool surfaces followed by RAP polishing. Due to the turning process a periodic pattern of peak and valleys is created, and by finely controlling the polishing procedure it is possible to create surfaces with a specified ratio between the smooth polished bearing area (BA) and valleys for lubricant retention. In Figure 2 and Figure 3 is shown an example of the step-wise polishing of a MUFU surface with a turning feed rate of 0.3mm. As can be seen from the corresponding material ratio curves it is possible achieve specific surface texture properties by finely controlling the grinding and polishing settings.

In many practical applications of textured surfaces, the texture – in our case the surface valleys – usually only covers a fraction of the surface, resulting in a bearing area percentage often between 75% and 95% [4-7,16,17]. Due to the novel production method of the MUFU surfaces, it is possible to create surfaces with a very broad range of bearing area – in theory between a few percent and 100%. The present paper considers characterisation and filtering of MUFU surfaces in general without specific consideration to the functional range of the bearing area.

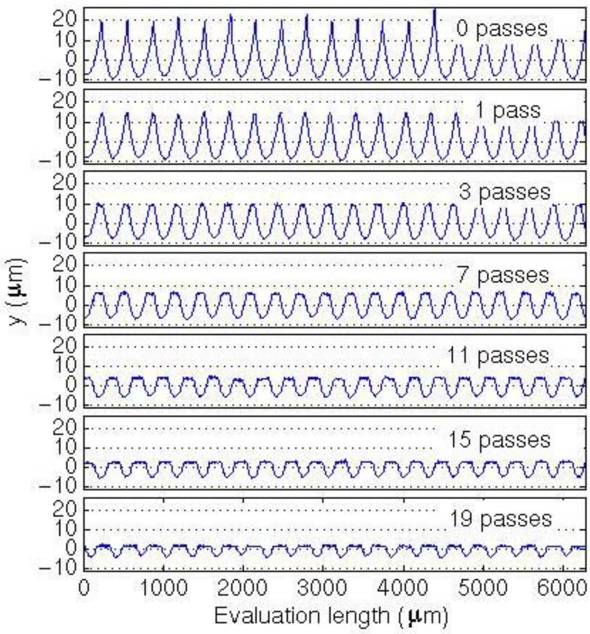

Figure 2: Variation of MUFU surface profiles with the number of passes.

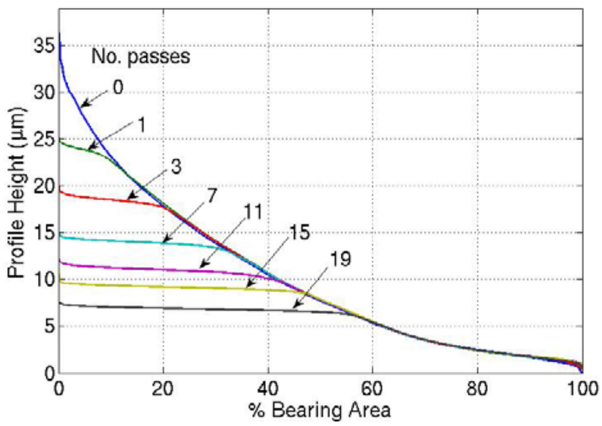

Figure 3: Linear material ratio curve variation MUFU surfaces.

3. CHARACTERISATION OF MUFU SURFACES USING ISO 13565

Characterisation of surfaces having stratified functional properties is explained in ISO13565 part 1 to 3 [9-11]. Part 1 describes the filtering technique for stratified surfaces. This technique builds on a 2 step Gaussian convolution filtering of the surface where the surface valleys are suppressed. Part 2 of the ISO13565 describes the surface characterisation using the linear material ratio curve, or the Abbott curve. The basis for this analysis is a three-layer surface model, evaluating the peaks, the core, and the valleys separately. Part 3 of the ISO standard provides a numerical characterisation of surfaces manufactured by superimposing two processes producing a random Gaussian surface texture. The standard requires that the two-surfaces have a close to random vertical distribution which is often the case in honed or grinded surfaces. In the following sections the characterisation of MUFU surfaces is described using the existing ISO13565 standard.

3.1 ISO 13565-part 1

The roughness profile from the phase correct Gaussian filter defined in ISO 11562 [18] will be distorted when the measured surface consists of relatively deep valleys under a finer plateau region. The valley suppression filtering consists of several stages. First an initial filtering of the entire surface is performed using the ISO 11562 filter. Then all valleys protruding below this mean line are removed by substituting them with the curve of the mean line. Finally the modified profile is filtered again using ISO 11562 and the mean line obtained is then used as the mean line for the original profile relative to which the roughness can be assessed.

This filtering technique is mainly applicable to surfaces where the valleys only introduce moderate to low distortion of the mean line in relation to the actual load bearing surface or plateau region. This is *not* the case for MUFU surfaces with a low or moderate bearing area percentage (~50%) where the turned profile can have a significant effect on the distortion. In Figure 4 is shown the filtering of a MUFU surface with a 0.3mm feed rate and polished to a plateau bearing area of approximately 50%.

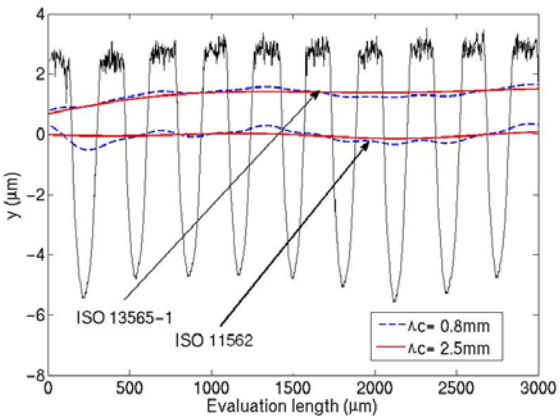

Figure 4: Filtering of MUFU (50% BA) surfaces showing profile and the filtered mean line according to ISO13565-1 and ISO11562 using 0.8mm and 2.5mm cut-off wavelengths.

Both the 0.8mm and 2.5mm cut-off filter described in the standard is applied and a linear form removal has been applied before the filtering. Both the standard filters from ISO 11562 and ISO 13565-1 are shown. As can be seen from the figure, the valley suppression filtering technique is not adequate to obtain a reference mean line following the surface plateau or bearing area region as the distortion from the valley region is to large. Filtering of MUFU surfaces with increasingly larger ratio of plateau bearing area, and hence much smaller valleys, will produce a better suppression of the valleys. However, as has been shown the filtering technique is not appropriate for filtering MUFU surfaces with an arbitrary bearing area and is therefore not generally applicable. In the following investigations the profiles have therefore not been filtered according to ISO13565-1, as this would distort the profile, and only linear form removal has been performed before the parameter calculation.

3.2 ISO 13565-part 2

The roughness parameters in ISO13565-2 [10] are only to be calculated for bearing curves with an S-shape, thus the curve should only have a single point of inflection. Figure 5 shows the bearing area curve for the MUFU surface shown in Figure 4.

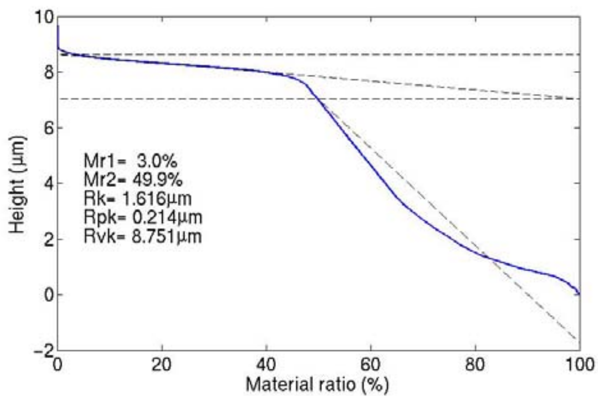

Figure 5: ISO13565-2 parameter calculation on MUFU surface.

It is clear that this curve is not S-shaped but has two points of inflection, one for the plateau region (BA~= 30%) and one for the valley region (BA~= 95%). Therefore, strictly speaking the standard can not be applied in this case. If this restriction is disregarded and the roughness parameters are calculated anyway, the calculated equivalent straight line and the peak, core and valley regions are shown in Figure 5. The average valley depth Rvk is in this case deeper than the maximum depth of the profile, which of course makes no physical sense. If the MUFU surface has a larger plateau region (close to 100%) the bearing area curve better resembles the characteristic S-shaped curve defined in the standard, and in this case the ISO 13565-2 roughness parameters are more useful for characterising the surface. However, as will be addressed in the discussion, the ISO 13565-2 parameters can be difficult to relate to the functional features of the MUFU surfaces.

3.3 *ISO 13565-part 3*

This part of the ISO standard [11] describes characterisation of stratified surfaces consisting of two vertical random components – a valley texture and a finer plateau texture. As the texture is close to be completely random, these two components will resemble two straight lines in a normal probability plot. The related parameters are, therefore, also (and only) suitable those kind of surfaces. The method was, in fact, originally developed for the characterisation of plateau-honing processes, but it can in principle be used to characterise two-process textures of many origins, as long as the processes produce random near-Gaussian distributed surface textures. MUFU surfaces are created through a two-process manufacturing scheme, but only the polishing process will produce a close to Gaussian surface texture distribution. The initial machining process creates a regular pattern of turning groves which will not resemble a straight line in a normal probability plot, and the parameters defined in ISO13565-3 is in practice undefined for MUFU surfaces. In Figure 6 is shown the MUFU profile from Figure 4 superimposed with an equivalent turned profile which has not been grinded or polished.

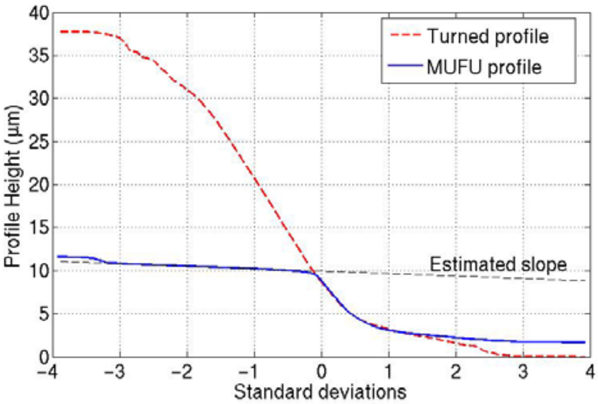

Figure 6: Probability plot of MUFU surface.

The upper plateau region is very close to a random process and therefore can be approximated with a straight line. The slope of this line equals the Rq value of the plateau surface [9,19]. The turned non-random valley region is not linear and can therefore not be used to directly access the roughness of the valley region.

3.4 *Discussion*

ISO 13565-2 assumes that the surface in question can be divided into a central core region with peaks and valleys extending out from this region. MUFU surfaces do typically not consist of a wide *core* region with smaller peak and valley regions. Rather it will consist of a plateau and a valley region with significantly different properties. ISO 13565-2 can in principle be used to evaluate overall characteristics of the MUFU surface, but whether the roughness parameters can be related to the functional properties of the MUFU surfaces is doubtful. Especially features such as flank angel and plateau roughness are expected to highly influence surface functionality but relating them to the ISO 13565-2 parameters is problematic.

Part 3 of ISO 13565 is especially useful when analysing processes creating a vertical random surface texture, such as the grinding and polishing process. The principles described by ISO13565-3 could therefore be employed to analyse only the roughness of the plateau region of the MUFU surfaces, as shown in Figure 6. This requires that a procedure is established for identifying the plateau region in the probability plot by estimating both the upper and lower plateau limits, UPL and LPL, as defined in the ISO13565-3. As the curve cannot be approximated with a conic section, the procedures described in the standard cannot readily be used. However, due to the MUFU surfaces being periodic the probability plot and the bearing area curve could be interpreted as the average curve of a single period. This opens up for the possibilities to relate features of the material ratio curve and the probability curve with specific surface features of the periodic MUFU profile. As an example, the shape of the curves in the valley region can be directly related to the shape of the cutting tool allowing for the alignment of several material ratio curves as shown in Figure 3. A dedicated investigation could identify more characteristic features of the curves and relate them to the specific profile geometry; however this is out of the scope of the present paper.

Effective characterisation of MUFU surfaces should involve quantification and evaluation of the surface features important for the functional properties of the surface. At the moment no standardised methods exist for performing such analysis. It has been shown how the average surface roughness Rpq of the plateau region can be approximated by using the principles from ISO13565 part 3 and estimating the slope of the linear plateau region of material ratio curve. However this only gives an average estimate of the roughness and does not allow for more in-depth characterisation of the plateaus. Features such as flank angel, rounding radius and volume of lubricant channels are not possible to estimate from known standard parameters. Most likely a type of feature identification and extraction algorithm is necessary in order to be able to fully identify and characterise the important functional features of MUFU surfaces. Regardless of the specific characterisation method it is of crucial importance that a standardised filtering procedure is established in order to remove form and to obtain a robust profile mean line as reference for the characterisation procedure. This is explored in the following sections.

4. ROBUST GAUSSIAN REGRESSION FILTERING USING ISO 16610-31

A proper filtering of stratified surfaces, such as MUFU surfaces, is essential for any type of characterisation of surface features and roughness. As it has been shown previously, the valley suppression filter technique described in ISO13565-1 is in many cases not adequate to obtain a mean line representative of the plateau surface. The Abbott curve and the material probability curve are both highly dependent on the levelling of the profile and the filtering procedure is therefore of crucial importance to the characterisation of the stratified surfaces. A standard filtering procedure is required in order to achieve consistent results. In relation to finding a robust filtering method for MUFU surfaces the robust Gaussian regression filtering technique has therefore been investigated.

The robust Gaussian regression filtering technique provides an iterative and robust solution to the profile mean line where outliers are given less or zero weight depending on their magnitude. The robust Gaussian regression filtering technique has been described by several authors [13-15,20] as well as in the ISO standards [12]. The filter builds on statistical regression using the m-estimation method and can be expressed as the solution to the following minimisation problem for the profile filter:

$$\int_0^l \rho\big(z(\tau)-w(x)\big)S(x-\tau)\,\mathrm{d}\tau \;\Rightarrow\; \underset{w(x)}{\mathrm{Min}} \qquad (1)$$

The problem states that for every point x of the profile z(x) a polynomial w(x) of order m is fitted with the specific weights given by the Gaussian weighing function S(x) in order to minimise the residual $\Delta z = z(x)-w(x)$, or more specific the error-metric function $\rho(\Delta z)$ which is the m-estimator. The robustness actually comes from the choice of error-metric function. If the function is chosen as the square function $\rho(x)=x^2/2$ the regression problems becomes the linear and non-robust Gaussian regression filter [15]. For robust regression the Tukey estimator is commonly chosen as the m-estimator used for engineering surfaces [12-14]. The solution to equation 1 can be found by zeroing the partial derivatives in the directions of the coefficients of the m-degree polynomial w(x). For the m=0 order polynomial the solution is given by the following equation:

$$\int_0^l \delta(\tau)S(x-\tau)w(x)\mathrm{d}\tau = \int_0^l \delta(\tau)z(\tau)S(x-\tau)\,\mathrm{d}\tau \qquad (2)$$

This equation is non-linear and results in the introduction of an additional re-weighing function $\delta(x)$ giving weights to the individual profile points, which is based on the following expression derived from the Tukey estimator [13,20]:

$$\delta(x) = \begin{cases} \left(1-\left(\dfrac{\Delta z}{c_B}\right)^2\right) & for \quad \left|\dfrac{\Delta z}{c_B}\right| < 1 \\ 0 & otherwise \end{cases} \qquad (3)$$

where c_B is the threshold value for considering a data-point as an outlier and thereby ignoring it in the calculations. Equation 2 can only be solved iteratively by updating the re-weighing function for each step based on the calculation of the threshold value c_B and finishing when the change in c_B is smaller than a given limit. The threshold value is most commonly calculated using the median absolute deviation (MAD) given by:

$$c_B = 4.4\; median\big(\left|z(x)-w(x)\right|\big) \qquad (4)$$

For a normal distribution it approximately holds that the standard deviation equals σ=1.483*MAD, and as the threshold value c_B often is estimated as 3 times the standard deviation σ of the profile distribution, the expression in equation 4 is obtained [21]. An overview of the described robust filtering iteration scheme is given in Figure 7.

The zero order Gaussian regression filters can not handle large form components and often the 2nd order regression filter is used. The procedure for estimating the filter mean line is the same as for the 0-order, although it becomes more computational expensive. Details regarding the 2nd order solution can be found in references [14,22].

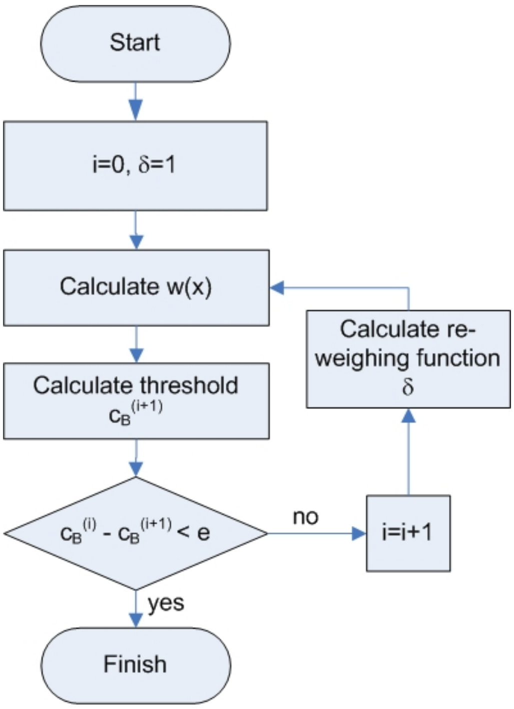

Figure 7: Flow chart of robust filtering algorithm [13].

4.1 Robust filtering of MUFU surfaces

The robust Gaussian regression filter of second order (RGR2) has been implemented and examples of MUFU surfaces have been filtered using standard cut-off lengths of 0.8mm and 2.5mm. The results are shown in Figure 8 and Figure 9 showing MUFU surfaces with approximately 50% bearing area and feed rates of f=0.1mm and f=0.3mm, respectively. As can be seen from the figures the robust estimator converges to a mean line which is heavily affected by the valleys and lying close to the centre of the profile – not the plateau surface which is desired. Furthermore, the filters show some end-effects which are caused by the abrupt stop of the periodic profile.

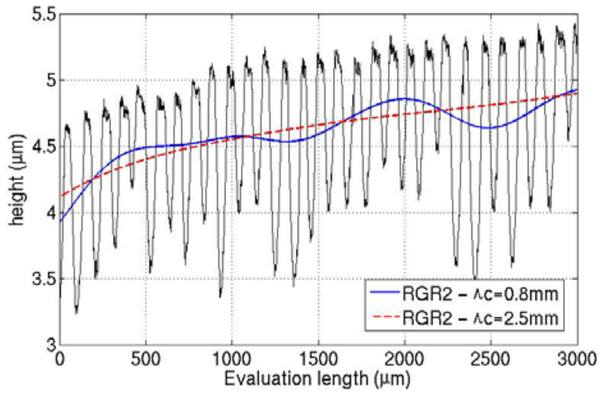

Figure 8: Robust Gaussian regression filtering of 0.1mm feed rate MUFU surface.

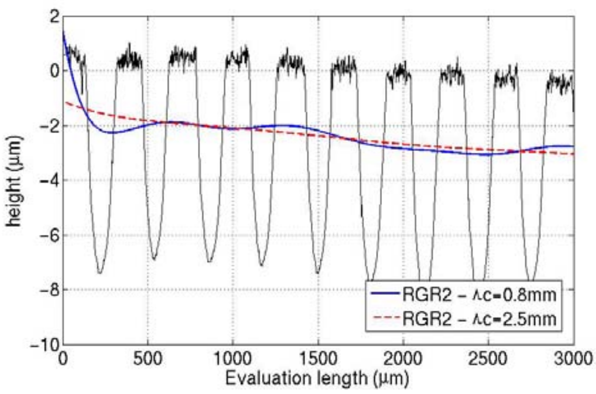

Figure 9: Robust Gaussian regression filtering of 0.3mm feed rate MUFU surface.

In the analysis of stratified surfaces, the valley suppression filter aims at removing the influence of the surface valleys resulting in the filter mean line following the plateau region of the surface. A robust filtering technique for MUFU surfaces should therefore preferably be able to suppress the surface valleys and fit a mean line through the plateaus.

Robust regression techniques are generally capable of removing the effect of gross outliers on the statistics of a data set. This technique requires that a suitable measure of scale is used in order to be able to detect outliers. The median absolute deviation (MAD) statistics is a very robust measure of scale with a breakdown point of 50%. However, if the data contain outliers, or, as in our case, surface valleys constituting a large part of the surface (close to or more than 50%), the MAD statistics become unstable and can in this case not be used as a robust estimator.

Another aspect of the robust Gaussian regression filtering procedure is the choice of m-estimator. The Tukey function is a commonly used estimator for engineering surfaces [13,22]. This function is re-descending and may therefore not have a unique solution, and the solution could therefore depend on the initial guess or 0-iteration step [21]. For most engineering surfaces that are relatively well-defined with only a limited number of outliers, the robust Gaussian regression filter will practically always converge to a single solution regardless of the starting point. But for MUFU surfaces where the plateau region is close to 50% the iteration starting point can influence the solution. In Figure 10 is shown an example hereof, where the profile in Figure 9 has been filtered with the robust Gaussian regression (λc = 2.5mm) after a linear form removal.

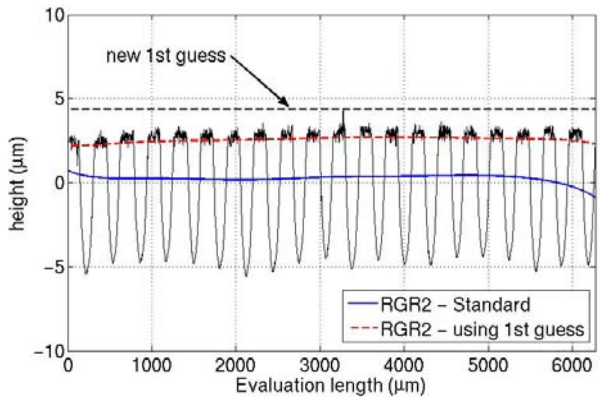

Figure 10: Influence of initial guess on the converged robust solution.

By choosing the initial guess as a constant line equal to the maximum height of the profile, the solution converges much closer to the plateau surface compared to the standard robust Gaussian regression that uses a normal Gaussian regression filter as the initial guess. However, as can be seen from Figure 10 the mean line is positioned just below the actual plateau roughness and it is therefore not an ideal plateau mean line. This is caused by the fact that the surface valleys are not freak outliers with very steep gradients, but they are smooth rounded valleys and a non-neglectable part of the valley edges will therefore have influence on the regression, hereby lowering the mean line.

The choice of using 3σ as the threshold implies that only approximately 1% the data points are expected to be freak values and therefore given zero weight in the regression filtering. For MUFU surfaces the scale difference between plateaus and valleys are relatively large and for surfaces with an approximated bearing area of 50% it is not expected that only 1% of the total profile consists of valleys. In Figure 11 is shown an example of the effect of reducing the outlier threshold value to only one standard deviation.

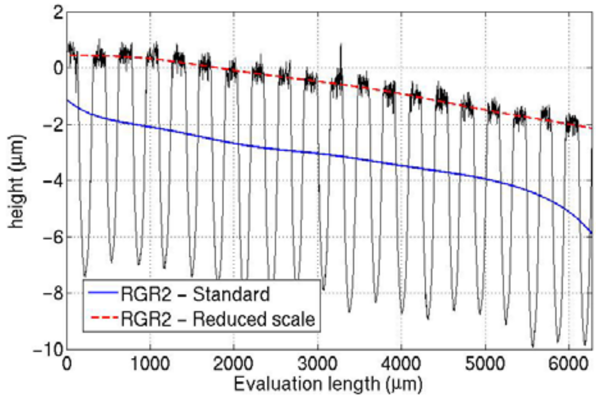

Figure 11: Effect of decreasing the scale factor for calculation of the threshold value cb.

As can be seen this greatly improves the convergence of the mean line to the plateau region of the surface. It can also be argued that the filtered mean line in this case is a more correct representation of the flat plateau region as only a minor part of the valleys will be given any weight in the filter.

4.2 MUFU surfaces with low bearing area ratio

So far mainly MUFU profiles having approximately 50% plateau bearing area has been addressed. Profiles with significantly more than 50% bearing area can typically be filtered using the standard robust Gaussian regression filtering procedure (ISO 16610-31) without major convergence problems. This is because the plateau bearing area percentage exceeds the breaking point of 50% of the MAD estimator which results in the MAD estimate of the scale of the plateau region actually originates from the residuals from the plateaus. Profiles with less than 50% bearing area consists of more than 50% valley region, and the MAD estimator is in this case not expected to be a representative estimate of the scale of the plateau region. A method for estimating the plateau mean line for such surfaces is to simultaneously change the MAD estimator *and* provide a good 1st guess to the iterative regression. Considering a 30% bearing area MUFU profile, the 1st quartile absolute deviation of the distribution can be used as an estimate of scale instead of the MAD estimator. If the initial guess is close to the final plateau mean line, the 1st quartile value of the residuals will be representative of the scale of the plateau region, because the final 70% of the residuals will be related to the valleys. It is important that the initial guess is an upper bound estimate of the plateau mean line thereby ensuring that the absolute value of the residuals to the valley region are larger than to the plateau region. An example hereof could be a closing morphological filter [23] as an initial guess. In Figure 12 is shown an example of the effect of using the 1st quartile estimator with and without a good initial guess of the mean line. The MUFU profile is an artificial computer generated MUFU surface having 30% bearing area. Together with the filter mean line the threshold values +/- c_B of the Tukey weighing function is plotted. As can be seen this procedure provides an improved estimate of the plateau mean line with minimal influence from the valley edges. Due to the solution being dependent on the initial guess the proposed procedure should be used with caution.

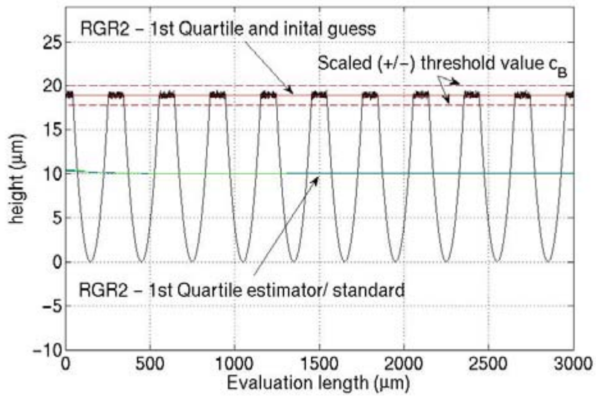

Figure 12: Example on use of 1st quartile estimator on robust Gaussian regression (RGR2) result.

5. CONCLUSION

In this paper it has been presented a newly developed typology of surfaces, the so-called multifunctional surfaces (MUFU). They are obtained through a two-step manufacturing process, namely hard turning and subsequently robot assisted polishing. The existing ISO 13565 standard for characterisation of stratified surfaces has generally been found to be inadequate to characterise this kind of surfaces. The surface suppression filter only gives reasonably estimates of the mean line for high degrees of load bearing area (>90%). Roughness parameters calculated from the material ratio curve could in principle provide some characterisation of the MUFU surfaces; however it is difficult to relate these parameters to the actual surface features giving the functional properties of the surface. It was shown how the material probability curve could be used to estimate the average roughness Rpq of the plateaus, but the procedure is limited by the accuracy of the filter and the subjective estimation of upper and lower plateau limits.

It is shown how the robust Gaussian regression filter is a superior choice to the ISO 13565-1 in estimating the plateau mean line while suppressing the surface valleys for MUFU profiles with a plateau bearing area higher than 50%. If the bearing area is close to 50%, or even below, the robust Gaussian regression filter becomes unstable due to the fraction of valleys being close to or even exceeding the breaking point of the MAD statistics. Procedures for robust filtering of low bearing area MUFU surfaces were suggested. Especially by improving the initial guess for the iteration procedure as well as modifying the calculation of the threshold value could improve the filter mean line. But as the procedure requires additional steps they introduce a higher risk of error in the filtering process. Modifying the standard robust Gaussian regression filter (ISO 16610-31) should therefore only be done with consideration to the individual profiles and it is important to verify the result of the iteration.

6. ACKNOWLEDGEMENTS

The authors would like to thank the Danish National Advanced Technology Foundation for funding this research under the project: Manufacture and characterisation of industrial multifunctional surfaces in industrial collaboration with Strecon A/S and Image Metrology A/S. René Sobiecki at DTU Mechanics is thanked for his assistance with surface measurements.

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