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A study on the Correlation of Peak counts between the Mechanical and the Optical Measurements in Surface Metrology

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Monitoring the surface profile real time on the manufacturing line of planar products has been accomplished by employing the scattering of a laser light. The laser beam was focused onto the surface and the direction of the reflected beam was utilized to obtain the slope of the surface facet. By taking data fast enough, it was possible to obtain the microscopic surface structure. The mean roughness thus obtained agreed well with the ones found with the mechanical stylus instrument. There was discrepancy between the two results as to the number of peaks per cm. A simple model based on the deconvolution of the raw data was found adequate to improve the agreement to an acceptable level.

I. INTRODUCTION

The scattering of light is observed when the light encounters a boundary between two media with differing refractive index. With an ideally flat boundary, the behavior of the light scattering is very much predictable with the well proven theory of electromagnetism. The boundary need not be transparent, and it can be of the reflective type as well. The point is that the boundary should be in such a shape that can be expressed in definite mathematical terms.

When we talk about the light scattering from planar surfaces, the ideally flat plane does not exist in the real world. However, should the mean roughness of the surface be far less than the wavelength of the impinging light, the surface can be considered to be a physical realization of the ideal surface and the practical scattering pattern from the surface can be made without great difficulties. Even with such smooth a surface, the exact description of the light scattering pattern is still a formidable task. The problem lies in the statistical treatment of the surface geometry. Electromagnetic theory demands that either the field strengths or the normal derivatives of the field at the boundary be known all over the area where light encounters the boundary. With the exact description of the boundaries unavailable, one has no other choice but to rely on the statistical approach to the problem. Even with such a critical limitation imposed on the problem, various authors suffessfully derived analytic expressions describing the scattering with a high degree of accuracy.[1-4] Based on those theories, one can utilize the scattering pattern to pursue the "inverse scattering" problem, i.e., investigating the scattering source from the distribution of scattered light.

The shortcoming of the above approach is in that one only can find the statistically significant parameters, like the mean surface roughness, the surface correlation length etc. If anyone is interested in finding a local defect or structures, he has to resort to some other means of metrology. On the other hand, compared to the other means of measuring the surface parameters, this approach can generate the data in a relatively fast time period, - fast enough to be real time. The instruments based on the total integrated scatter (*TIS*)[5] are currently under development to measure the surface roughness for moving planar samples.

Most of the scattering-based instruments utilize the theories that, in the course of their development, assumed the mean surface roughness was far smaller than the wavelength of the the light. Those assumptions were necessary to introduce the approximations, transforming the complicated analytical expressions into simpler ones. For the surfaces satisfying the requirements, the agreement with experiments was excellent.[1] On the other hand, should the mean roughness be comparable to or larger than the wavelength of the roughness, one can not guarantee the same kind of agreement. There are a few cases where the approach still gave good agreement,[6] but it appears that they were rather exceptional.

When the mean surface roughness is relatively large, one alternative available is the facet or the geometrical optics model. With this model, one assumes the test surface as composed of plane, flat facets with the lateral dimension larger than the wavelength and that each facets behaves as a plane mirror. Rays incident on each facet are reflected according to the law of geometrical optics, and from the distribution of the scattered light, one might be able to refer to the surface structure. If, instead, one should make the beam size smaller than the facet size, one can picture the miniature version of light bouncing off a plane mirror. The direction of the highest scattered intensity should correspond to that of the geometrical reflection.

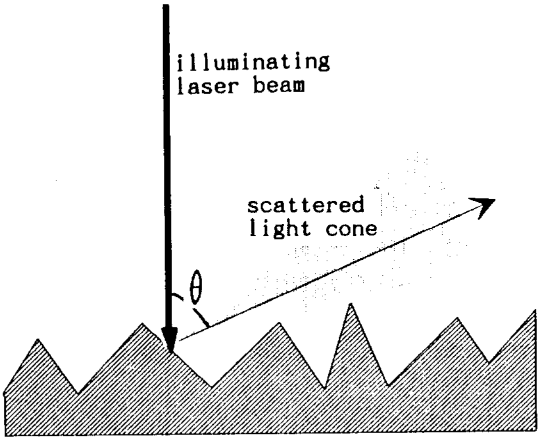

Fig. 1. The basic idea of SORM. The slope of the reflecting facet is determined from the direction of the reflection.

Thus, by locating the direction of the geometrical reflection with respect to the incoming light beam, one obtains the information of the slope of the particular facet that gave rise to that reflection. In Fig. 1, if one should measure the angle of the specular reflection with respect to a reference, say the plane normal to the test surface, one would find the slope of the illuminated facet. Klüpfel[7] showed that, if the data were taken in a row, with each data point Δx apart on the sample, the height of thefacet could be found as

$$H = \Delta x \cdot \tan(\theta). \quad (1)$$

Here θ is the angle of the reflection as shown in Fig. 1. With a fast data processing system, one can obtain the surface profile for a moving sample.

This principle was implemented on a Sick Optical Roughness Measurement (SORM) system. The Fig. 2. is the representation of its electronic assembly. As for the detailed description of SORM, one is referred to a patent literatrure[8]or articles by Weber[9] and Schumalfuss.[10] According to Schumalfuss, this seemingly simple idea was very much successful in measuring the mean roughness of a continuously moving planar samples in the roughness range between 1 to 10 microns. Thus, in spite of the inadequacy and difficulty in explaining the scattering phenomena for smooth surfaces, the facet model established its niche in its prochical application.

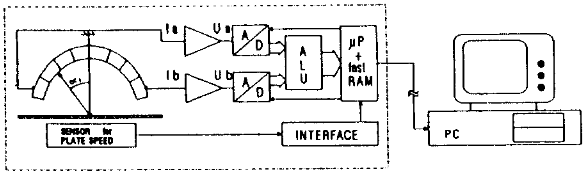

Fig. 2. The electronic assembly and data flow of the SORM. The semicircle on the left indicates the detector array.

II. PEAK COUNT

There are a few different parameters used to denote the quality of the surface finish. Usually a diamond stylus scans over the test surface. The tip of the stylus traces the surface profile to a certain limit and its spatial movement is picked up by the subsequent electronics to display the surface profile in human-readable forms.

There are a few parameters used to denote the roughness of the surface. The most widely used is the mean roughness defined as

$$R_a = \frac{\Sigma \mid z_i - z_o \mid}{N} = \frac{1}{L} \int_0^L \mid z(x) - z_o \mid dx \qquad (2)$$

where $\mid z_i - z_o \mid$ is the deviation of the surface from the mean z_o at the i^{th} sampling point and L the scan length of the sampling interval. Another frequently used parameter is R_z. This is the algebraic mean of the P-V values of 5 segments divided equally on the full scan length. More information is available in ANSI/ASME B 46.1-1985.

Aside from measuring the surface texture in terms of R_a or R_z, a new parameter for the evaluation of the surface finish has been introduced lately. The new parameter is a measure of linear peak density. That is, the number of peaks per cm. In the stylus measurement or in any kind of linear topography measurements, the results often come in as an array of one dimensional data. The new parameter is concerned with the number of humps and bumps for the given distance. There are a few established means of counting peaks, but it is not clearly established as to which methods should be used for what purpose. A stylus instrument such as the one used in this study (model M4P from Perthen GMBH) counts the peaks according to the scheme code named "S". Here once the stream of linear data points forms a hump over a threshold set by the operator, it is counted as one peak no matter what happens before of after that particular peak.

In this study, the feasibility of utilizing the SORM instrument to measure the linear peak density (Peak Count, PC hereafter) was investigated. Literatures[8,9] on this instrument provide convincing evidences that the correlation of R_a as measured with the stylus and the ones by the optical instrument (SORM) is very strong. However, the peak count correlation revealed a correlation coefficient to be 0.7858, which leaves something to be desired. In view of this problem, the goal for this study was set on improving the correlation of the peak count between the two differing means of measurements while not greatly disturbing the R_a correlation.

III. EXPERIMENT

The SORM system produced for the continuous monitoring of a steel mill line was modified for the laboratory environment. With this lab model, the sample mounted on the flat bed moves at 1 m/sec to simulate the continuously moving steel plate. The software was modified so that data were taken only for the duration the sample passed under the measuring spot. The probing laser beam was focused down to 10 μm in diameter and the sampling interval was also 10 μm so that one could obtain continuous data over the scan length.

Eleven steel samples were provided by the manufacturer of the SORM, four aluminum samples prepared in the in-house machine shop, each measuring around 5 cm × 15 cm × 0.3 cm. The steel samples were supposedly chosen from theactual steel mill line and their surface finish was not well controlled for the experiment. Some of them had brownish decoloration on the surface. The detailed procedure for preparing the aluminum surface was not provided, but each one was homogeneous by visual inspection. The roughness range of 0.4 to 1.1 μm as measured with the stylus instrument.

For mechanical measurements, at least 10 scans were made on each sample at randomly chosen sites with the stylus profilometer equipped with a diamond tip 10 μm in radius and the average was taken to represent the mean roughness of the sample. The error range with the mechanical measurement as determined by the standard deviation was around 10% of their nominal values. Optical data were generated by the software that accompanied the SORM and R_a was computed by a simple program.

Fig. 3 is the preliminary results for all 15 samples. Here, the abscissa is the peak counts as measured with a the stylus instrument and the ordinate with the SORM. The results from the stylus instrument were assumed closest to the true values. Thus, if the the results from the SORM were just as trustworthy as the others, one would expect a very strong correlation, meaning all the data points in the Fig. 2 would line up on the 45° line.

Of the 15 samples represented in Fig. 2, eight samples including the four aluminum pieces were selected in such a way that they covered the whole range of R_a of the 15 samples. Removed from further measurements were the samples that exhibited spuriously high optical results. Upon examination of those sample, it was noticed that the surfaces had inhomogenieties in their textures-some rusts and unspecified decoloration was observed. No investigation was made to look into the effect of the rust on the optical scattering pattern. Those selected samples were subject to further measurements on SORM and the peak counts were computed from the SORM data sets.

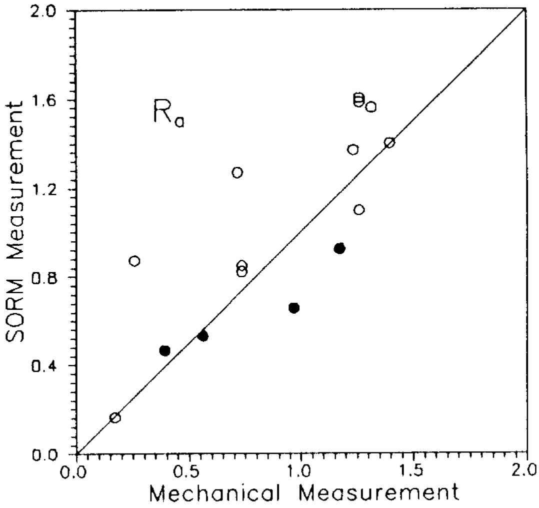

Fig. 3. The preliminary returns of R_a from the SORM. The solid circles represent the result from the controlled Al samples.

IV. PEAK COUNT MODEL AND DATA PROCESSING

As will be shown in Fig. 5, the correlation of R_a between the stylus and the optical measurements is in relatively good shape even before the devonvolution was applied. One would expect that, with such a agreement of two differing means of measurement, the peak count is bound to agree. However, the result represented in Fig. 4 proves that is not always the case. The correlation coefficient here is moderate 0.874. It is most likely the consequences of the basic limitation of the facet or the geometrical model. With this model, one assumed that the individual facets behaves like small pieces of the mirror. The actual surface however would be like a fractal structure. Thus, each facet again is made up of even smaller structures which may or may not follow the rules of reflection set by the larger facets. Besides, the laser beam size was 10 micrometers in diameter, which is relatively large compared to the typical surface height of 1 micrometer. Thus, one is led to a picture in which the finer topographic structures play their roles as independent scatterers. What is observed then is the result of the convolution between the surface structure and the point spread function of each finer segments. This relation is expressed as

$$m(x)=s(x)*f(x) \tag{3}$$

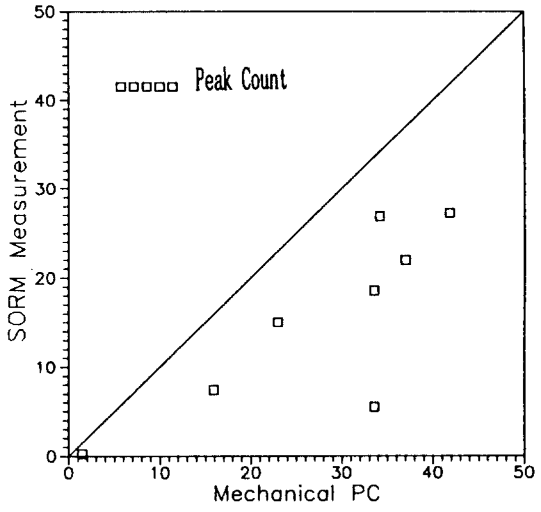

Fig. 4. The number of Peaks/cm, as measured for a selected 8 samples. The threshold for the peak was 1.3 μm.

where $m(x)$ stands for the observed data, $s(x)$ the true surface profile and $f(x)$ the point spread function (PSF) of the surface and $*$ denotes the convolution operation. From the well known relations between the convolution and the Fourier transform, the above relation can be arranged to give

$$s(x)=F^{-1}\left[\frac{M(k)}{F(k)}\right] \tag{4}$$

where $M(k)$ and $F(k)$ are the fourier transforms of $m(x)$ and $f(x)$ each and F^{-1} represents the process of inverse fourier transformation. As such, the exact knowledge of $f(x)$ or $F(k)$ is essential for the retrieval of the true surface structure. However, the exact point spread function $f(x)$ was not determined experimentally. Rather, a simple model was tried based on the observed general behavior of light scattering.

The simplest and reasonable model will be a Gaussian one. This implies that the intensity of the scattered light would be assumed to be distributed like $f(x)=\mathrm{Exp}(-(x^2/\alpha^2))$, with x as the coordiate from the specular reflection such as the angle θ in the figure 1, and α the gaussian half width. Since the fourier transform of the gaussian function is also gaussian, one only has to work with $F(k)$, the point spread function in the spatial frequency domain to retrieve the true surface structure from the relation (4). A typical form would be $F(k)=\mathrm{Exp}(-(k^2/G^2))$.

It was brought into attention that the PSF of the surface has to have something to do with the surface. In other words, the surface finish parameters like R_a needs be taken into consideration when modeling a PSF from the surface under test. With the gaussian PSF defined as above, there is no room for surface roughness parameters. After all, it is only logical to conclude that the way a surface scatter light, which is the meaning of the PSF, should be different from a surface with smooth facets to the one with rough facets. An analogy can be found in the definition of *TIS*, where the fraction of light scattered into direction other than that of the specular reflection (*TIS*) is given as

$$TIS=1-e^{-[\frac{4\pi\delta}{\lambda}]^2} \tag{5}$$

where δ is the rms height of the surface microroughness and λ the wavelength of the light. This clearly indicates that the surface roughness (δ) certainly plays a definite role in the way the surface scatters the incident light.

As such, with the basic form of the PSF assumed as gaussian, one needs to introduce the mean roughness as a variable in the gaussian expression. The only adjustable parameter in the gaussian expression is the gaussian width, usually set at e^{-2} point. With this in mind the PSF was formulated in the fourier space as

$$F(k)=e^{-[-\frac{j}{G(R_a)}]^2} \tag{6}$$

with

$$G(R_a)=\alpha(1+be^{-[\frac{R_a}{g}]^2} \tag{7}$$

where R_a is the mean deviation (roughness) of the surface as computed from the raw data set for the surface and α, b, g were adjusted for the overall best fit. Literally, the gaussian halfwidth of the PSF in the fourier space is also modeled gaussian of R_a with a constant bias of α. It is assumed that the mean roughness as measured by SORM was in the neighborhood of the one measured with the stylus so that the R_a values to be used in (7) is not too far from the stylus values.

As for the computation, all the forward and the inverse fourier transforms were performed with the fortran FFT libraries provided by Microway Co. 8192 data points out of 9700 were used from each data set for the computation.

V. RESULTS AND ANALYSIS

The results of deconvolution on all 8 samples are shown in Fig. 5 and 6 with the appropriate parameter values as given in the figures. These parameters were chosen on the basis of the best correlation coefficient. Here, One finds that the correlation of R_a was not severely degraded while that of the peak count improved

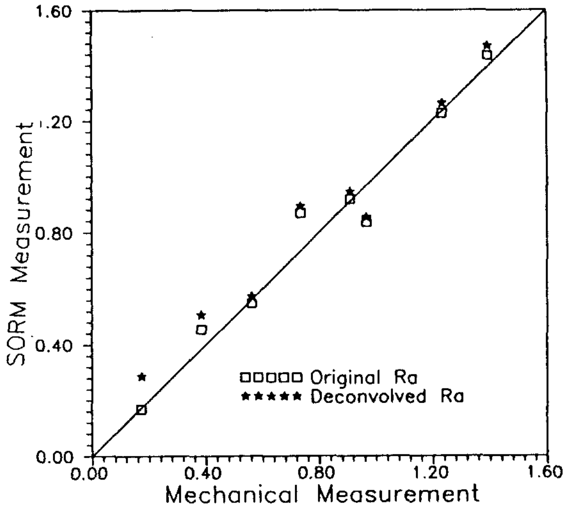

Fig. 5. The effect of deconvolution on R_a. $a=0.025$, $b=0.033$, $g=0.4$

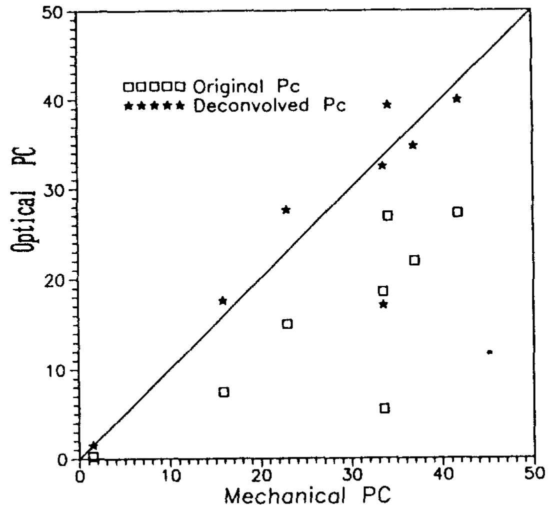

Fig. 6. The effect of deconvolution on the peak count P_c. $a=0.025$, $b=0.033$, $g=0.4$

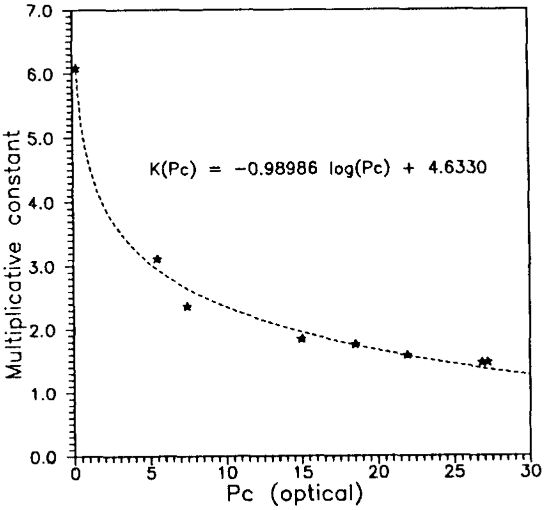

Fig. 7. The multiplication factor as a function of P_c as measured by SORM. The result from the optical measurement are to be multiplied by the values on the dotted line. The dotted line is the result of the logarithmic regression.

significantly, which increased from 0.874 for the unprocessed data to 0.934 after the deconvolution. Except for one sample with the mechanically measured P_c at 33.57, the rest of the samples in the batch are seen to fall close enough to the ideal correlation line. The result of the deconvolution operation, as it turned out, was bringing the individual values up by multiplicative factors depending on the peak count as measured by optical means. The multiplicative factor or calibration function could be best expressed as

$$K(P_c) = -0.98986\,log\,(P_c) + 4.6330 \qquad (8)$$

where $K(P_c)$ is the multiplicative factor that should be multiplied P_a(Peak count) to bring it in line with the mechanical counterparts. This function and the corresponding multiplication constant data are shown in Fig. 7. The general trend is that the calibration factor decreases with the increasing P_c. One would assume however that the factor would not be less than unity in the range of roughness and P_a where this methodology is to be applied. In this respect, the fact that the function expressed by (8) would become less than unity at P_a around 30 poses a problem. If one assumes that the maximum P_a to be around 100 peaks/cm and that the trend of the calibration factor dictates that the factor should approach unity around here, one can find a different expression in place of (8) as

$$K(P_c) = 4.2314\,(P_c)^{-0.30362} \qquad (9)$$

The behavior of this relation is shown in Fig. 8. It

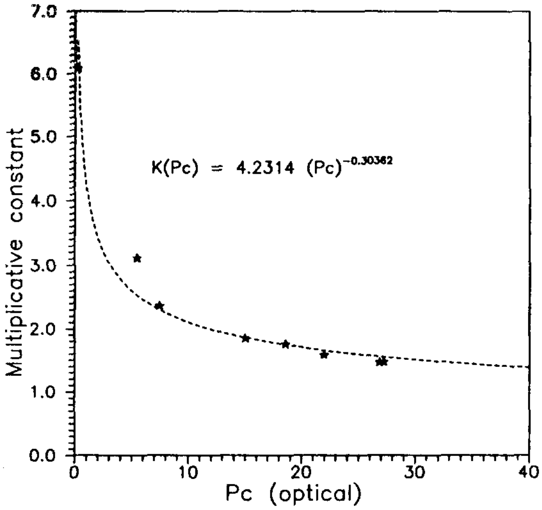

Fig. 8. The multiplication factor as a function of P_c as measured by SORM. The dotted line is the result of the exponential regression.

should be left to the user to decide which formula would be more appropriate for his/her application. One should be discreet in applying above relations to a general test samples. The model expressed by the relations (6) and (7) still needs fine tuning as surfaces prepared by different procedures would have different topography and thus render different combinations of constants in the relations. An etched surface would be different from the milled one. However, for a batch of samples from the same production line, it will be reasonable to assume that the surface ill have similar structures. They may have different R_a values depending on the uncontrolled variables in the course of manufacturing, but it will be reasonable to assume the basic nature of the surface would belong to a similar or the same kind as a whole. Then, only a few calibration runs would be needed to find a set of parameters that can be used in interpreting the peak count values measured by an optics-based surface test system like SORM.

VI. CONCLUSION

The standard and most trusted means of measuring the surface profile of a flat sample is the the diamond-tipped stylus instrument. This instrument however is slow and can only measure a scan length of less than 1 cm at a time. Applying such an instrument on a moving sample such as the production steel mill line was simply impossible. The SORM system, which relies on the reflection of a focused laser beam, was proven to be applicable for such a moving planar sample. The agreement of P_a values between the stylus and the optical measurements by SORM was demonstrated. The remaining disprepancy of the linear peak density between the two means was brought into agreement by deconvolving the optically measured surface profile with the surface point spread function. The deconvolution model introduced in this work could be adapted to different surface texture easily. As such, it was proven that the optical non-contact, real-time measurement of a moving planar sample could be realized to measure the surface profile and the linear peak density as well. This principle applied to steel mill line for example would prove helpful in controling the quality of the finished product.

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