A LASER BASED OPTICAL DIAGNOSTIC TECHNIQUE FOR SURFACE ROUGHNESS ASSESSMENT

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ABSTRACT

This study establishes the basis for a computer assisted laser based optical diagnostic technique to characterize surface textures produced under different manufacturing conditions. Test specimens having different surface textures and representing several machining processes are examined using He-Ne laser light. The field back scattered from the laser illuminated surface is scanned using a motor driven photodiode working under computer control. The signal from the photodiode is analyzed to derive surface related diagnostic parameters. Several diagnostic parameters are considered in the study. The proposed parameters are compared with surface texture parameters calculated from the digitized roughness heights measured by a standard stylus instrument. The investigation shows good correlation between the reflectivity distribution curve and the characteristics of the surface texture as measured by the standard stylus instrument.

Keywords: Surface roughness assessment, Laser measuring techniques, Diagnostic techniques, Optical measuring systems.

TERMINOLOGY

R_q	root mean square (rms) of roughness value
R_a	the cla roughness value
S_q	the root mean square (rms) of roughness slope
S_a	the average roughness slope
K_p	Kurtosis of coordinate distribution
SK_p	Skew of coordinate distribution
R_{max}	the max. reflectivity
K_o	Kurtosis of the reflectivity distribution
SK_o	Skew of the reflectivity distribution
σ_{res}	rms of residuals signal
K_r	kurtosis of residuals distribution
SK_r	skew of residuals distribution
CLA	the ave. dev. of residuals signal
Lc	correlation length of residuals signal
R_r	the ratio σ_{res}/R_{max}
$R(\Theta_2)$	the recorded reflectivity distribution
$\Phi(\Theta_2)$	a normal distribution function with the same average and standard deviation as the Rd curve.
$R_{res}(\Theta_2$	the residuals reflectivity function
Rd	reflectivity distribution
OPD	Optical Diagnostic Parameters

INTRODUCTION

When a rough surface is interrogated by a laser light, the reflected field is modulated in phase, amplitude and direction according to the nature and characteristics of the surface texture. Several optical techniques have been proposed to assess the texture of laser illuminated surfaces on the basis of the field back scattered from these surfaces. T.V. Vorburger and E.C. Teague [1] classified optical techniques into two major groups; profiling techniques and parametric techniques. Profiling techniques utilize mainly interferometers besides other less used principles. Despite their accuracy, interferometers are not ideally suited for rapid, on-line surface measurement. Generally, it requires surfaces that have a high reflectivity so that the contrast of the fringes will be high.

Parametric techniques include several categories among them is the specular reflectance technique. This technique is suitable for surfaces with root mean square roughness (R_q)<λ having a Gaussian height distribution. Experimental investigation by L.H.Tanner and M. Fahoum [2], and M.A.Younes et.al [3] showed that for Ground surfaces, with a profile height approximated to a Gaussian distribution, Rq values up to 0.4 μm can be measured using He-Ne laser. In fact extensive investigation by J.Peters et.al [7] showed that the ordinate distribution of ground surfaces are not exactly normal, a skew of 0.32 to - 0.23, and a kurtosis of 2.27 to 0.7 were recorded. L.Cao et.al. [4] proposed a technique to estimate the root mean square (rms) slope of the rough surfaces having well defined lay. The rms slope of tested surfaces was calculated from the sampled readings of the reflected field.

Total integrated scatter (tis) technique [8] measures the total intensity of the diffusely scattered light. The tis has the same strengths and weaknesses as specular reflectance, but it is more related to R_q.

S.M. Yoo et.al [9] used a laser based technique to characterize surface roughness of wood products by measurement of positional change of reflected light. A two-axis lateral effect photodiode was used, which detects the position of a spot of light on the surface. However the fact that the laser spot is typically 2 mm in diameter suggests that the technique measures waviness rather than roughness. Moreover, relatively smooth surfaces with a limited range of slope variation should be considered.

Other techniques measure surface characteristics by measuring the displacement of the surface relative to a defined reference [5,6]. R. Valliapan and D.K. Lieu [5] used laser doppler vibrometry for surface profile measurement in rolling bearing balls. The resolution of the system is high but maintaining an absolute reference is a limiting factor specially for flat surfaces since any deviation from a well defined reference greatly affects the results of measurement. T. Matumoto et.al. [6] measured the distance to the surface by using triangulation based on the change of the critical angle of the total reflection. The range and the accuracy of the technique make it suitable for surface profile (shape) measurement.

This study is an attempt to extend the application of laser based measurement techniques over a wider range of rough surfaces produced by several machining processes. The investigation showed that, depending on the type of the manufacturing process and the roughness parameters, a laser illuminated surface will produce a unique reflectivity distribution (Rd) curve. The Rd curve can be considered as a finger print of the surface texture directly related to its characteristics. Some optical diagnostic parameters (ODP) are proposed to relate the Rd curve with the texture characteristics. The ODP include the maximum (or specular) reflectivity, the shape and characteristics of the Rd curve and the effect of the change in the incidence angle.

The ODP are compared with the surface texture parameters calculated from the digitized roughness heights as measured by a Talysurf-4 stylus instrument coupled with a PC computer. Good correlations are observed between the proposed ODP and the texture parameters derived from the profile trace.

EXPERIMENTAL WORK

I-Laser Measurement

The experimental work of this study was conducted at the Production Engineering Department of the University of Alexandria, Egypt. An experimental rig was designed to hold the test specimen and the scanning photodiode, with the necessary computer interfacing to drive the stepper motor and control the scanning and data acquisition processes. Figure (1) shows a schematic diagram of the experimental rig. A 7 mW He-Ne laser source (λ=0.6328 μm), (1), is used to interrogate the surface of the test specimen (2). A rotating Table (3) provided with a circular scale is used to fix and set the test specimen at the chosen incidence angle. A photodetector (5) driven by a computer controlled stepper motor (4) is used to scan the field back scattered from the laser illuminated surface. The photodetector signal is amplified by a multi-range amplifier (6), then recorded using the UV recorder (7), and/or digitized via the A/D convertor (8) and stored in the PC computer (9) for further analysis.

The UV recorder (7) was used to record Rd graphs for test surfaces before computer sampling. The recorded graphs helped to set the amplifier at the suitable range for each surface. It was also used to monitor the quality of the sampling process, specially at early stages of the study. the stepper motor was driven at a continuous mode during UV recording.

Three sets of roughness comparison specimens (Robert & Co. ltd, Composite Pocket Set No. 130) representing; Grinding, Turning and Vertical Milling are used in the study. Every set contains 4 specimens each with a different surface texture, and covering a considerable range of roughness values. Test specimens are hold against the parallel laser beam at a chosen incidence angle (Θ_1). The motor driven photodetector scans the reflected field around an arc in steps of 0.42° degrees each. The amplified signal from the photodetector is sampled and digitized via the A/D convertor at the rest cycles of the stepper motor to eliminate the effect of the vibration resulting in the transient periods between steps. Reflectivity values at specified observation angles (Θ_2) are recorded to form a reflectivity distribution (Rd) curve for the test surface at the chosen incidence angle.

II-Mechanical Measurement

To verify the results of the laser measurement, these are compared with the results of surface measurement by a standard mechanical instrument. A Talysurf-4 stylus instrument coupled with a PC computer via an A/D convertor is used to trace the profile of tested surfaces. Figure (2) shows a schematic diagram of the measurement set-up. As the stylus (6) traces the surface of the tested specimen (1), the pick-up (2) generates an electric signal proportional to the roughness height as measured from a specified datum. The signal is digitized via an A/D convertor (4) and a calibrated reading of the roughness height is sampled and stored every 40 μm of the stylus travel.

The digitized roughness height values of the profile trace of the tested surfaces are analyzed, and several roughness parameters are calculated for each surface. A 2 mm meter cut-off is considered in the analysis of the profile trace data, to match with the size of the laser spot size which is typically 2 mm in diameter.

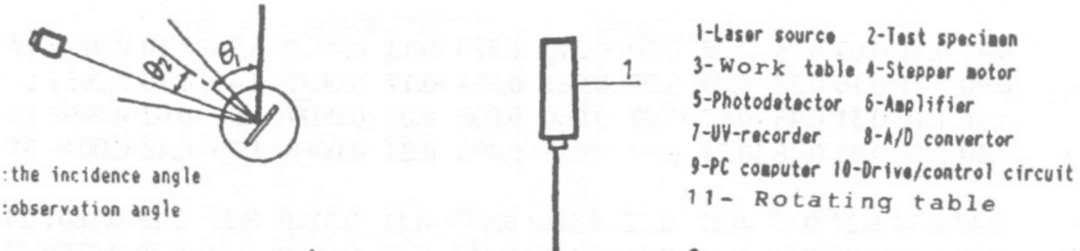

Figure 1. The optical measurement set-up.

1-Test specimen 2-Surface texture pick-up
3-Chart recorder 4-A/D converter
5-PC computer 6-Measuring stylus

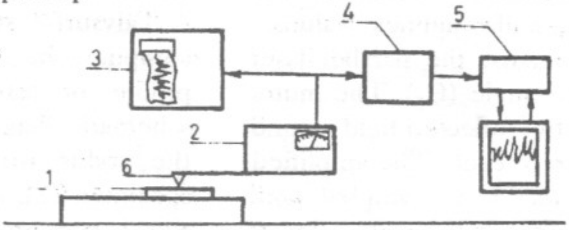

Figure 2. Profile trace recording set-up.

Table (1) Calculated parameters of the profile trace, the reflectivity distribution and the residuals function for the 12 tested surfaces.

Parameters	Profile height						Reflectivity			Residuals function					
Specimen	R_q	R_a (μm)	S_a (μm)	S_q	K_p	Sk_p	R_{max} Θ_2=40	K_o	Sk_o	σ_{res}	K_r	Sk_r	Ave. dev.	Lc	R_r
GS1	0.05						5.0	2.503	0.84	0.5450	31.29	5.20	0.2095	20	0.109
GS2	0.11	0.08	0.12	0.21	0.14	0.32	1.50	0.107	0.11	0.1150	11.45	3.00	0.0610	41	0.075
GS3	0.20	0.16	0.23	0.41	-0.19	-0.24	0.550	0.153	-0.19	0.0255	0.94	0.24	0.0197	48	0.046
GS4	0.45	0.35	0.25	0.32	0.15	0.10	0.090	-0.127	-0.33	0.0052	-0.46	-0.20	0.0041	73	0.058
TS1	0.41	0.31	0.09	0.25	0.20	0.70	0.240	1.570	-0.13	0.0310	6.58	2.10	0.0179	17	0.129
TS2	0.90	0.71	0.16	0.32	0.09	-0.07	0.081	0.554	-0.17	0.0037	2.46	1.10	0.0054	21	0.045
TS3	1.40	1.19	0.31	0.45	-0.67	0.02	0.060	0.008	0.07	0.0047	1.55	-0.02	0.0069	29	0.078
TS4	2.50	2.12	0.38	0.48	-0.74	0.29	0.055	-0.490	0.23	0.0068	1.50	0.42	0.0049	31	0.124
MS1	0.42	0.34	0.27	0.43	-0.27	0.22	4.500	0.475	-0.11	0.3190	8.17	2.12	0.1801	24	0.071
MS2	0.76	0.60	0.25	0.38	-0.63	-0.08	0.630	-0.653	0.15	0.0840	1.34	-0.20	0.0580	34	0.133
MS3	1.40	1.14	0.40	0.50	-0.83	0.29	0.380	0.325	-0.34	0.0347	1.28	-0.25	0.0257	29	0.091
MS4	3.20	2.50	0.54	0.76	0.54	1.21	0.300	-0.441	-0.12	0.0378	2.61	0.17	0.0245	45	0.123

RESULTS AND ANALYSIS

The digitized roughness height coordinates measured by the Talysurf-4 stylus instrument are used to calculate several statistical and spectral parameters of tested surfaces. After linear regression, several roughness parameters were calculated. The estimated parameters included the roughness value (R_a), previously known as the CLA value, the roughness parameter (R_q) which refers to the root mean square roughness height, the slope average and root mean square values and the roughness height distribution. The autocorrelation function and the spectral density function of the profile height function are also estimated. Figures (3,4,5) show the profile graph, the roughness height distribution, the spectral density function and the reflectivity distribution curves for the 12 test specimens. It should be noted that the reflectivity values shown in the Rd curves represent the digitized values stored in the computer. The R_q and R_a values for test surfaces together with other parameters are given in Table (1). The slope average S_a and root mean square value S_q are also given in Table (1). The profile graph of specimen GS1 was practically a straight line, even with the highest magnification available on the stylus instrument. The roughness value of 0.05 μm given by the manufacturer is considered in the study.

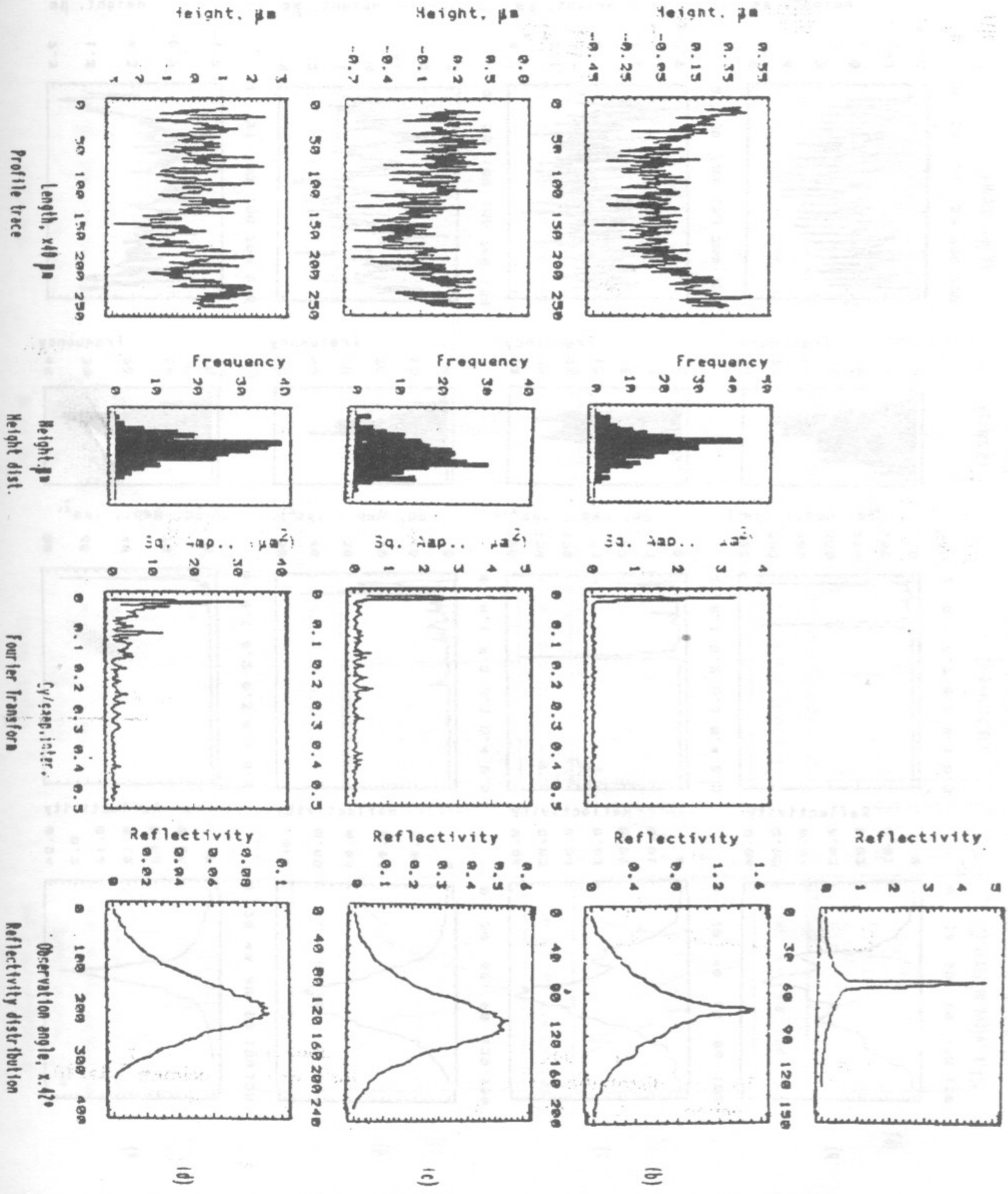

Figure 3. The profile trace, roughness height distribution, spectral density function and the reflectivity distribution (at θ_1=40°) for ground surfaces: specimen GS1, (a), specimen GS2, (b), specimen GS3, (c) and specimen GS4, (d).

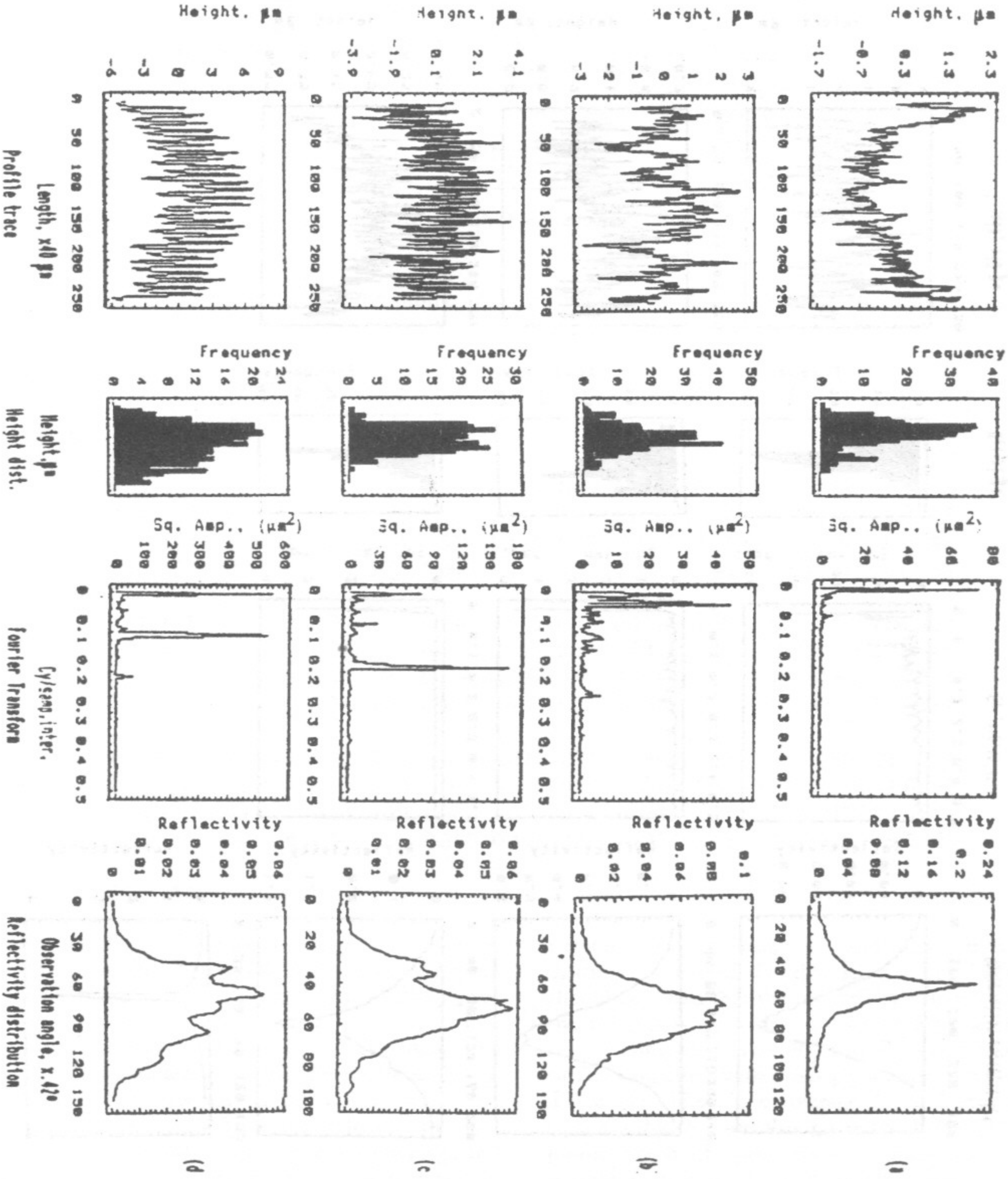

Figure 4. The profile trace, roughness height distribution, spectral density function and the reflectivity distribution (at θ_1=40°) for ground surfaces specimen TS1, (a), specimen TS2, (b), specimen TS3, (c) and specimen TS4, (d).

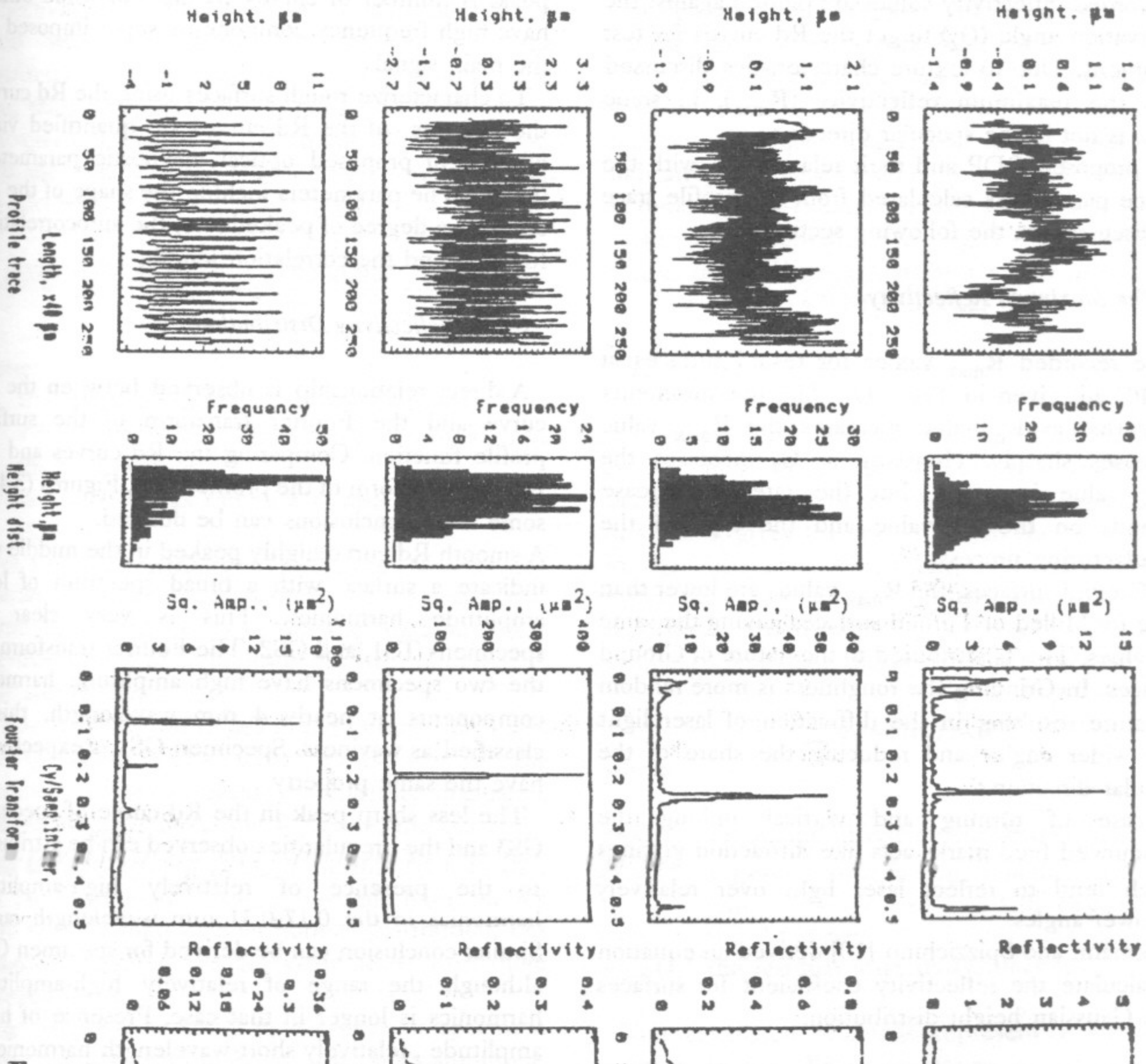

Figure 5. The profile trace, roughness height distribution, spectral density function and the reflectivity distribution (at θ_1=40°) for ground surfaces specimen MS1, (a), specimen MS2, (b), specimen MS3, (c) and specimen MS4, (d).

Recorded reflectivity values are plotted against the observation angle (Θ_2) to get the Rd curves for test specimens. Due to texture characteristics discussed later, the maximum reflectivity (R_{max}), in some cases, is not in the specular direction.

The proposed ODP and their relationship with the surface parameters calculated from the profile trace are discussed in the following sections.

A-The Maximum Reflectivity

The recorded R_{max} values for tested surfaces at Θ_1=40° are given in Table (1). The measurements show that as R_q value increases the R_{max} value decreases sharply. However, as Θ_1 increases the R_{max} value increases, but the rate of increase depends on the R_q value and the type of the manufacturing process.

For Ground surfaces, the R_{max} values are lower than those for Milled or Turned surfaces having the same R_q values. This is attributed to the nature of Ground surfaces. In Grinding the roughness is more random in nature resulting in the diffraction of laser light over wider angles and reducing the share of the specular direction.

In case of turning and vertical milling the pronounced feed marks acts like diffraction gratings which tend to reflect laser light over relatively narrower angles.

Beckmann and Spizzichino [10] derived an equation to calculate the reflectivity coefficient for surfaces with Gaussian height distribution.

B-The Reflectance Curve

Reflectivity values sampled and stored in the PC computer are plotted against the corresponding Θ_2 values to get the reflectivity distribution (Rd) curves. Figures (3,4,5) show the Rd curves for the 12 test specimens at Θ_1=40°. The curves show that every surface produces a unique Rd curve when illuminated by a laser beam. The Rd curve may be considered as a "finger print" of the surface.

The graphs clearly show that some Rd curves have sharp peaks with thin tails, while others are flattened with little or no tails, and some have more than one peak. A number of curves are smooth while others have high frequency components super imposed on the main signal.

To characterize rough surfaces using the Rd curve, the features of the Rd curves are quantified via a number of proposed optical diagnostic parameters (ODP). The parameters include the shape of the Rd curve, the degree of peakedness, the autocorrelation function and the correlation length.

i- The Reflectivity Distribution:

A direct relationship is observed between the Rd curve and the Fourier transform of the surface profile function. Comparing the Rd curves and the Fourier transform of the profile trace, Figures (3,4,5), some main conclusions can be derived.

A smooth Rd curve highly peaked in the middle will indicate a surface with a broad spectrum of low-amplitude harmonics. This is very clear for specimens TS1, and GS2. The Fourier transform for the two specimens have high amplitude harmonic components at nearly 4 mm wavelength, this is classified as waviness. Specimen GS1 is expected to have the same property.

The less sharp peak in the Rd curve of specimen GS3 and the irregularities observed can be attributed to the presence of relatively high-amplitude harmonics in the 0.17-0.31 mm wavelength range. Similar conclusion can be derived for specimen GS4, although the range of relatively high-amplitude harmonics is longer in that case. Presence of high-amplitude , relatively short-wavelength harmonics (1 mm or less) in the surface profile results in a multi-peaked Rc curve, e.g. specimens TS3, TS4, MS1 and MS2, Figures (4) and (5). In fact the number of peaks is directly related to the number of high-amplitude harmonics. Consequently, it is possible to determine the main harmonics of the surface profile from the Rd curve.

ii- The Degree of Peakedness

To measure the degree of peakedness, the Rd curve is compared with a normal distribution having the same average and standard deviation as the reflectivity distribution curve. A parameter "K" is used which measures the tendency of the distribution to have a sharp peak in the middle with long tails, compared with a normal distribution, or conversely to be flat in the middle with little or no tails. the parameter "K" is called the kurtosis and can be calculated using the formula [8],

$$K=\frac{n^3\Sigma R\theta^4-4n^2(\Sigma R\theta^3)(\Sigma R\theta)+6n(\Sigma R\theta^2)(\Sigma R\theta)^2-3(\Sigma R\theta)^4}{[n\Sigma R\theta^2-(\Sigma R\theta)^2]^2}-3$$

where:

R the sampled reading at an observation angle Θ.

θ value of the observation angle measured from the start position.

n sum of readings sampled at different values of Θ.

For a normal distribution K=0.0 (i.e. Mesokurtic). Positive values of K indicate a "Leptokurtic" distribution with a peak in the middle, while negative values of K indicate flat distribution with little tails "Platykurtic".

Table (1) gives the values of the kurtosis for the 12 test specimens. The table shows that as the roughness value increases the kurtosis decreases. This means that for a low R_q value, the Rd curve tends to have a sharp peak in the middle with thin tails. As R_q value increases, to a certain limit, the Rd curve starts to follow a near-normal distribution, but further increase in the R_q value leads to a more flattened curve.

The negative kurtosis, in the case of specimen MS2, can be attributed to the high-amplitude harmonics with relatively short-wavelengths observed ($\simeq$ 0.16 mm) in the Fourier transform of the surface profile trace, together with the less pronounced harmonics at the short (0.1 mm) and the long (4.8 mm) wavelengths ranges, Figure (5). These pronounced harmonics results in a multi-peaked Rd curve and lead to a more uniform distribution of the reflected field over a relatively wide angle. On the other hand, the presence of a single high-amplitude harmonic in the spectral density function of the specimen MS3 results in a peaked Rc curve with a positive K parameter, Figure (5). While the presence of a broad band of harmonics in the case of ground surfaces with higher amplitude only in the long wavelength range (waviness) results in a peaked Rd curves with positive K parameter except at the high R_q values. Despite the low R_{max} values, turned surfaces produce also Rd curves with positive K parameter which decreases as R_q increases, indicating the presence of high amplitude harmonics in the longer wavelengths range, with low-amplitude harmonics otherwise. This agrees well with the results of the Fourier transform of the profile trace of turned surfaces TS1 and TS2.

iii- The Autocorrelation Function

Autocorrelation function gives a visual picture of the way in which the dependence in a series damps out with the lag between points in the series [9]. In our case it gives the way in which the dependence in the Rd curve damps out with increasing the difference in Θ_2, but in its initial form the Rd curve represents a non-stationary process. To get a near stationary process, a transformation is proposed,

$$R_{res}(\theta_2)=\phi(\theta_2)-R(\theta_2)$$

where:

$R(\Theta_2)$	the recorded reflectivity distribution
$\phi(\Theta_2)$	a normal distribution function with the same average and standard deviation as the Rd curve.
$R_{res}(\Theta_2)$	the residual reflectivity function.

The calculated residuals represent a stationary process. In fact, linear regression of the residuals function resulted in almost no change in the statistical characteristics of the function. This proves that the transformation using the normal distribution function is statistically reasonable. Figures (6, 7, 8) show the residuals function for the 12 test specimens. The figures also show the autocorrelation function (acf) and the gaussian curve fitted for each of the 12 test specimens. The correlation length (the lag at which the acf reaches zero) is also estimated, Table (1). The estimated values show that, in general, as the R_q value increases the correlation length Lc increases too.

iv- The Residuals Function:

The residuals function $R_{res}(\Theta_2)$ was analyzed to study its characteristics. The standard deviation σ_{res} and the average deviation are calculated together with the kurtosis K_r and the skew SK_r of the residuals distribution. The correlation function and the correlation length L_r have also been estimated as mentioned in the above paragraph. The resulting values are given in Table (1).

The results show that, for the three machining processes considered, the residuals function becomes more random as the R_q value increases. The values of the Kurtosis and the Skew decrease while the correlation length increases indicating that, as R_q value increases the reflectivity distribution becomes more closer to a Gaussian (random) distribution.

The standard deviation of the residuals function σ_{res} decreases as the R_q value increases, but when divided by the R_{max}, the ratio (σ_{res}/R_{max}) decreases down to a certain limit and then starts to go up again. This is only true for Ground and Turned specimens. For Vertically milled surfaces the trend is not clearly defined.

CONCLUSIONS

1- The reflectivity distribution curve can be considered as a finger print that can be used to characterize a rough surface via a number of diagnostic parameters.

2- The maximum reflectivity is directly related to the R_q roughness value. However, assuming a normal height distribution, the linear relationship is valid only for R_q values less than the wavelength of the laser source used.

3- For the same R_q values, vertically milled surfaces will produce higher reflectivity values (R_{max}), and ground surfaces will produce lower values. This is attributed to the random nature of ground surfaces which leads to the scatter of laser light over relatively wider angles. On the other hand, milled surfaces have prominent lay marks acting as diffraction grating which tend to scatter laser light over smaller angles.

4- A highly peaked reflectivity curve will indicate a relatively smooth surface with a broad spectrum of low-amplitude harmonics. This is observed in the case of ground surfaces and fine turned or milled surfaces.

5- Presence of high-amplitude, relatively short-wavelength harmonics (1 mm or less) in the surface profile results in a multi-peaked Rd curve.

6- Well separated peaks in the Rd curve indicate that the differences in the wavelength between the pronounced high-amplitude harmonics of the surface profile is large.

7- The number of predominant peaks observed in the Rd curve is directly related to the high-amplitude harmonics present in the profile curve.

8- Relatively rough surfaces tend to produce rather flattened Rd curves with low or negative kurtosis.

9- As the R_q value increases the correlation length calculated for the residuals function increases too. This can be attributed to the gradual change in the rather flattened Rd curve of these surfaces.

10- Comparison of the reflectivity distribution with the Gaussian distribution proves to be a good tool for differentiating between different surface profiles. The Kurtosis and Skew provide good diagnostic parameters to characterize these Rd curves.

11- The Residuals Function resulting from the proposed transformation $[R_{res}(\Theta_2)=\phi(\Theta_2)-R(\Theta_2)]$ provides also a good tool for differentiating between different surface profiles. As the R_q value increases, the Residuals function becomes more random in nature with increased correlation length and decreased rms value.

12- As the R_q value increases, the ratio between the standard deviation of the Residuals Function and the maximum reflectivity decreases down to a certain limit and then starts to go up again. This is obvious for Ground and Turned surfaces. The trend for the vertically milled surfaces is not clearly defined.

13- Interrogation of a wider range of specimen are still needed to reach generalized conclusions.

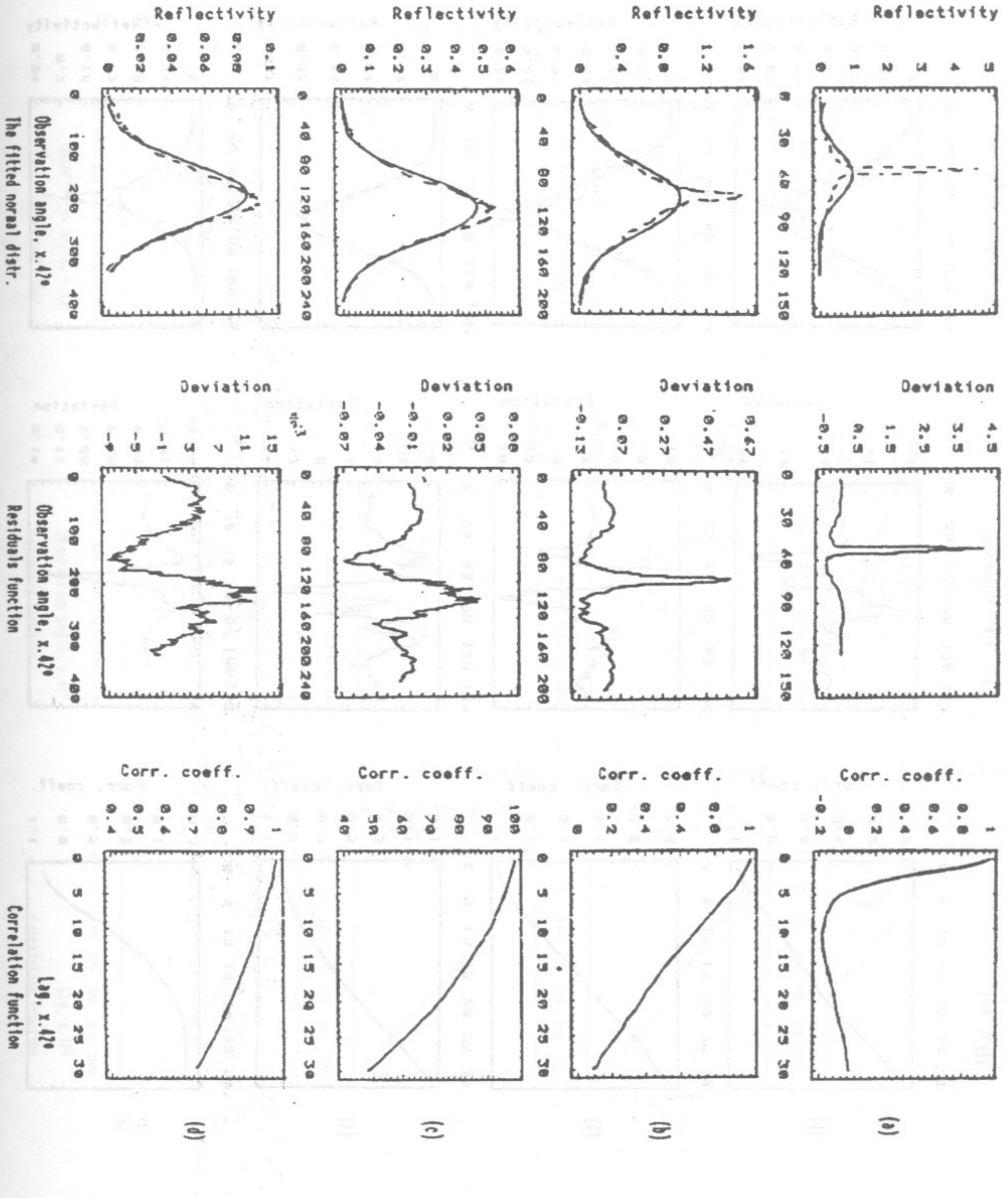

Figure 6. The normal distribution fitted to the reflectivity curve, the residuals function, and the correlation function for ground surfaces: specimen GS1, (a) specimen GS2 (b), specimen GS3 (c) and specimen GS4 (d).

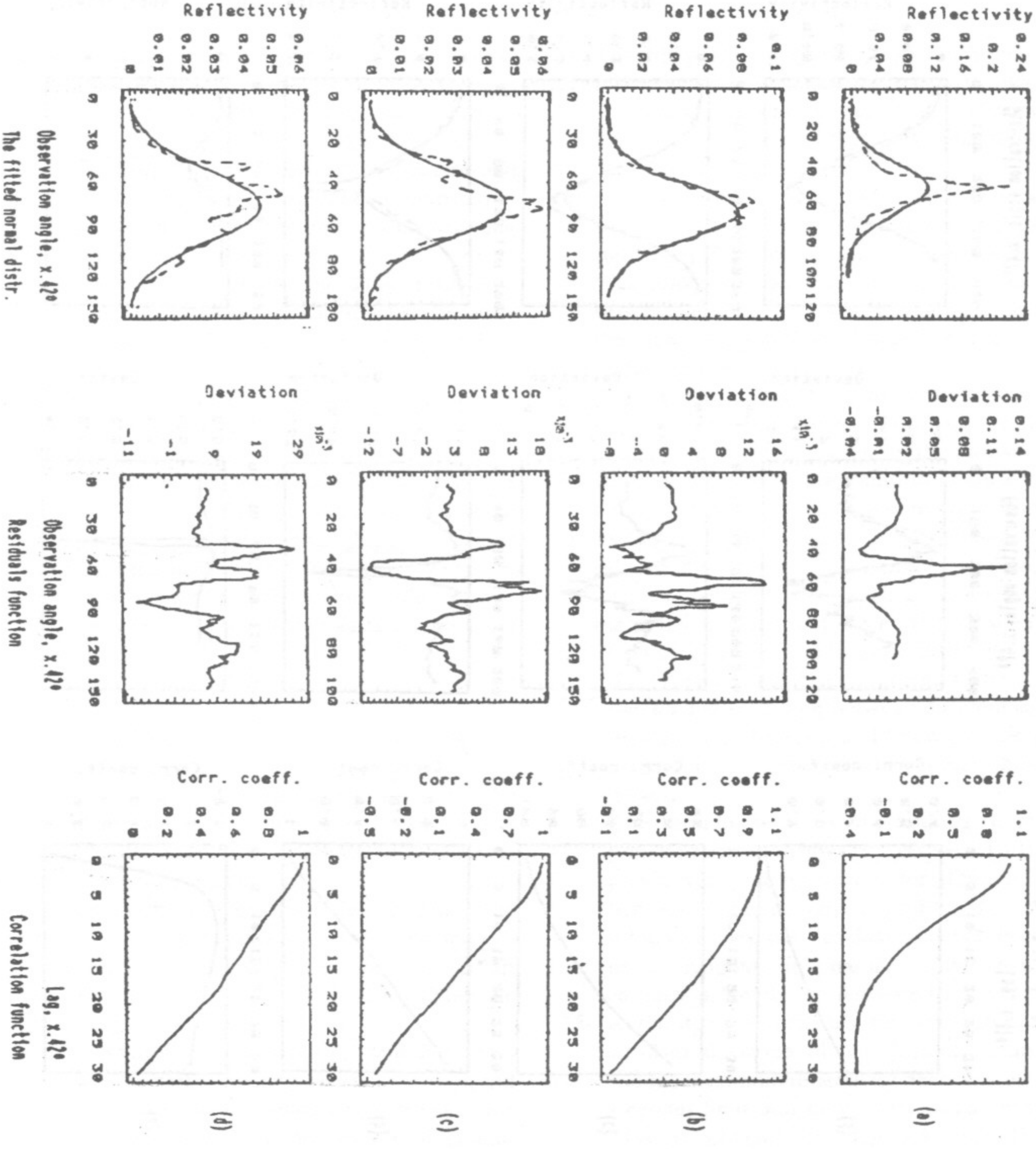

Figure 7. The normal distribution fitted to the reflectivity curve, the residuals function, and the correlation function for ground surfaces: specimen TS1, (a) specimen TS2 (b), specimen TS3 (c) and specimen TS4 (d).

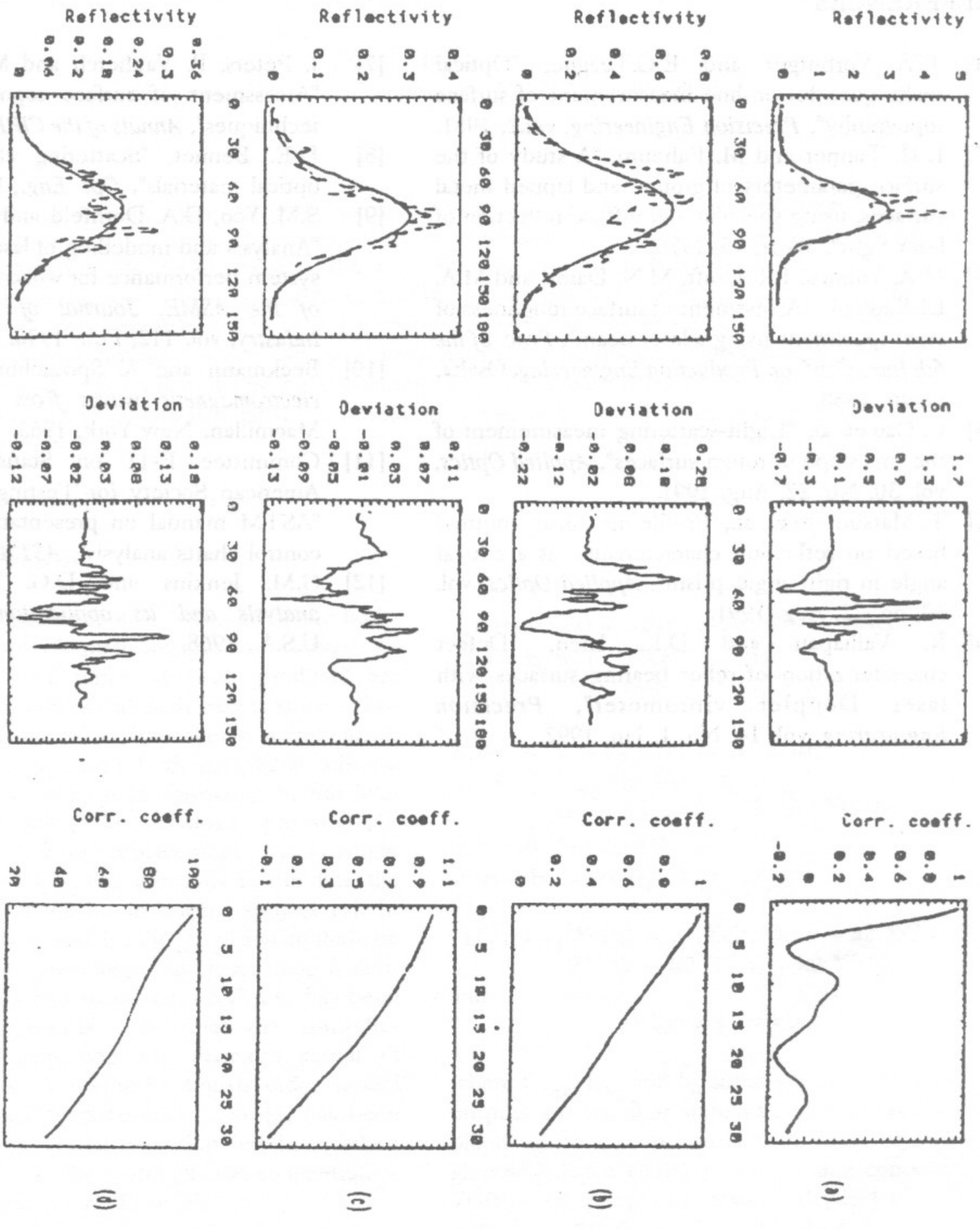

Figure 8. The normal distribution fitted to the reflectivity curve, the residuals function, and the correlation function for milled surfaces: specimen MS1, (a) specimen MS2 (b), specimen MS3 (c) and specimen MS4 (d).

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