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AN ANALYSIS OF THE REFERENCE LINES OF THE SURFACE PROFILE AND ITS TRUE REPLICA

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Summary

The roughness of surfaces normally not accessible by conventional stylus instruments is often measured by a replica technique. The replica surface is the mirror image of the original surface. This paper deals briefly with an analysis of the reference lines used in practice for roughness measurements from surface profiles of original as well as replica surface. A statistical analysis of surfaces produced by different processes and of their true replicas is reported.

Introduction

The quality of a surface affects to a great extent its behaviour when in contact with another surface. The peaks on a surface and their distribution have a significant influence on the friction and wear characteristics, load-carrying capacity and joint stiffness. In sealing, the valleys also play an important role [1].

In industrial practice and research the roughness is measured from the original surface or from a replica of the surface, depending on the practical limitations of the measuring instrument. However, reproduction of the surface texture depends on the characteristics of the replica material used. In the replica method the peaks of the original surface become the valleys and the valleys become the peaks of the replica. Therefore a certain amount of difference may be expected between the original profile and its replica, as far as the profile analysis is concerned.

Stylus instruments measure the roughness from a two-dimensional profile of the surface and establish reference lines that represent the waviness present in the profile. The surface roughness is measured as the average deviation of the profile from these reference lines, thereby eliminating the waviness. Two basic systems are followed for fixing the reference lines on a profile: the mean-line system and the envelope system. The mean-line system (M system) reference line is obtained by an electrical filtering of the signal representing the surface profile (by RC-filters) [2]. This reference line is commonly known as the electrical mean line. The envelope traced by a circle rolling over the profile is the reference line in the envelope system (E system) [3]. Different amounts of waviness separation can be achieved by choosing different cut-off values for the electrical filter in the M system or by having different rolling circle radii in the E system. Digitised surface profiles obtained with reference to a fixed datum attachment were used for the present analysis. Assuming perfect reproduction, the profile of the replica can be obtained as the mirror image of the original profile. This paper deals with the computer simulation of the replica and the analysis of the profile and this replica.

Roughness values for the profile and its replica

According to M system standards, the mean line is defined as the line which has the form of the nominal profile within the limits of the meter cut-off and which is so-placed that within the meter cut-off the sum of the squares of the deviation of the profile from the mean line is a minimum [4]. As the determination of such a mean line has practical difficulties, all instruments measuring according to the M system refer to an electrical mean line of alternating current which represents the profile. In the E system an enveloping profile is obtained by rolling a circle of specific radius over the profile form to provide the reference line according to a standard [5]. Depending on the cut-off (M system) or rolling circle radius (E system), these reference lines take different shapes and result in different amounts of waviness separation. The average deviation of the profile from these reference lines is defined as R_a (M system) or R_p (E system). Both the systems correlate at their extreme limits, *i.e.* with zero cut-off and zero radius for the rolling circle the reference lines follow the profile itself while they become straight lines for infinite cut-off and radius.

The procedure for computing the electrical mean line has been reported [6]. Knowing the weighting function for the standard RC-filter, the mean-line ordinates are computed as the weighted average of the profile ordinates. For computing the envelope, the peaks are selected first and the arc of the rolling circle is placed over them [7]. The envelope computation can be adopted only when the radius of the rolling circle is above 2.5 mm. When the radius is smaller, the envelope is also controlled by the profile flanks and hence a different procedure has to be used [8].

Figures 1 - 3 show the original and replica profiles of shaped, turned and ground surfaces, respectively, together with the M system and the E system reference lines. Table 1 gives the computed roughness values based on the two systems. The electrical mean line for the replica is simply the inverted electrical mean line of the original profile. This is confirmed by the roughness values obtained for both the original and the replica by the M system. The replica profile was obtained by changing the datum and reversing all the profile ordinates to this datum. As the electrical mean line is

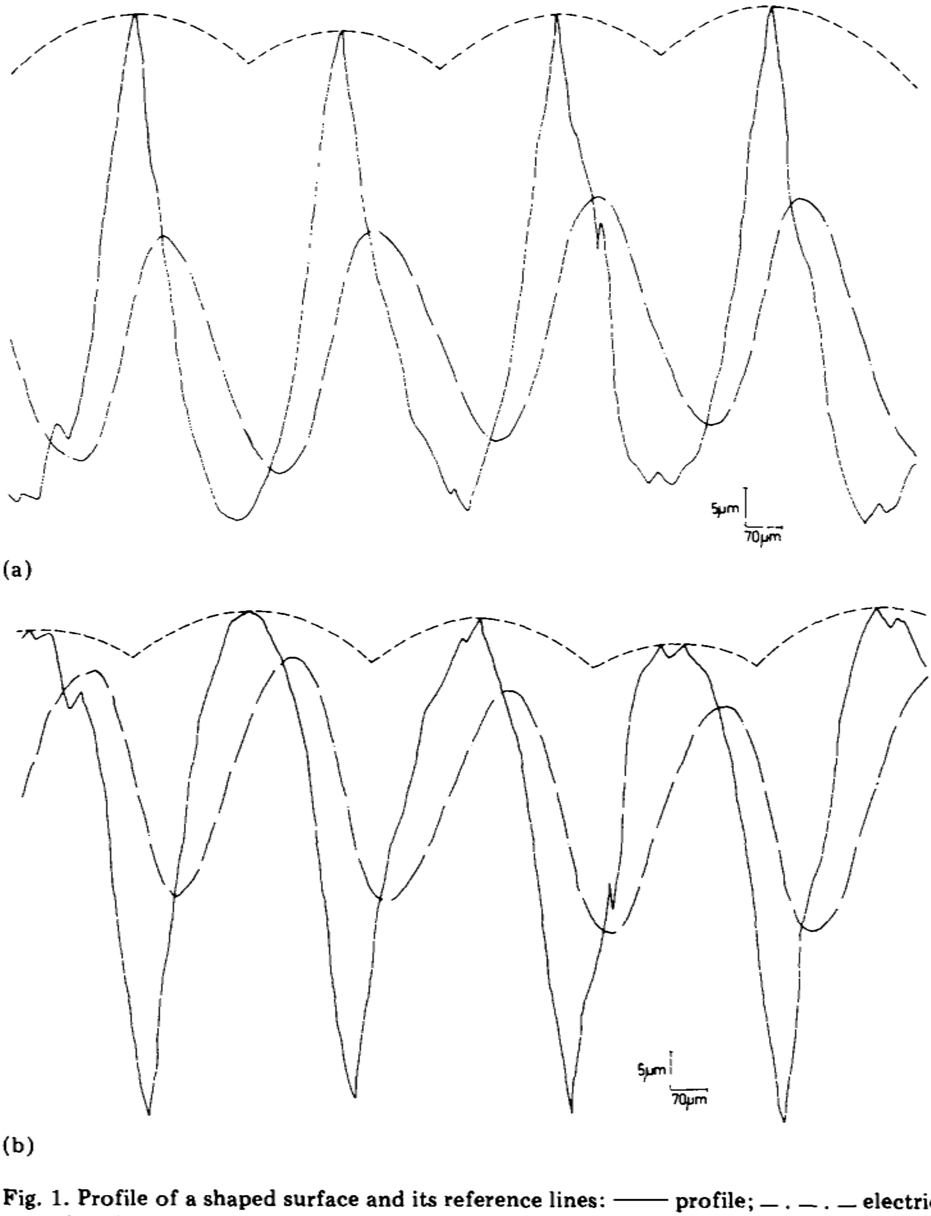


Fig. 1. Profile of a shaped surface and its reference lines: —— profile; — . — . — electrical mean line (cut-off 0.75 mm); -------- envelope (rolling circle radius 3.2 mm). (a) Original profile, (b) replica profile.

obtained as a weighted average of the profile ordinates, this change in the datum inverts it without affecting its shape.

In the E system, the shape of the envelope is influenced by the peak heights and their spacing [9]; the envelope tries to take up the waviness defined by the peaks. In certain rolling contacts, this is of significance. From

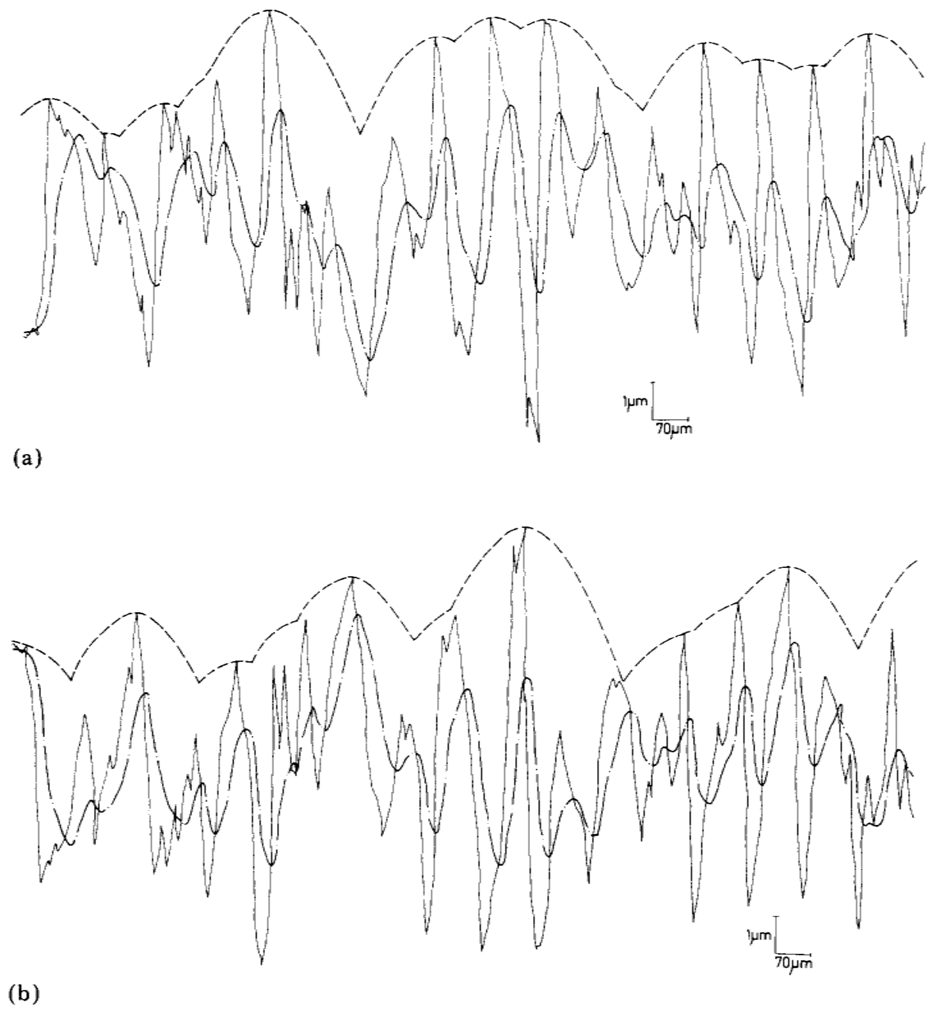
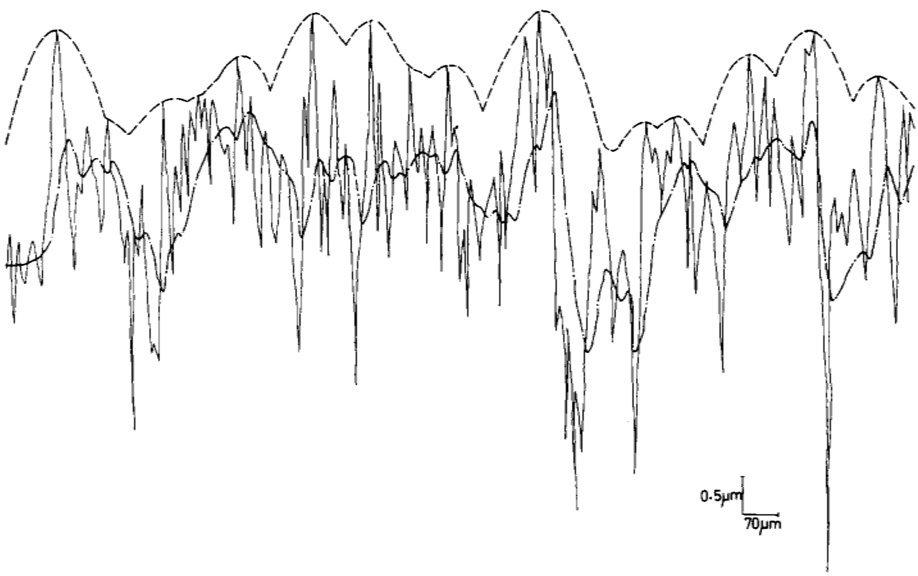
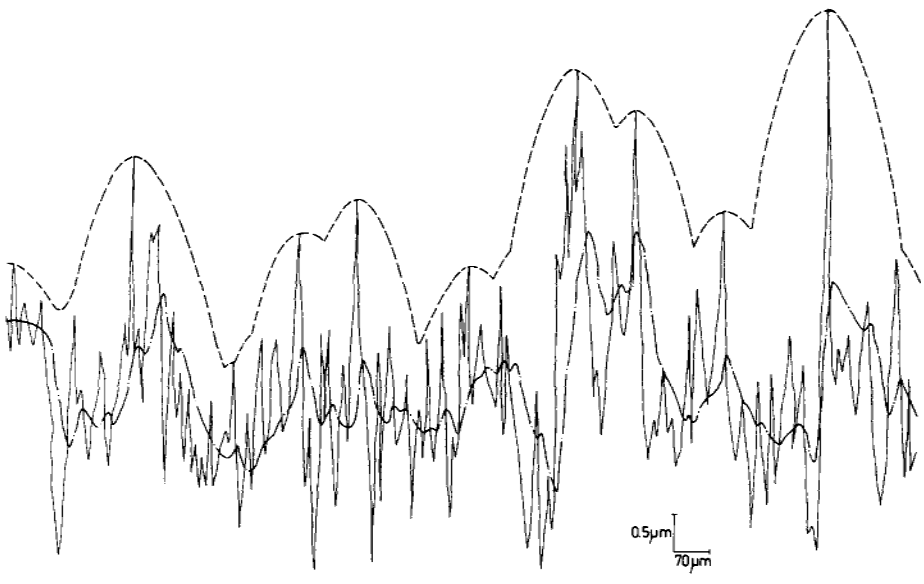


Fig. 2. Profile of a turned surface and its reference lines (details as in Fig. 1 except that the cut-off is 0.25 mm).

Table 1 the roughness values are different for the replica. The shape of the reference lines is seen in Figs. 1 - 3. The ground surface (Fig. 3) clearly shows the difference between the replica and the original profile, with regard to their peak heights and spacings. To bring out this difference more clearly, the peak distributions for the original profile and the replica are given in Fig. 4, for the three surfaces shown in Fig. 3. The distribution is obtained by dividing the range $\pm 5\ \sigma$ (σ is the standard deviation) into 50 classes and by classifying after conversion to a zero mean value. On comparing the original profile with the replica, the R_p values for the three surfaces are found to be dependent on the standard deviation of the peak ordinate heights. A greater



(a)



(b)

Fig. 3. Profile of a ground surface and its reference lines (details as in Fig. 1 except that the cut-off is 0.25 mm).

spread of the peak heights results in higher R_p values. The shaped and turned surfaces having greater dispersions of peaks in the original profile have higher roughness values in the E system. Peaks of the replica of the ground surface have a greater standard deviation, resulting in a higher R_p value.

TABLE 1

Process	Roughness value (μm)		
	M system R_a (cut-off in mm)	E system R_p (circle radius: 3.2 mm)	
	Original and replica	Original	Replica
Shaping	16.363 (0.75)	38.23	22.23
Turning	2.289 (0.25)	5.301	5.068
Grinding	0.718 (0.25)	1.530	2.099

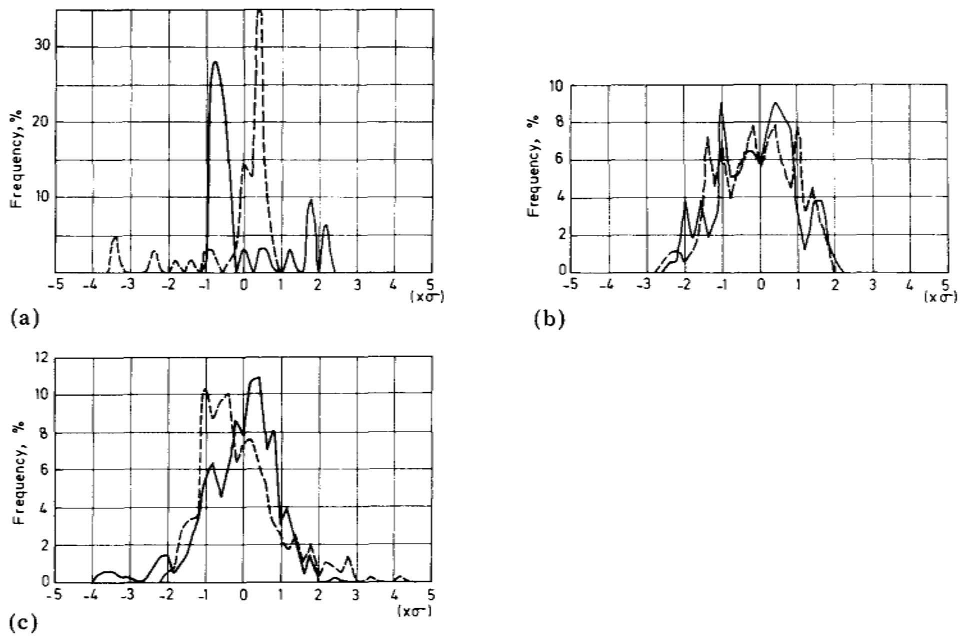


Fig. 4. Peak distribution; $\bar{X}$ is the mean value (μm), σ is the standard deviation (μm) and N is the total number of peaks. (a) Shaped surface: —— original profile ($\bar{X}$ = 29.65, σ = 22.45, N = 32); — — — replica profile ($\bar{X}$ = 52.18, σ = 15.45, N = 63). (b) Turned surface: —— original profile ($\bar{X}$ = 13.35, σ = 3.665, N = 156); — — — replica profile ($\bar{X}$ = 13.93, σ = 3.534, N = 179). (c) Ground surface: —— original surface ($\bar{X}$ = 6.07, σ = 1.0325, N = 369); — — — replica surface ($\bar{X}$ = 6.037, σ = 1.127, N = 379).

Analysis based on information theory

The usual statistical height distribution plots do not include the sequence of variation in height along the length of the profile. However, with the stationary and ergodicity assumptions of the stochastic process, a detailed investigation of the surface can be carried out to get this information

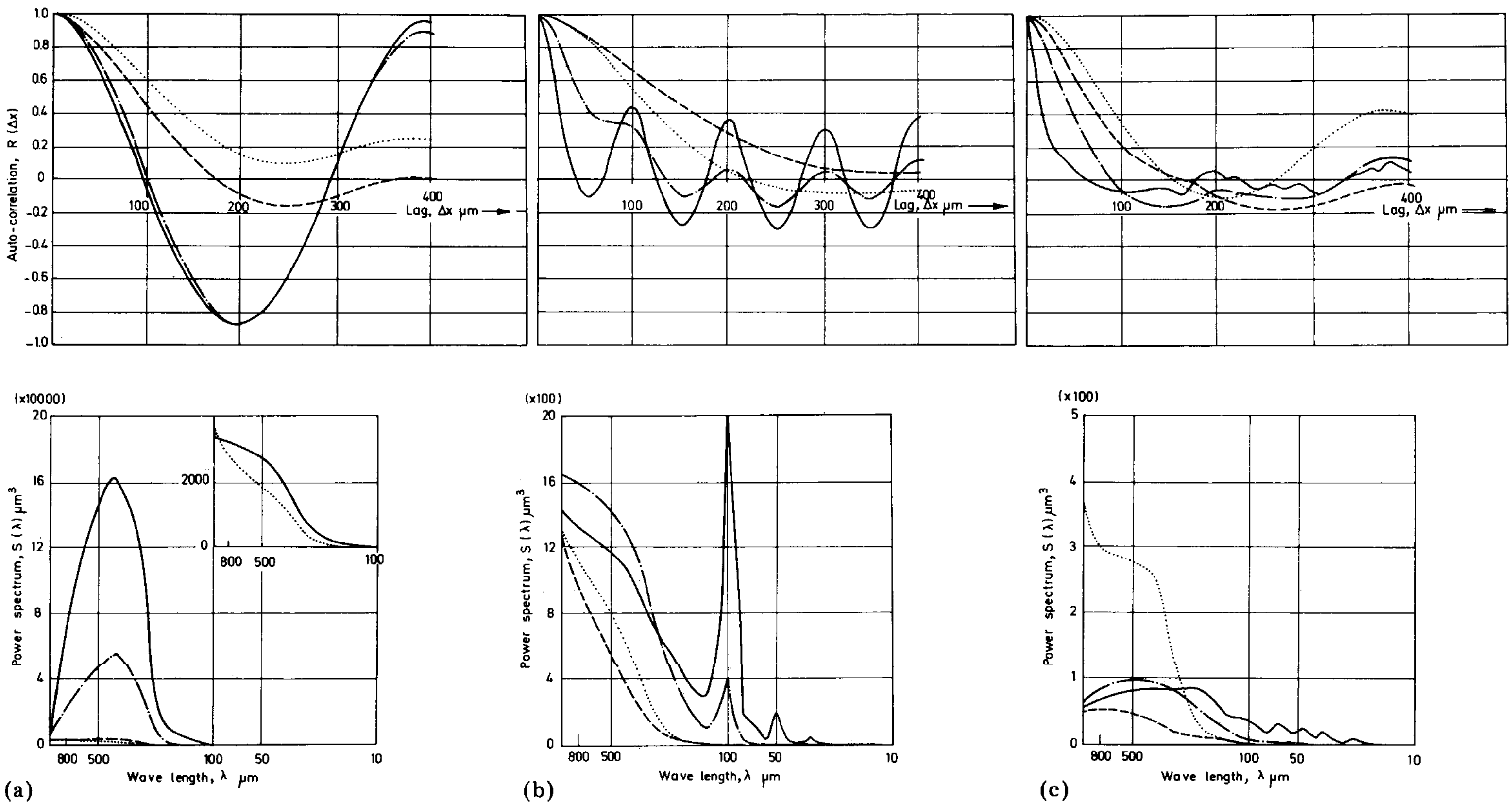


Fig. 5. Autocorrelation and power spectrum; ——— profile and its replica (σ_1, μm); —.—.— electrical mean line for the original and replica profiles (σ_2, μm); - - - - - - envelope for original profile (σ_3, μm); .... envelope for replica profile (σ_4, μm). (a) Shaped surface (σ_1 = 20.4, σ_2 = 11.82, σ_3 = 3.22, σ_4 = 2.61), (b) turned surface (σ_1 = 3.59, σ_2 = 2.71, σ_3 = 1.615, σ_4 = 1.81), (c) ground surface (σ_1 = 1.11, σ_2 = 0.738, σ_3 = 0.467, σ_4 = 1.085). The rolling circle radius is 3.2 mm; the cut-off is 0.75 mm for shaped and 0.25 mm for turned and ground surfaces.

[10, 11] using the autocorrelation function and its Fourier transform, *i.e.* the power spectrum [12, 13].

The autocorrelation function gives a clear idea of the randomness or the periodicity present in the profile. When the profile is perfectly periodic, the autocorrelation function is also periodic. However, for ideally random profiles the autocorrelation function approximates to an exponential function, falling to zero. The decay constant for this exponential function characterises the type of random profile. As it decreases, the autocorrelation function falls very slowly to zero, at which point a constant autocorrelation function is obtained leading to a deterministic profile, *i.e.* a straight line [14]. The power spectrum shows the same information in the frequency domain. From these plots the predominant frequency can be obtained directly. This, like the autocorrelation function, also contains information about the standard deviation of the profile. The area under the spectral density curve gives the standard deviation (r.m.s.) of the profile.

Figure 5 shows the normalised autocorrelation functions and the power spectra for different surfaces, replicas and their reference lines. The shaped surface exhibits periodicity in the autocorrelation function and a peak in the power spectrum (Fig. 5(a)). This profile is highly periodic due to the feed marks on the surface. The autocorrelation function and the spectrum remain the same for the replica. The electrical mean line of this profile has an autocorrelation function which closely fits that of the profile. Its power spectrum shows a peak which corresponds to the periodicity of the profile, but which has a lower spectral density (Fig. 5(a)) due to the elimination of the shorter waves and to the reduced amplitude of the electrical mean line. Although the cut-off used is 0.75 mm compared with the feed of 0.4 mm per stroke, a certain percentage of the amplitude of this shorter wave corresponding to the feed is also contained in the electrical mean line owing to the rolling off nature (not sharp) of the transmission curve of the standard filters. The envelopes with a radius of 3.2 mm do not show the frequency corresponding to the feed mark. In comparison with the electrical mean line, these envelopes have a very low spectral density lying close to the frequency axis and are flatter. The envelope of the replica profile is more flattened, but owing to the convex nature of the replica profile it gives a lower R_p value (Table 1). The autocorrelation function of the turned surface has a lower amplitude due to the randomness contained in the profile (Fig. 5(b)). The power spectrum has a high peak showing the presence of a periodic wave. Due to the flattened envelope and the concave nature of the original profile, a higher R_p value is obtained for the original surface.

The ground surface (Fig. 5(c)) has very weak periodic waves with a high random content, as seen by the steep fall of the autocorrelation function and as confirmed by the spectral density plot. The reference lines contain longer waves and the randomness present in the lines is not as high as in the profile or its replica. Compared with the original profile, the envelope of the replica shows a prominent periodicity due to the presence of very high peaks. This wavy envelope leads to a higher R_p value (Table 1).

Conclusion

From the analysis, measurements based on the M system do not differentiate between the original profile and its replica. The E system gives different roughness values for the original profile and its replica, depending on the concave or convex nature of the profile and the waviness defined by the peaks in the profile. Highly random surfaces, such as ground surfaces, exhibit deep scratches rather than high peaks and the spacing of the peaks and the valleys differs. Such variation gives a different value for R_p by the E system. All statistical functions, except the height distribution, remain the same for the profile and its true replica. Statistical analysis is in progress to study replicas in different materials and their ability to give a good representation of the surface.

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