Comparison of surface roughness measurements by stylus profiler, AFM and non-contact optical profiler

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Abstract

Surface roughness measurements were performed on a glass–ceramic disk substrate by stylus profiler (SP), atomic force microscope (AFM) and non-contact optical profiler (NOP). Results of surface measurements are presented and the differences between SP, AFM and NOP roughness measurements are discussed. The effects of stylus size, scan size and sampling interval on roughness parameters are investigated. The methodology of choosing the scan size and sampling interval is suggested. AFM is concluded to be the most suitable surface measuring instrument for roughness measurement on the glass–ceramic substrate. If SP is used to make the measurement, the tip radius should be in the order of 0.2 μm. However, localized damage to the test surface may occur owing to high contact stress. NOP using an objective magnification of 40 or lower is not recommended because the glass–ceramic substrate contains submicron roughness.

Keywords: Comparison of surface profilers; Stylus size; Scan size; Sampling interval; Glass–ceramic thin film disk substrate

1. Introduction

Surface topography plays an important part in understanding the nature of sliding surfaces. No matter how finely finished, most machinery rubbing surfaces are rough from a microscopic viewpoint. As a result, the microtopography of a single surface and the nature of a contact between two surfaces form an essential background for developing a fundamental concept of the nature of friction between two sliding surfaces.

In recent years, the availability of modern measuring technology and the advent of the digital computer have enabled us to measure and describe the shape of surface. There are a large number of different types of surface measuring instruments (e.g. optical, electrical, hydraulic, pneumatic), a review of some of these is contained in [1–3].

The measurement technique can be divided into two broad categories: (1) contact types and (2) non-contact types. On the microscopic scale of surface measurements, a contact type stylus profiler (SP) using electronic amplification is the most popular. In SP, the stylus is loaded on the surface to be measured and then moved across the surface at a constant velocity to obtain surface height variation [3,4]. More recently, a non-contact optical profiler (NOP) [5–9] based on the principle of two-beam optical interferometry was developed and is now widely used in industry.

On the ultramicroscopic scale of surface measurements, two techniques, namely scanning tunneling microscopy (STM) and atomic force microscopy (AFM) have recently been developed to obtain fine details of surfaces on a molecular scale. In STM, a metal tip is maintained within a very small distance (usually 0.2 nm) from the surface to be measured. A voltage is applied between the two electrodes of the metal tip and the test surface. A tunneling current will flow between the two electrodes according to their separation. By moving the metal tip across the surface at a constant reference level, the tunneling current, which changes with the surface height variation, can be measured and the corresponding topographic structure of the surface can be obtained. Alternatively, the current can be maintained by a control feedback system at a constant value by moving the metal tip away or closer to the surface. The movement of the metal tip represents the surface height variation.

STM requires that the surface to be measured be electrically conductive. This restriction is removed by the introduction of AFM which combines the principles of the STM and the stylus profiler. In AFM, the force between the tip and sample is detected rather than the tunneling current to sense the proximity of the tip to the sample. A sharp tip with a radius of about 20 to 50 nm, located at the end of a lever made of material with extremely low stiffness, is maintained in contact with the surface under very small loads (typically...
in the order of 1 nN). The normal force on the tip can be calculated by the deflection and spring constant of the lever. As the tip is moved across the surface, the normal force is kept constant by moving the sample away or closer to the scanned surface by a control feedback system. The movement of the sample represents the surface height variation. AFM can also be used for other measurements associated with forces, such as magnetism, electrostatic attraction, chemical attraction, adhesion, friction, wear and lubrication [10].

The topographic structure of a surface is generally digitized through the use of fast analog to digital conversion techniques in a microcomputer linked to a surface measuring system. The surface data can then be analyzed to study the importance of surface texture in its relation to the surface performance. But the question is, what features of the texture are important. Some features appear as roughness in one application of a surface may well constitute waviness in another. To complicate the problem further, surfaces cover a broad bandwidth of wavelengths and measured surface profile depends on the scale of measurement, whereby real surfaces reveal new complexities in their structure as this is examined in finer and finer detail. It has been argued by Sayles and Thomas [11] that this is an inescapable consequence of the mechanism of their formation. Surface measurement is also limited by the resolution of surface measuring instruments where the real surface topography may be misrepresented owing to finite dimension of the stylus tip of stylus instruments [3,4,12,13] stylus kinematics [14] stylus load [1,4], electrical filtering [11], size of the photodiode detector and objective lens magnification used by a non-contact optical profiler (NOP) [1] and errors in sampling due to discretization process [1,3,15,16]. Errors caused by the stylus dimension have been investigated by a number of workers [14,17,18] using different machined surfaces (turned, ground, planed or milled), it was concluded that the error caused by a 2 μm radius tip was not significant. However, it should be noted that roughness of the surfaces they used was in the range of 0.1–1 μm \( R_s \) (center-line average roughness) or higher. The wavelength structure or correlation length of the surface was considerably longer than many surfaces used today. In view of the so-called scale-of-size problem, 2 μm radius tip may not present a problem in the past. In the ever growing magnetic storage industry, the roughness of the media surface is required to be as smooth as possible to increase the storage density. The thin film disk surface of rigid disk drive is on the order of 2 nm RMS. It has been known the disk surface texture plays an important role in controlling the disk's performance and durability [19,20]. In order to assess the disk surface roughness in its relation to the disk's performance and durability, accurate roughness measurement is essential. Most commonly used instruments in the magnetic recording industry are NOP (400× objective magnification) and SP (SP-P2 with either 2 μm tip radius with 20 mg load or 0.2 μm tip radius with 0.5 mg load). Stylus measurements by a disk manufacturer are made as follows: Measurements are made along radial lines every 60° apart. At each location, 25 μm long profiles are made 10 times to get a total profile length of 250 μm. An average value of RMS roughness or other surface parameters are then calculated. In view of the roughness scale of disk surface, the adequacy of using the 2 μm radius tip is doubtful and require further investigation.

In this paper surface roughness of a glass–ceramic disk substrate, being developed for construction of data processing magnetic disks, was measured by SP, AFM and NOP. Roughness parameters such as RMS roughness \( R_p \), peak to valley distance P–V, mean roughness \( R_m \), correlation length \( \beta \) are used to compare the difference between SP, AFM and NOP roughness measurements [21]. The effect of stylus size, scan size and sampling interval on roughness parameters are investigated. The methodology of choosing the scan size and sampling interval is suggested.

2. Roughness measurements

In this section, surface roughness of a glass–ceramic substrate was measured by SP, AFM and NOP. Comparison of the results are presented in next section.

2.1. Measurement by stylus profiler (SP)

Surface roughness profiles were initially measured by Ten- cor alpha-step 200 (SP-α200) using a 5 μm radius tip with 9 mg stylus load and a 0.1 μm radius diamond tip with the minimum applicable 1 mg stylus load. When SP-α200 was used for roughness measurements, two important problems were experienced. Firstly, roughness profiles were found to contain significant low frequency noise which must be removed before surface roughness parameters can be accurately calculated. A digital filter known as cubic spline filter method is used to remove the low frequency noise from the raw data of SP-α200 measurements. The identification and the removal of the low frequency noise by the cubic spline filter are discussed in detail in Appendix A. Secondly, when the 0.1 μm radius tip is used, surface indentation higher than the surface height variation is found to produce even at a minimum applicable 1 mg stylus load. Because of presence of pits, it is difficult to see the damage. Therefore, to demonstrate that damage can occur, a smooth Ni–P coated Al–Mg surface of comparable hardness was scanned. Fig. 1 shows the micrographs of surface damage produced by a 0.1 μm radius tip sliding on the Ni–P coated Al–Mg substrate under 1 mg load. Fig. 1 (a) is the optical micrograph showing significant damage at the starting point owing to the kinematics of dropping stylus. Away from the starting point, a visible track can be seen and a higher magnification of this track by SEM is shown in Fig. 1 (b). The maximum contact pressure \( P_o \) of the stylus on the flat surface can be calculated by the Hertzian equations of a ball on a flat surface, given by

\[
P_o = \left( \frac{6WE}{\pi R^2} \right)^{1/3}
\]
where \( W \) is the stylus load, \( R \) the stylus tip radius and \( E' \) the effective Young’s modulus of two contacting bodies equal to
\[
\left( \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \right)^{-1}
\]

Taking \( R = 0.1 \mu m, W = 1 \text{ mg} \) for glass–ceramic, Ni–P and diamond tip as 83, 130 and 1140 GPa respectively and the corresponding \( v \) as 0.25, 0.36 and 0.07, the maximum Hertzian pressure \( p_{ij} \) is 11.4 and 15.0 GPa for glass–ceramic and Ni–P respectively, which is higher than the hardness (about 5.5 GPa Knoop hardness) of glass–ceramic and Ni–P substrates [22]. If the radius of disk asperities is included, the maximum contact pressure will be even higher. Therefore, the surface damage is expected to be produced by plastic deformation. Fig. 2 shows the profiles of glass–ceramic and Ni–P coated Al–Mg substrates at different locations (about 10 \( \mu m \) apart) using a 0.1 \( \mu m \) radius tip under stylus load of 1 mg, 4 mg and 9 mg. It can be seen that surface height variation, produced by plastic deformation, increases with stylus load.

The problem of stylus indentation is minimized by Tencor P2 (SP-P2) using a 0.2 \( \mu m \) radius tip and 0.5 mg stylus load. Roughness profiles given by SP-P2, as will be shown later, do not contain steep valley. Therefore, stylus indentation, if it exists, is not significant. However, the problem of low frequency noise still remains in SP-P2 measurements.

As explained in Appendix A, the low frequency noise of SP-a200 or SP-P2 exists in time domain, i.e. a profile measured in a longer period of time is expected to contain more of the low frequency noise. Fig. 3 shows two profiles of the glass–ceramic substrate having the same scan size \( L = 400 \mu m \) measured at the same location by SP-a200. Profile (a) contains 400 data points measured in 8 s while profile (b) contains 2000 points measured in 40 s. The pair of profiles (a) and (b) are expected to have similar \( Rq \) values since \( Rq \) is not sensitive to sampling interval \( \tau \), sometimes referred to as sampling distance or sampling resolution [23]. The waviness in profile (b) is believed to be low frequency noise. The roughness profiles, shown in Fig. 4 as given by SP-P2, also show the similar pattern. These two profiles have the same scan size of 100 \( \mu m \) at the same location. Profile (a) contains 500 data points measured in 10 s and profile (b) contains 5000 data points measured in 100 s. The waviness in profile (b) is not expected from the surface and believed to be the low frequency noise.

In the SP-a200, various scan lengths \( L \) and sampling intervals \( \tau \) can be selected by the user. The maximum \( L \) is 2 mm and two values of \( \tau \) can be selected for a given \( L \) and they are 0.04 \( \mu m \) and 0.2 \( \mu m \) for \( L \leq 80 \mu m \), 0.2 and 1.0 \( \mu m \) for \( 80 \mu m < L \leq 400 \mu m \) and 1.0 \( \mu m \) and 5.0 \( \mu m \) for \( 400 \mu m < L \leq 2000 \mu m \). For each scan length of 80 \( \mu m \), 400 \( \mu m \) or 2000 \( \mu m \), the profile contains two different number of sampling points 400 and 2000. SP-a200 only provides a filter for removing high frequency signal using a cut-off of 5 Hz. High frequency noise of SP-a200 has been investigated and was concluded to be insignificant. By turning the filter on, real surface fine features may be smoothed out without justification. Therefore, the filter was turned off to obtain raw roughness profiles. The scan size and sampling interval of the measurements are 80 \( \mu m \) and 0.04 \( \mu m \), 400 \( \mu m \) and 0.2 \( \mu m \) and 2000 \( \mu m \) and 1 \( \mu m \) respectively. All profiles contain...
Fig. 5. SP-a200 profiles with different scan sizes measured in 40 s after low frequency noise removal.

Fig. 6. SP-P2 profiles with different scan sizes measured in 40 s after low frequency noise removal.

2000 data points collected in 40 s. The low frequency noise was removed externally by a digital filter known as cubic spline filtering method as explained in Appendix A. Referring to Appendix A, the low frequency noise is removed using a cut-off length equal to the length measured in 4 s. Therefore, the filter lengths used are 8 μm, 40 μm and 200 μm, respectively. The filtered profiles are shown in Fig. 5. A faster scan was not used because the corresponding number of data points and sampling interval are reduced. It has been shown that the glass-ceramic substrate contains submicron detail and longer sampling interval may result in loss of information.

Using a smaller stylus tip and lower stylus load, raw roughness profiles were measured by SP-P2. The scan size and sampling interval were 80 μm and 0.02 μm, 400 μm and 0.2 μm and 800 μm and 0.4 μm, respectively. The top profile contains 4000 data points and the bottom two contain 2000 data points collected in 40 s. The filtered lengths to remove the low frequency noise from the profiles are 8 μm, 40 μm and 80 μm. The filtered profiles are shown in Fig. 6.

2.2. Measurement by atomic force microscope (AFM)

Three-dimensional surface roughnesses were measured on the glass-ceramic substrate. The scan size by AFM can be chosen any value up to 100 μm. Each measurement contains 256 × 256 data points. Therefore, the sampling interval is determined by the scan size. In the surface measurement by AFM, the scan sizes are 4 μm, 8 μm, 16 μm, 32 μm, 64 μm and 100 μm. During the measurement, errors can easily occur by external vibration, improper engagement of the tip on the sample. The error can easily be detected by in situ comparison of the trace and retrace profiles viewed on a monitor. The three-dimensional profile were taken in a raster scan pattern. Fig. 7 shows the surface maps of glass-ceramic substrate for the scan size 4 μm, 8 μm, 16 μm and 64 μm.

Fig. 7. AFM surface profiles: (a) L=4 μm, τ=0.016 μm; (b) L=8 μm, τ=0.031 μm; (c) L=16 μm, τ=0.063 μm; (d) L=64 μm, τ=0.25 μm.
obtained from two and three-dimensional measurement is 

profile, roughness parameters is presented. For a two-dimensional Line profiles (two-dimensional) were made by SP while NOP. Obviously, two-dimensional profile is different from difference between the roughness parameters R,, R, are used to compare the differences between the roughness measurements by SP, AFM and NOP. Line profiles (two-dimensional) were made by SP while surface profiles (three-dimensional) were made by AFM and NOP. Obviously, two-dimensional profile is different from three-dimensional profile and the corresponding roughness parameters may also be different. In the following, the difference between the roughness parameters R,, R,, P-V obtained from two and three-dimensional measurement is first discussed before comparison of SP, AFM and NOP roughness parameters is presented. For a two-dimensional profile, Rq is given by

\[
R_q = \left( \frac{1}{n} \sum_{i=1}^{n} z_i^2 \right)^{1/2}
\]

where zi is the surface height from a reference line at point i. For a three-dimensional surface, Rq is calculated by including all surface heights from the reference plane. For an isotropic, Gaussian surface, it can be shown that Rq given by a two-dimensional profile is the same as given by a three-dimensional profile [21]. If the reference line is same as the mean line, then Rq is equal to the standard derivation of surface heights σ. In this paper, Rq is equal to σ.

Rp is the distance between maximum peak or summit and mean line. For a two-dimensional profile, the peak is defined as a point higher than its two adjacent points greater than a threshold value. For a three-dimensional profile, the summit is defined as a point higher than its four adjacent points greater than a threshold value. P–V is given by the distance between maximum peak or summit to minimum valley. A valley is defined in the same way as a peak or a summit but in a reversed order.

Nayak [25] modeled rough surfaces as isotropic, Gaussian random processes, and analyzed them with the techniques of random process theory. He obtained expressions of the distribution of peak height, profile slope, profile curvature for two-dimensional profile and the distribution of summit height, surface gradient and surface curvature for three-dimensional profile in terms of the spectral moments m0, m2 and m4. For the comparison between the distribution of peak height with summit height, he concluded that the mean/maximum peak height is lower than the mean/max summit height, i.e. R,,(2D) < R,,(3D). Although Nayak [25] has not shown the difference between the valley height of a profile and that of a surface. By direct analogy, it is expected P–V(2D) < P–V(3D). Therefore, one should be careful to interpret the difference between the two-dimensional and three-dimensional measuring instruments in terms of R,, and P–V.

R,, Rp and P–V are vertical roughness parameters. β* is a spatial parameter giving information about how surface heights are oriented in space. The knowledge of spatial variation in surface height is essential, as it affects the distribution and density of asperity contacts. Whitehouse and Archard [12] expressed the plasticity index in terms of Rq and β*. Hirst and Holland [26] provided experimental evidence that surface damage can be related to R,, as well as β*. β* is given by the autocorrelation function (ACF). For a two-dimensional profile, the ACF is defined as

\[
\rho(\tau) = \frac{1}{\sigma^2 L} \int_{-L/2}^{L/2} z(x) z(x+\tau) \, dx
\]

or

\[
\rho(\tau) = \frac{1}{\sigma^2} \sum_{i=1}^{n} z_i z_{i-\Delta \tau}, \Delta \tau \quad \text{where} \quad \sigma = R_q
\]

An exponential model found to fit the autocorrelation function of random surfaces is

\[
\rho(\tau) = \exp \left( -\frac{\tau}{\beta^*} \right)
\]

where 1/β* is the decay rate of the function. The correlation length can be defined as ρ(τ) = 0.1 (when τ = 2.3β*) or ρ(τ) = 1/ε (when τ = β*). Both forms are considered to be a measure of the length at which single height readings become statistically independent of one another. In the calculation of β* from SP, AFM and NOP measurement, β* is given by ρ(τ) = 1/ε. To make a convenient comparison of β* given by two and three-dimensional measurements, AFM and NOP profiles are considered to contain 256 line profiles. β* is calculated by the averaged value of the 256 profiles.
In the following, comparison of the roughness parameters given by SP, AFM and NOP is presented. All parameters were calculated by in-house statistical software in our laboratory. Roughness parameters by SP-α200 and SP-P2 respectively, are calculated from the filtered profiles shown in Fig. 5 and Fig. 6. In the calculation of peak/summit from the measured data, the peak/summit was taken at least 0.5 nm above the adjacent points to reduce the effect of noise and ensure that every peak or summit identified is truly substantial. The variation of \( R_q, R_p, P-V \) and \( \beta^* \) given by SP, AFM and NOP for different scan sizes are shown in Fig. 9. The results are summarized as follows:

1. \( R_q, R_p, P-V \) values given by different measuring instruments increase in the following order, NOP < SP < AFM.
2. \( \beta^* \) generally increases with the scan size and increases in the order AF'M < SP < NOP.
3. By using a finer tip radius on SP, \( R_q, R_p, P-V \) values increase and \( \beta^* \) decreases.
4. From the AFM measurement, \( R_q, R_p, P-V \) values increase with the scan size initially and each appears to approach a constant value for the scan size greater than 16 \( \mu m \).

4. Discussions

From the roughness measurements on glass-ceramic substrate, the roughness parameters \( R_q, R_p, P-V \) and \( \beta^* \) have been shown to be different by SP, AFM and NOP. SP and AFM are stylus instruments from which surface roughness is obtained by the locus of some points on the stylus. Owing to the finite dimension of the stylus tip, it may not reach the bottom of the steep-sided features. The stylus size used by SP is different from AFM. It is natural to investigate the effect of stylus size on the roughness measurement in an attempt to explain the difference between SP and AFM roughness parameters. On the other hand, the sampling interval of the roughness measurement by SP, AFM and NOP is different owing to different spatial resolution and measuring ranges. The effect of sampling interval on the roughness measurement are discussed and the choice of a suitable sampling interval for a given wavelength feature are suggested.

4.1. Effect of spatial resolution

The spatial resolution refers to the stylus size of SP and AFM and magnification of the objective lens used in NOP for roughness measurement. For stylus instruments, the ability of the stylus to reproduce the original surface features depend on the stylus size. The smaller the stylus size, the closer it will follow the original profile. The stylus tip radius of AFM is smaller than SP and therefore AFM measurement is expected to be more accurate. A profile measured by AFM is used to assess the effect of stylus size on the accuracy of roughness measurements. Fig. 10 shows the loci of different stylus radii on a AFM profile. By increasing the stylus size, the original profile is distorted resulting in the underestimation of \( R_q \) and the overestimation of \( \beta^* \). \( R_q \) drops from 4.70 \( \mu m \) to 4.06 \( \mu m \) by 14% and \( \beta^* \) increases from 0.16 \( \mu m \) to 0.44 \( \mu m \) by 175% when the stylus tip radius increases to 5 \( \mu m \).

NOP is an optical technique to measure surface roughness using the optical interference technique. The light intensity of the fringes is related to the surface height. In the optical system, the fringe pattern is discretized into 256 × 256 pixels. Within one pixel or one sampling interval, the light intensity
Fig. 10. Simulated profiles of different stylus sizes sliding on the original AFM profile.

Fig. 11. Comparison of AFM, SP-P2, SP-α200 and NOP profiles extracted from the measurements. The profile length and sampling interval are chosen to be about the same in order to make a fair comparison between AFM, SP and NOP measurements. The maximum scan size of AFM measurement is 100 μm and the sampling interval of NOP measurement is 1 μm. The profile length and sampling interval are chosen as 100 μm and 1 μm respectively. The AFM profile is extracted from a three-dimensional surface profile of scan size 100 × 100 μm². Every third point of profile initially containing 256 points is selected to give 1.12 μm sampling interval. The SP-P2 profile is obtained from one section (100 μm in length) of the profile in Fig. 6(b) and then every fifth point is selected to give 1 μm sampling interval. The SP-α200 profile is obtained from the first 100 points of the profile in Fig. 5(b). The NOP profile is extracted from a three-dimensional surface profile and the corresponding profile is 250 μm long containing 250 points. The first 100 points are used for the comparison. \( R_q \), \( P-V \), \( R_p \), and \( \beta^* \) of profiles are listed in Table 1. The ratio of \( R_q \) and \( \beta^* \) given by AFM, SP-P2, SP-α200 and NOP are 1: 0.94: 0.7: 0.5 and 1: 1.03: 1.5: 6.6 respectively.

From the above investigation, the roughness measurement are affected by the stylus size of a stylus instrument or the magnification of an optical instrument. From the profiles in Fig. 10 and Fig. 11, the vertical roughness parameters \( R_q \), \( R_p \) and \( P-V \) are seen to increase with the measuring instruments in the following order NOP < SP < AFM. On the other hand, the spatial parameter \( \beta^* \) is seen to decrease in the reverse order, i.e. AFM < SP < NOP. The results in Fig. 9 show a similar trend and therefore the differences are related to different instrument spatial resolution. The stylus tip radius of AFM is the smallest and the roughness measurement is expected to be more accurate than SP and NOP. By using a smaller radius tip, the accuracy of SP measurement have been shown to improve and therefore should be used.

4.2. Effect of scan size

It is commonly observed that the roughness parameters of engineering surfaces change with the scan size. In particular \( R_q \) and \( \beta^* \) generally increase with scan size. It is due to longer wavelength features are included as the scan size is increased [11]. From Fig. 9, \( R_q \), \( R_p \) and \( P-V \) are seen to increase with the measuring instruments in the following order NOP < SP < AFM. On the other hand, the spatial parameter \( \beta^* \) is seen to decrease in the reverse order, i.e. AFM < SP < NOP. The results in Fig. 9 show a similar trend and therefore the differences are related to different instrument spatial resolution. The stylus tip radius of AFM is the smallest and the roughness measurement is expected to be more accurate than SP and NOP. By using a smaller radius tip, the accuracy of SP measurement have been shown to improve and therefore should be used.
Fig. 12. AFM original profile and profiles with different sampling intervals showing the effect of aliasing.

If the sampling interval can be kept the same for all scan sizes, $\beta^*$ is expected to approach a constant value as the form shown in Figs. 9(a)–9(c). In order to show this view, ten successive 10 $\mu$m long profiles, each separating 10 $\mu$m apart and containing 512 points, were measured on the glass–ceramic substrate by AFM and then joined to form a 100 $\mu$m long profile containing 5120 data points. Before joining the profiles, it is important to include the slope or tilt of individual profiles. Otherwise, it will introduce a cut-off length of 10 $\mu$m and remove the wavelength features greater than 10 $\mu$m. After joining the profiles, a single least square line is used to remove the tilt from the roughness data and the corresponding profile is shown in Fig. 12(a). $\beta^*$ for different scan sizes can be calculated using different cut-off lengths in the cubic spline filtering method. The advantage of using this filtering method is that only one single profile is required in which roughness for different scan sizes can be studied by rejecting the waviness longer than the cut-off length. Therefore, the cut-off length is essentially the same as the scan size. Fig. 13 shows the variation of $\beta^*$ with cut-off length for the glass–ceramic substrate. As expected, $\beta^*$ approaches a constant value which is 0.33 $\mu$m for the cut-off length $\approx 16$ $\mu$m and therefore the long wavelength limit is 16 $\mu$m.

4.3. Effect of sampling interval

Sampling too often results in highly correlated and redundant information, whereas sampling too rarely may cause aliasing to occur. Aliasing results from the higher frequencies in the profile appearing as a lower frequency in the digitized signal [3,15]. The effect of aliasing is shown in Figs. 12(b)–12(d) in which different profiles with different sampling interval $\tau$ are obtained by using some alternate points of the original profile (a). As the sampling interval increases, the high frequency feature of the original profile gradually disappears and results in a larger value of $\beta^*$. The variation of $\beta^*$, $R_q$, $R_p$ and P–V with $\tau$ is shown in Fig. 14. $\beta^*$ remains at a constant value below a sampling interval of about 0.5 $\mu$m after which it continues to increase. However, the vertical roughness parameters $R_q$, $R_p$, and P–V do not change significantly with $\tau$. These results can help to explain why in Fig. 9 $\beta^*$ increases with scan size while $R_q$, $R_p$, and P–V remain constant. In all the measurements in Fig. 9, the sampling intervals for different instruments increase with scan sizes due to limited number of digitized surface points being used. The surface studied contains predominantly submicron details and increasing sampling interval will result in loss of information due to aliasing effect. As the sampling interval increases, high frequency features of the original profile gradually disappear and consequently $\beta^*$ increases with scan size as $\tau$ increases.

4.4. Selection of scan size

The selection of scan size and sampling interval can change the roughness parameters $R_q$, $R_p$, P–V and $\beta^*$. The question is: what are the suitable scan size and sampling interval? In this and the following subsection, the methodology of choos-

![Fig. 13. Variation of correlation length with cut-off length.](image)

![Fig. 14. Variation of $R_q$, $R_p$, P–V and $\beta^*$ with sampling interval.](image)
ing the scan size and sampling interval is discussed and example is provided based on the roughness measurements of glass–ceramic substrate.

In practice, the scan size should be related to the bandwidth covered by the nominal contact width of the physical problem involved. If a surface contains a broad bandwidth of wavelengths up to or longer than the contact width, then the scan size should be chosen as the contact width. On the other hand, if a surface contains a long-wavelength limit smaller than the contact width, then the scan size can be set equal to the long-wavelength limit. From the surface roughness measurement of glass–ceramic substrate disk, there exists a long-wavelength limit of about 16 μm, based on plots of statistical parameters as function of scan size (Fig. 9), which is far less than the nominal contact width of a magnetic slider on a hard disk. Therefore, the scan size of the roughness measurement for glass–ceramic substrate disk can be chosen as 16 μm.

4.5. Selection of sampling interval

The principal of choosing a suitable sampling interval can be illustrated by a sinusoidal profile represented by different number of sampling points per wavelength as shown in Fig. 15. The initial phase of a sinusoidal profile is chosen such that the profile has a minimum value of \( R_w \). The wave form of the sinusoidal profile is distorted when the number of sampling points decreases. The values of \( R_w \), \( R_p \), P–V and \( \beta^* \) for each curve have been calculated and do not change significantly until the sampling points equal to 6. Therefore, the minimum number of sampling points required to represent a wavelength structure may be set to 6, i.e. the optimum sampling interval is \( \lambda/6 \) where \( \lambda \) is the wavelength of the sinusoidal profile.

By analogy, the suitable sampling interval should be related to the wavelength structure of a random profile which is represented by \( \beta^* \). However, \( \beta^* \) is a function of the bandwidth of the measurement and thus is not intrinsic properties.

For a given scan size, \( \beta^* \) is mainly affected by the broad scale waviness structure and for convenient defined as the main structure and finer structure constitutes the roughness. In plastic deformation, the finer scale structure will be obliterate by plastic flow during the first traversal and the broader scale structure is more important. In elastic contact, the finer structure is also important for it affects the number, size and area of asperity contacts.

In the past, problems of contact were mainly focused on plastic deformation in which micro-asperities were assumed to be ironed out. It led some authors \([12, 27]\) to suggest a sampling interval of \( 2.3 \beta^* \) to be sufficient. In magnetic recording components, surface roughness can be produced in nanoscale and asperity contacts may be predominantly elastic. Using the plasticity index \( \psi \) derived by Onions and Archard \([27]\) based on Greenwood and Williamson’s approach \([28]\) \( \psi \) is given by

\[
\psi = \frac{E' R_w}{H \beta^*}
\]

The contact is predominantly elastic for \( \Psi < 0.6 \) and predominantly plastic for \( \Psi > 1 \). Taking the surface roughness and material properties of glass–ceramic substrate disk, we have \( R_w = 5 \text{ nm}, \beta^* = 0.33 \mu\text{m}, E' = 100 \text{ GPa} \) and \( H = 5.5 \text{ GPa} \) \([22]\). It follows that \( \psi = 0.28 \) and the contact is expected to be predominantly elastic. In fact, contact analysis has been performed by a 3D numerical rough surface contact model \([29]\). On the AFM profiles of different scan sizes. Under the practical nominal pressure of 0.032 MPa, asperity contact pressure was always found lower than \( H = 5.5 \text{ GPa} \) down to the scan size 4 μm with sampling interval 0.015 μm.

In elastic contact, sampling interval should be small to include the finer details. The question now arising is what the sampling interval is considered as sufficient to include the finer structure. From SEM images, surface contains finer and finer details as magnification increases. It suggests that there is no natural limit to the spatial size of features on most engineering surfaces. Intuitively, a natural limit must exist when approaching atomic dimensions, but in view of the scale of size involved its significance to most engineering applications will be negligible. \( \beta^* \) represents the main wavelength structure for a given size of interest, it is reasonable to use a fraction of \( \beta^* \), i.e. \( \tau = c \beta^* \), as an appropriate sampling resolution to collect details which are of significance to their contact.

In the past two decades, a statistical approach has been widely used to predict the relationship between load \( W \) and contact area \( A_c \) in terms of roughness parameters and material properties. Onions and Archard \([27]\) provide a simple expression of load/area in terms of \( R_w \) and \( \beta^* \) and \( E' \) (see Appendix B following the approach of Greenwood and Williamson \([28]\)). But their use of \( \tau = 2.3 \beta^* \) is considered to be too large for elastic contact. Considering \( \tau = c \beta^* \) to be of physical significance to the contact situation, Eq. (B4) in Appendix B becomes

![Fig. 15. Sinusoidal profiles with different number of sampling points per wavelength.](image)
As discussed in Section 4.3, sampling too rarely may cause aliasing to occur in which the digitized profile may not include the required finer scale structure. Referring to Fig. 14, aliasing occurs in the region where $\beta^*$ increases with $\tau$. Since $\beta^*$ of a surface must be first obtained before $\tau$ can be assessed. If initial $\tau$ is chosen in the aliasing region, $\beta^*$ will be overestimated and results in a larger $\tau$ than it should be. Therefore, $\tau$ should be chosen where $\beta^*$ does not change with $\tau$. It may be achieved by two or more measurements on the same location by different $\tau$ until the corresponding $\beta^*$ becomes stable.

From the 3D numerical rough surface contact analysis [29], $W/A_r$ and $E'R_{q}/\beta^*$ are related by Eq. (8) as shown in Fig. 16. It is interesting to note that the results represent different surfaces of various scan sizes and sampling intervals, i.e. from the roughness parameters $R_q$ and $\beta^*$, the real contact area can be predicted for a given load regardless of the wavelength or sampling interval. However, it does not imply that $W/A_r$ is independent of the scan size or sampling interval. $W/A_r$ is affected only by $R_q$ and $\beta^*$ which are dependent on scan size or sampling interval. Therefore, it is important to define the size of interest and sampling process based on the physical application so that appropriate roughness parameters can be obtained.

5. Conclusions

Comparison of roughness measurements of glass–ceramic substrate has been studied by SP, AFM and NOP. The accuracy of the measurement depends on the spatial resolution of the instrument. Poor spatial resolution will result in the underestimation of the vertical parameters $R_p$, $P-V$, $R_q$ and the overestimation of the spatial parameter $\beta^*$. The spatial resolution of instruments increase in the following order, NOP $<$ SP $<$ AFM. This explains why $R_p$, $P-V$, $R_q$ increase and $\beta^*$ decreases with NOP, SP and AFM measurements. AFM has better spatial resolution and therefore provides the most accurate roughness measurement.

From the AFM measurement of glass–ceramic substrate, the substrate was found to contain submicron wavelength structures. These submicron details, as have been shown in Fig. 10, are expected to be smoothed out by NOP measurement. Similarly, when the substrate roughness is measured by SP with 5 $\mu$m radius tip, the submicron details are expected not to be collected and results are expected to be accurate. If SP is required to perform the roughness measurement, a 0.2 $\mu$m radius tip is desirable to give a more accurate measurement.

The methodology of choosing the scan size $L$ and sampling interval $\tau$ has been discussed. The scan size can be chosen to be the nominal contact width of the physical problem involved or the long-wavelength limit, whichever the smaller. From the plot of statistical parameters as a function of scan size (Fig. 9 and Fig. 13), each parameter approach a constant value at a scan size of 16 $\mu$m and the corresponding $\beta^* = 0.33$ $\mu$m. Therefore, the long-wavelength limit of the...
glass–ceramic substrate disk is 16 μm which is much smaller than the contact width of head/disk interface of magnetic storage system. The scan size for the glass–ceramic substrate can be chosen as $L = 16 \mu m$ and the suitable sampling interval is given by $\tau = 0.4 \beta' = 0.1 \mu m$ as discussed in Section 4.5.

In conclusion, the remarks on using different surface measuring instruments on the glass–ceramic substrate are summarized as follow.

AFM
Most suitable for surface measurement on glass–ceramic substrate.
Sampling interval = 0.1 μm.
Scan size = 16 μm.

SP (Tencor)
Smaller stylus tip radius should be used.
Tip radius = 5 μm results in underestimation of $R_p$, $P-V$, $R_q$ and overestimation of $\beta'$. Tip radius = 0.2 μm is more desirable for glass–ceramic substrate.

NOP (Wyko)
Objective lens with magnification of 40 or lower is not suitable for measurement.

Acknowledgements

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Appendix A

Surface roughness measurements by stylus profilier using Tencor instruments of both models alpha-step 200 (SP-α200) and P2 (SP-P2) were found to contain low frequency noise which must be removed before surface roughness parameters can be accurately calculated. In the following, the identification and the removal of the low frequency are discussed in detail for SP-α200. SP-α200 only provides a filter for removing high frequency signal using a cut-off of 5 Hz.

High frequency noise of SP-α200 has been investigated and was concluded to be insignificant. By turning the filter on, real surface fine features may be smoothed out without justification. Therefore, the filter was turned off to obtain raw surface roughness profiles and analyzed by computer programming. An optical flat is used to investigate the waveband of the low frequency noise. The optical flat is known to have a RMS roughness $R_q$ value less than 1.5 nm for scan size above microscale. Fig. 17 shows the roughness profiles of the optical flat measured at the same location. The scan size is 80 μm for profiles (a) and (b), 400 μm for profiles (c) and (d) and 2000 μm for profiles (e) and (f). The profiles (a), (c) and (e) contain 400 data points measured in 8 s while the profiles (b), (d) and (f) contain 2000 points measured in 40 s. The pair of profiles (a) and (b), (c) and (d) or (e) and (f) are expected to have similar $R_q$ values since $R_q$ is not sensitive to sampling interval. However, the $R_q$ of the profiles (b), (d) and (f) consistently show a longer wavelength feature and have $R_q$ values higher than expected. On the other hand, the profiles (a), (c) and (e) have values of $R_q$ less than 1.5 nm and therefore expected to be the correct measurement. The long wavelength feature of profiles (b), (d) and (f) is believed to be low frequency noise and is not part of the real surface feature. The reason why these profiles possess a longer wavelength feature may be attributed to a longer sampling time of 40 s as compared with 8 s required for the corresponding profiles (a), (c) and (e). The longer it takes to measure the roughness profile, the higher the tendency for the profile to contain the system low frequency noise.

The wavebands of low frequency noise is investigated by a cubic spline filtering method in which the filter operates by splitting the profile into a series of cut-off lengths and then a cubic spline curve is fitted through the mean of each cut-off. Therefore, a cubic spline curve is obtained through the mean of each cut-off length [30]. For example, the profile (d) in Fig. 17 is used to show how the filter operates to separate waviness from the required roughness profile. For clarity, the original profile is reproduced as shown in Fig. 18(a). For a cut-off length of 200 μm. The profile is split into 400/200 = 2 cut-offs. A cubic spline curve is fitted through the mean of each cut-off and the low-pass output. By subtracting this low-pass output from the original profile, the resultant profile, shown in Fig. 18(c), is called the high-pass output which is free from the wavelength features greater than the cut-off length of 200 μm.

![Fig. 17. Optical flat roughness profiles measured by SP-α200.](image-url)

Appendix B

Onions and Archard [27] followed the approach of Greenwood and Williamson [28] and used a sampling interval of $\tau = 2.3\beta^*$ to relate area of contact and load in terms of $R_q$ and $\beta^*$ and the effective Young's modulus $E'$ of contacting bodies. From Eqs. (13b) and (14b) of their paper for real area $A_r$ and load $W$, the term $2.3\beta^*$ is replaced by $r$. Therefore

$$A_r = \pi \eta A_n (2.3\beta^*)^2 F_A(d) = \pi \eta A_n \tau^2 F_A(d) \quad (B1)$$

and

$$W = \frac{4A_n E' R_q}{15(2.3\beta^*)} F_w(d) = \frac{4A_n E' R_q}{15\tau} F_w(d) \quad (B2)$$

where $\eta$ is the density of asperities per unit area, $A_n$ the apparent area, $F_A$ and $F_w$ are integral functions depending on the separation $d$, normalized by $R_q$, from the mean line given in Table 2. From Eq. (B1) and Eq. (B2), $W/A_r$ is given by

<table>
<thead>
<tr>
<th>$d$</th>
<th>$F_A(d)$</th>
<th>$F_w(d)$</th>
<th>$F_w/F_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.3885</td>
<td>0.6120</td>
<td>1.5753</td>
</tr>
<tr>
<td>0.2</td>
<td>0.3035</td>
<td>0.4617</td>
<td>1.4966</td>
</tr>
<tr>
<td>0.4</td>
<td>0.2202</td>
<td>0.3381</td>
<td>1.5354</td>
</tr>
<tr>
<td>0.6</td>
<td>0.1568</td>
<td>0.2403</td>
<td>1.5325</td>
</tr>
<tr>
<td>0.8</td>
<td>0.1070</td>
<td>0.1647</td>
<td>1.5392</td>
</tr>
<tr>
<td>1.0</td>
<td>0.7050 x 10^{-1}</td>
<td>0.1098</td>
<td>1.5574</td>
</tr>
<tr>
<td>1.4</td>
<td>0.2760 x 10^{-1}</td>
<td>0.4392 x 10^{-1}</td>
<td>1.5913</td>
</tr>
<tr>
<td>1.8</td>
<td>0.9390 x 10^{-2}</td>
<td>0.1536 x 10^{-1}</td>
<td>1.6358</td>
</tr>
<tr>
<td>2.2</td>
<td>0.2805 x 10^{-2}</td>
<td>0.4695 x 10^{-2}</td>
<td>1.6738</td>
</tr>
<tr>
<td>2.6</td>
<td>0.7360 x 10^{-3}</td>
<td>0.1266 x 10^{-2}</td>
<td>1.7201</td>
</tr>
<tr>
<td>3.0</td>
<td>0.1710 x 10^{-3}</td>
<td>0.2988 x 10^{-3}</td>
<td>1.7474</td>
</tr>
<tr>
<td>3.5</td>
<td>0.2295 x 10^{-4}</td>
<td>0.4083 x 10^{-4}</td>
<td>1.7791</td>
</tr>
<tr>
<td>4.0</td>
<td>0.2493 x 10^{-5}</td>
<td>0.4494 x 10^{-5}</td>
<td>1.8027</td>
</tr>
</tbody>
</table>
W = \frac{4E'R_3}{A_1} \frac{F_W}{F_A} \frac{1}{\sqrt{\pi \tau}} \frac{F_A}{r} \tag{B3}

From Table 2, \(F_W/F_A\) stays about the same when \(d < 1.4\) and increases slightly when \(d > 1.4\). Since contact is expected to occur on the upper part of asperities, the ratio \(F_W/F_A\) is calculated from the averaged value between \(d = 1.4\) to 4.0 and gives \(F_W/F_A = 1.707\). Therefore, Eq. (B3) becomes

\[
\frac{W}{A_1} = 0.7245 \frac{E'R_3}{\tau} \tag{B4}
\]

References