On the characterization of surface topography at different length scales

Anand Panzade, Sandip Panda, Mihir Sarangi

Abstract

A concerted effort has been made to find an optimum way of characterizing roughness features of real engineering surfaces at different length scales with different instruments. Freshly prepared 316L stainless steel disc surfaces were measured by both contact stylus profilometer and non-contact optical profilometer. The roughness data obtained by two different instruments were then analyzed to obtain various statistical roughness parameters such as c.l.a, r.m.s, skewness, kurtosis, average slope, correlation length etc. Different methodologies to estimate the correlation length from surface heights data were also investigated. The effects of measurement length scale/instrument's cut-off length on roughness parameters have been studied. The role of correlation distance and plasticity index to determine suitable cut-off length for contact profilometer has been discussed in some details. The study has been concluded with some remarks on the suitability of using any particular instrument to connect the measurement scales with roughness scale and nominal contact width.

Keywords: Surface roughness, Autocorrelation function, Cut-off length, Plasticity index

1. Introduction

Real engineering surfaces have small scale geometric features with random shapes and sizes which are inherited from the machining processes. Such small scale geometric features are called asperities, and distribution of the asperities over the surface forms a random geometric structure which is in general known as 'surface roughness'. Surface roughness has an unquestionable role in determining and controlling the condition of friction, wear, lubrication, and any other surface emanated phenomena. A surface should be strictly called rough if there is any detectable undulation present at any length scale. All surfaces are microscopically rough at least at one or more length scales of magnification. A general typology of rough surfaces is shown in Fig. 1 [1].

Anand Panzade
Department of Mechanical Engineering, IIT Kharagpur, Kharagpur-721302, India, panzade.as@gmail.com

Sandip Panda (Corresponding author)
Department of Mechanical Engineering, IIT Kharagpur, Kharagpur-721302, India, sandippanda13@gmail.com

Mihir Sarangi
Department of Mechanical Engineering, IIT Kharagpur, Kharagpur-721302, India, smihir@mech.iitkgp.ernet.in

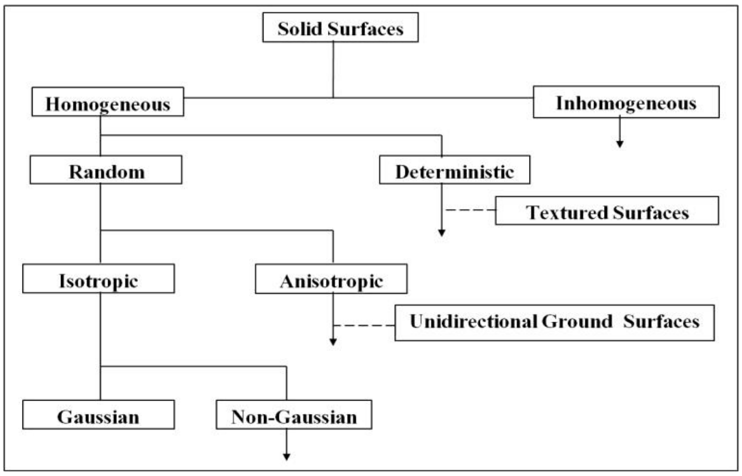

Fig. 1. General typology of rough surfaces [1]

Random micro-geometries of real engineering surfaces are complex by nature, and they do not follow Euclidian geometry; however, such geometries can be conveniently described with statistical description as well as with some other techniques such as fractals, wavelets etc. A three dimensional random structure of a solid surface and a schematic two dimensional representation of a profile are shown in Fig. 4.

Characterizing rough surfaces with statistical parameters is most common in practice because of simplicity involved in measuring and interpreting roughness data. The technique involved in obtaining the image of surface micro-geometry is called surface profilometry. The most common and widely used instrument to measure microscopic surface profile is the stylus profilometer, and a little unconventional one is the non-contact optical profilometer. More advanced methods to measure roughness particularly at nano-scale have also been introduced and popularized by several researchers, and these techniques involve use of sophisticated instruments like Atomic Force Microscope, Scanning Tunneling Microscope; Scanning Electron Microscope etc. [2, 5] . However, the present work will focus on measuring micro-scale surface roughness with the help of a contact stylus profilometer (SP) and a non-contact optical profilometer (NOP).

Surface roughness has significant impact on the contact condition and the resultant friction and wear [1, 4, 7]. Hence it has also been equally important to focus on proper characterization of geometric features of the contacting surfaces while studying contact between two surfaces. Despite wide acceptance of statistical roughness parameters, it must be noted here that these parameters are scale dependent as their magnitudes depend on the measurement scale or cut-off length of any particular instrument. This means that the measured shapes and sizes of asperities are influenced by the measuring instruments. Scale induced issues in statistical surface roughness characterization may be justified with the help of a parameter called ‘correlation distance’ [2, 3]. The objective of the present work is to analyze micro-scale roughness data to obtain the ‘correlation distance’, and to use it for comparing the surfaces with different roughness scales and associated measuring instruments.

2. Roughness Measurement Methodology

Numerous statistical roughness parameters may be obtained by analyzing the roughness data from any profilometer measurement. The parameters are generally categorized in three types: height parameters; spatial parameters; and hybrid parameters. Height parameters are obtained to measure variation of asperities along ordinate and with respect to a reference mean plane. Spatial parameters indicate the characteristics of the asperities along horizontal direction. Hybrid parameters are considered to be more powerful representation because these are obtained by combining both height and spatial characteristics of asperities. A complete description of the complex and random nature of surface roughness may not be obtained with one or few such parameters; however, the most commonly used parameters to describe a convincible characterization of the surface roughness are listed in Appendix B. In the present work, emphasizes were given on obtaining 'correlation distance' of the surfaces based on the roughness data obtained from a SP and an NOP.

2.1. Stylus Profilometer (SP) and Non-Contact Optical Profilometer (NOP) Measurement Techniques

Stylus profilometer works in contact mode with surface where a small diamond tip stylus is slightly loaded ($\sim 10^{-3}$ N) against the surface and moves at a constant speed to obtain surface data. The cantilever containing the diamond tip randomly oscillates due to surface undulations. These random oscillations of the cantilever is recorded, filtered, and amplified to produce a magnified image of the surface micro-geometry. In certain cases, stylus profilometer may damage the surface during measurement; hence the technique is not completely non-destructive. On the other hand optical profilometer works on the principle of either with light interference or with confocal microscopy schemes; and thus the technique is completely non-destructive. However, the surface under examination needs to have well reflectivity for better data acquisition. A detailed description of these instruments may be obtained in reference [6].

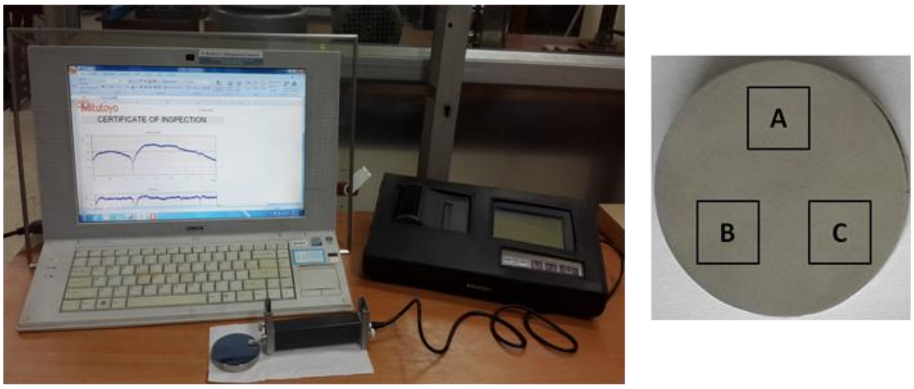

Fig. 2. Mechanical stylus probe type profiler (SJ-301) and Locations A, B and C on a sample surface (courtesy: Tribology Lab, Department of Mechanical Engineering, IIT Kharagpur)

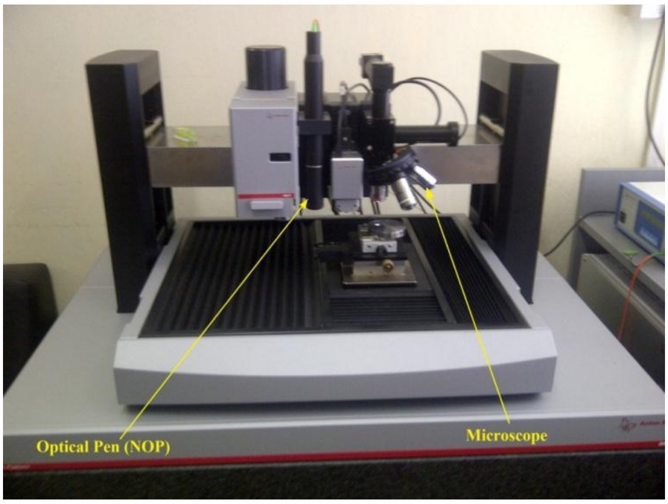

Fig. 3. NOP Instrument (courtesy: Tribology Lab, Department of Mechanical Engineering, IIT Kharagpur)

Surface heights data were obtained for each freshly prepared 316L stainless steel disc surfaces. The disc surfaces were mechanically-polished and lapped. Fig. 2 shows a sample disc surface with the marked locations for scanning. Two cut-off lengths 0.08 mm and 0.8 mm were selected for scanning with the SP, and a scanning area of 0.08 × 0.08 mm^2 and 0.8 × 0.8 mm^2 were chosen for the OP. OP scanning was performed first and then the SP scanning was done. Ten parallel scanning was done with the SP on the same location, and roughness parameters were obtained by taking average of 10 parallel profiles. The roughness measurement instruments and arrangements have been shown in Fig. 2 and Fig. 3.

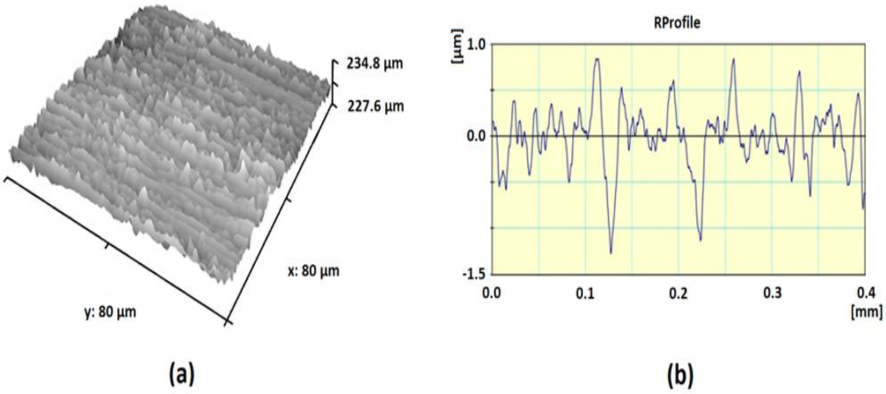

Fig. **4**. : Sample surface topography: (a) Optical profilometer; (b) Stylus profilometer
Four roughness parameters, namely, centre line average roughness (R_a), root mean square roughness (R_a), skewness (R_{sk}), kurtosis (R_{ku}) have been directly noted from the instruments' output, and correlation distance (β) has been obtained by analyzing the surface heights data. The roughness parameters have been shown Table 1.

Table 1: Measure roughness parameters

			Average Roughness Parameters					
			Location A		Location B		Location C	
			0.08	0.8	0.08	0.8	0.08	0.8
Surface 1	Profilometer	*Ra* (μm)	0.038	0.173	0.013	0.026	0.043	0.117
		Rq (μm)	0.05	0.233	0.021	0.036	0.058	0.157
		Rsk	-1.136	-0.69	-0.105	0.029	-1.32	-0.925
		Rku	5.208	4.456	3.12	3.617	5.926	7.169
	NOP	*Ra* (μm)	0.142	0.1	0.036	0.056	0.157	0.156
		Rq (μm)	0.190	0.178	0.051	0.1	0.215	0.226
		Rsk	0.247	0.401	-0.336	0.645	0.377	0.596
		Rku	3.793	8.380	6.294	6.861	5.420	7.450
Surface 2	Profilometer	*Ra* (μm)	0.197	0.416	0.193	0.296	0.2	0.383
		Rq (μm)	0.249	0.559	0.257	0.391	0.264	0.5
		Rsk	-0.582	-0.912	-0.256	-0.65	-0.533	-0.854
		Rku	3.375	5.486	3.621	4.635	3.947	5.157
	NOP	*Ra* (μm)	0.330	0.511	0.507	0.611	0.206	0.433
		Rq (μm)	0.427	0.756	0.644	0.867	0.278	0.622
		Rsk	-0.119	-0.232	-0.296	-1.238	-0.248	-0.706
		Rku	3.457	5.137	3.358	9.344	5.721	9.156
Surface 3	Profilometer	*Ra* (μm)	0.268	0.457	0.299	0.471	0.258	0.493
		Rq (μm)	0.331	0.593	0.37	0.614	0.32	0.661
		Rsk	-0.248	-0.687	-0.314	-0.661	-0.299	-1.082
		Rku	3.013	4.227	2.783	4.104	2.837	5.736
	NOP	*Ra* (μm)	0.415	0.522	0.429	0.511	0.444	0.611
		Rq (μm)	0.521	0.667	0.533	0.678	0.533	0.822
		Rsk	-0.305	0.055	-0.126	-0.220	-0.197	-0.224
		Rku	3.090	3.444	2.549	3.972	2.595	7.149

2.2 Estimation of correlation length using conventional methods

In the present study auto correlation function (ACF) and height-height correlation function (H-H) methods were used to evaluate 'correlation distance'.

An autocorrelation function is the arithmetic average of the product between the profile *z(x)* with its replica at $x=x+\tau$ i.e. $z(x+\tau)$. Mathematically, the autocorrelation function may be expressed as

$$C(\tau) = \frac{1}{R_q^2 L}\int_0^L z(x).z(x+\tau)dx \quad (1)$$

$$R_q = \left[\frac{1}{L}\int_0^L z(x)^2\right]^{1/2} \quad (2)$$

where L = sampling length.

The correlation distance is found by obtaining the length at which the ACF decays to near zero. In many cases the ACF appears as exponentially decaying function [2, 3]. The exponential form of ACF may be expressed as

$$C(\tau) = \exp\left(-\frac{\tau}{\beta}\right) \quad (3)$$

where β = correlation distance.

The relation between τ and β may be obtained by choosing the value of $C(\tau) = 0.1$, i.e. 10% of its original value. Thus, when the correlation drops to 10%, then $\tau = 2.3\ \beta$.

Sometimes a height to height correlation is also evaluated to obtain the correlation distance Eq. 4.

$$H_x(\tau_x) = \frac{1}{(N(M-m))} \sum_{l=1}^{N} \sum_{n=1}^{M-m} (z_{n+m,l} - z_{n,l})^2 \tag{4}$$

The exponential form of H-H may be given by

$$H_x(\tau_x) = 2\sigma^2 \left[1 - \exp\left(-\frac{\tau_x}{T}\right)\right] \tag{5}$$

While using H-H method, in theory correlation length is defined as the distance between origin and the point where H-H function becomes constant; which was usually observed in nano-scale surface measurement results [10]. In our cases, we have considered a distance upto first local maxima. Estimated correlation distances for all surfaces and at different measurement locations were reported in Table 2.

Table 2: Estimated correlation distance

		β (μm)					
		Location A		Location B		Location C	
		0.08	0.8	0.08	0.8	0.08	0.8
Surface 1	SP All Scan Average ACF	4.478	60.3	2.462	71.85	4.783	52.4
	SP All ACF Average	3.875	72.25	1.459	25.795	4.148	43.215
	SP All Scan Average H-H	16.318	116.25	11.31	292.2	13.675	128.05
	SP All H-H Average	9.488	204.1	10.678	145.75	15.41	159.65
	NOP ACF	0.9521	3.906	4.390	3.955	0.835	2.734
Surface 2	SP All Scan Average ACF	4.833	24.26	3.835	7.905	6.1325	16.245
	SP All ACF Average	5.073	17.765	3.63	10.365	5.7	9.67
	SP All Scan Average H-H	10.7	62.85	9.378	15.45	19.023	37.34
	SP All H-H Average	20.848	91.65	11.328	55.3	15.198	75.2
	NOP ACF	1.650	2.490	1.353	11.231	6.973	84.473
Surface 3	SP All Scan Average ACF	6.618	15.37	7.205	14.13	5.333	15.725
	SP All ACF Average	5.598	14.62	5.663	14.26	5.408	14.905
	SP All Scan Average H-H	14.428	57.9	20.24	35.095	15.678	48.03
	SP All H-H Average	15.66	58.3	19.835	48.495	17.663	52.05
	NOP ACF	1.201	2.881	1.436	2.832	0.762	2.295

2.3. Effect of plastic deformation during contact measurement

Greenwood and Williamson [9] have analyzed the contact problems between rough deformable surfaces, where both elastic and plastic deformations were demonstrated. The average pressure on the contact area was found to be as given below:

$$p_c = \frac{W}{A} = \frac{4E}{3\pi}\sqrt{\frac{\delta}{R}} \tag{6}$$

For convenience, a dimensionless parameter for the plastic deformation was used to determine whether the contact is elastic or plastic.

$$\psi = \sqrt{\frac{\sigma}{\delta}} = \frac{E\prime}{H}\sqrt{\frac{\sigma}{\beta}} \quad (7)$$

$$\frac{1}{E\prime} = \frac{1-\nu_2^2}{E_2} + \frac{1-\nu_1^2}{E_1} \quad (8)$$

Previous studies on contact problems were mainly concentrated on plastic deformation in which micro-asperities were assumed to be completely flattened.

3. Results and Discussions

It was observed from the measured and estimated roughness data that the magnitude of surface roughness parameters vary as the length scale of measurement varies. R_a, R_q, and β generally increase with increase in cut-off length, and this because of including longer wavelength features when measurements were taken at larger scale. Effect of overestimation of roughness parameters with respect to resolution was observed; SP collected 1600, 8000 and 1600 data points for 0.4*mm*, 4*mm* and 8*mm* evaluation lengths. Several other factors such as scan speed, measuring force, contact pressure also affect the parameter measurement, and few more investigations were required to reveal most of these facts. The effect of the factors discussed above may be clearly seen and particularly noticeable for 8*mm* cutoff length stylus profiler measurement in Fig. 5. Hence Table 1 shows results for the next part using only 0.08*mm* and 0.8*mm* cutoff lengths. It was observed in other studies that measurements taken using non-contact methods give underestimated values of R_a and R_q [2]. This was not observed in this case, which may be due to large stylus tip radius. Submicron to nano-scale surface features was hard to measure with microscopic stylus tip, and Atomic Force Microscopy may be attempted to obtain such features of surfaces.

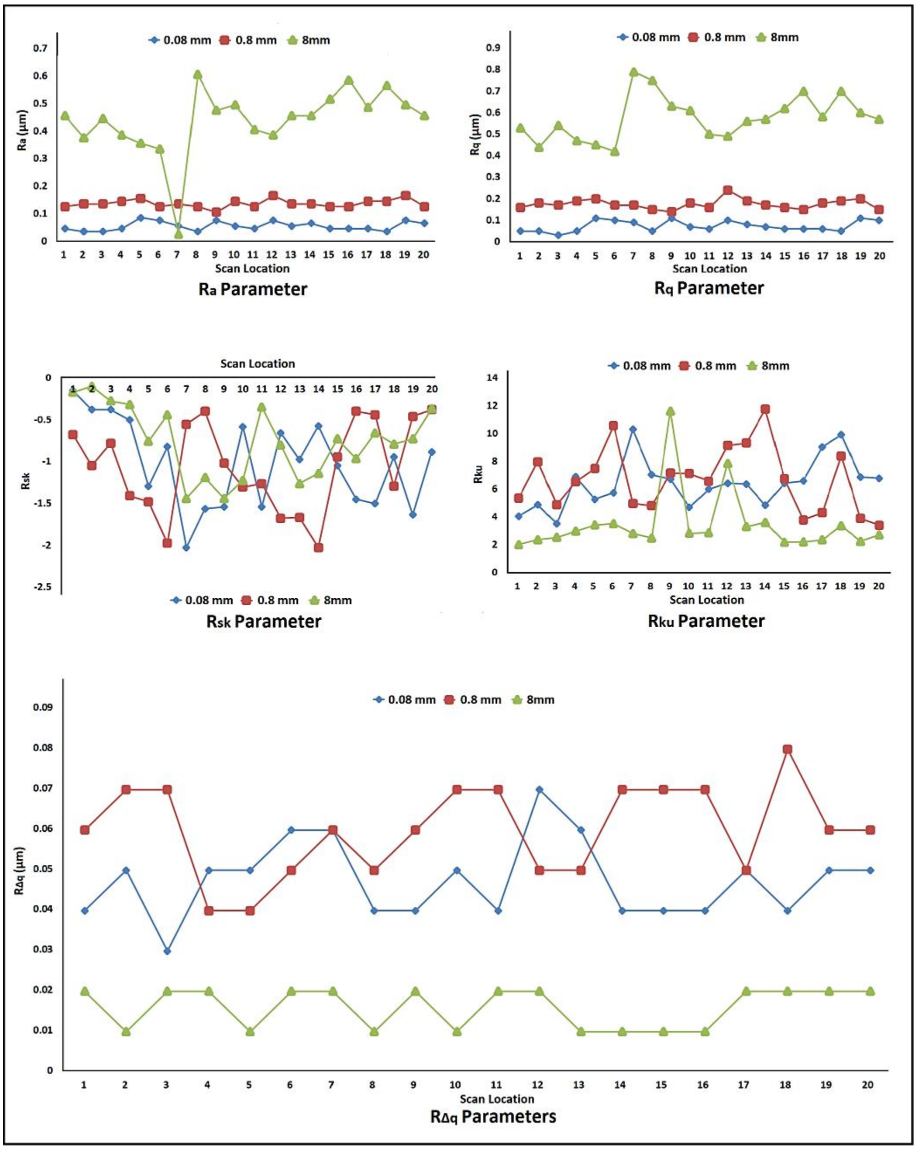

Fig. 5. Roughness Parameter Variation at Different Length Scales

3.1. Comparison between methods for the evaluation of Correlation Length (*β*)

Fig. 6 gives comparison between different methods and instruments used to evaluate β. 0.8 and 0.08 refer to cutoff length used to collect the data i.e. 0.8*mm* and 0.08*mm* respectively. A, B and C are referring to different locations on the surfaces as shown in Fig. 2. All scan average implies β was calculated using superimposed profile of 10 scans. All ACF average implies average of all β calculated using ACF for 10 scans. All H-H average implies average of all β calculated using Height-Height correlation function for 10 Scans. Since β value should be lower than cutoff length, all results are valid. Therotically, H-H and ACF are very similar, Fig. 7 shows they produce "mirrored" results.

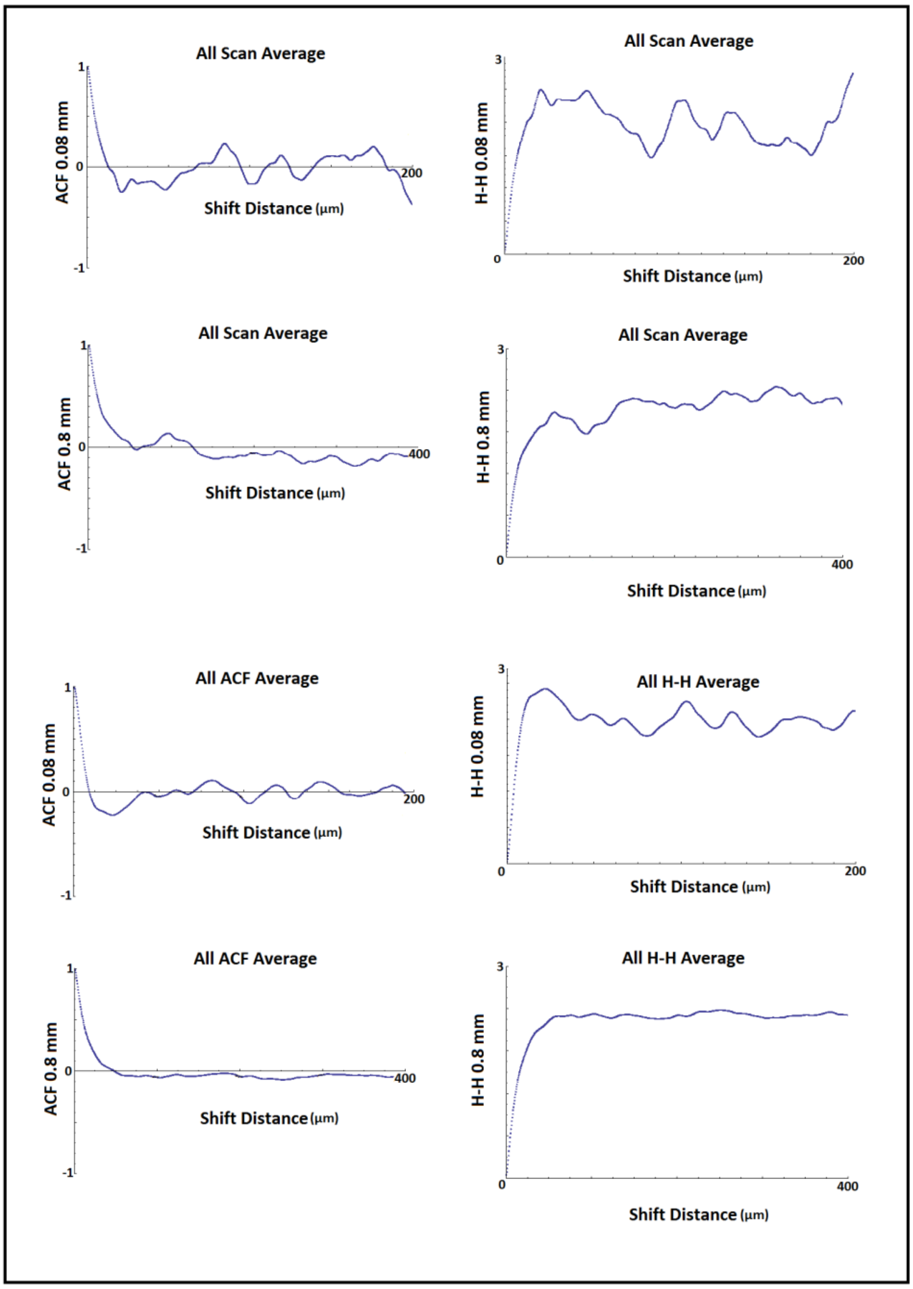

Fig. 6. Comparison between different β calculation methods

3.2. Comparison of estimated cutoff lengths for different steel surfaces

Fig. 7 shows variation of average β for cut-off lengths ranging from 16μm to 800μm for each surface. As more and more points get included in β calculation fluctuation gets reduced and eventually becomes constant. A point at which these fluctuations become more or less stable is considered to be the suitable sampling length for the concerned surface. The sampling lengths obtained this way were noted to be 0.32mm, 0.384mm and 0.48mm for surfaces 3, 2 and 1, respectively. Thus after calculating β, and it's variation as length scale varies help selecting suitable sampling lengths for any given surface.

β

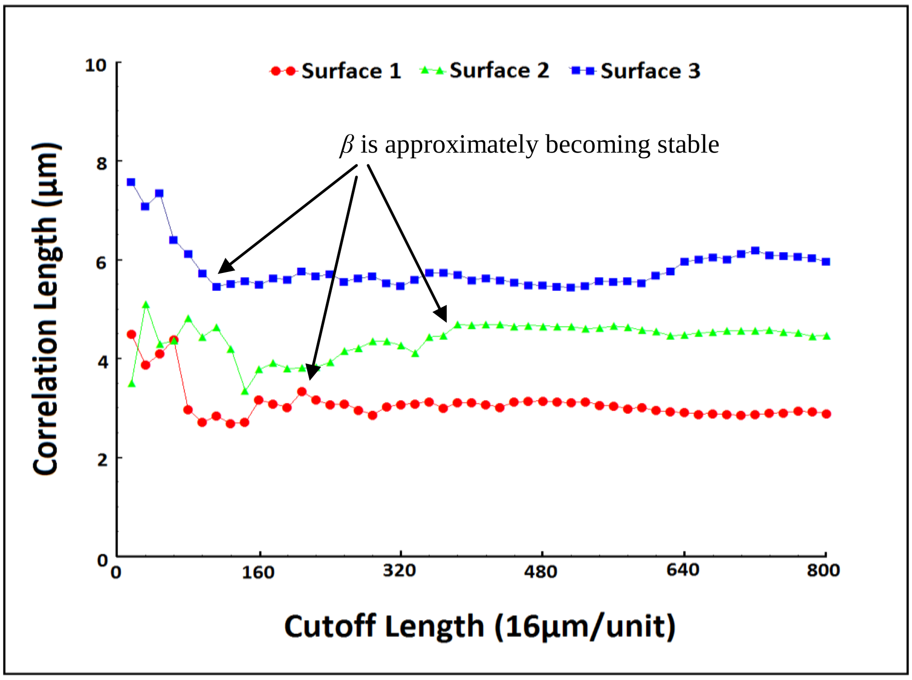

Fig. 7. Comparison between estimated cutoff lengths for different Surfaces

3.3. Plasticity indices and effect of plastic deformation

A commercially available stylus profilometer (Mitutoyo SJ-301) having tip radius of 5μm and measuring force of 4mN was used for study. Substantial plastic deformation during stylus profilometer measurement was observed as shown in Fig. 8**.** Plasticity indices for all examined surfaces were calculated, and it was found that the indices were higher in case of rough surfaces. As noted in section 2.3, customized resolution for respective surfaces may be 7.28μm, 10.89μm and 12.17μm, respectively, as per the definition of the parameter to be 2.3 β* [3]. The results implicate shorter cut-off length should be preferred to study rougher surface.

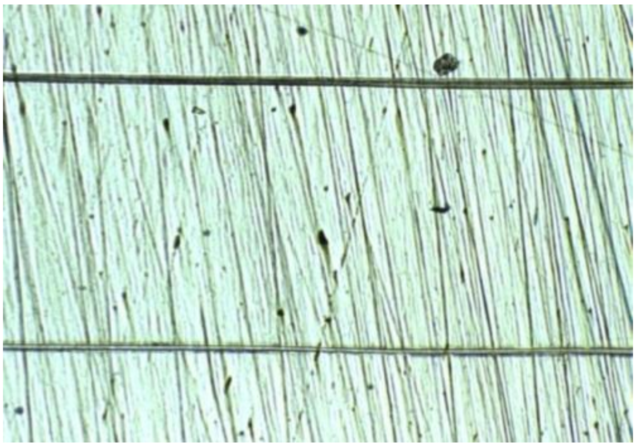

Fig. 8. Plastic Deformation surface

4. Conclusions

The work was planned to obtain a suitable cut-off length for stylus profilometer measurement technique and not to determine whether it is the only suitable instrument for measurement. Various scan lengths as per standard were tried for the available surface specimen with a mechanical stylus profilometer and a non-contact optical profilometer. Some simplified approaches for estimating ‘correlation length’ were also attempted, and ACF was found to be the most suitable tool for evaluating this particular roughness parameter.

Analyses with plasticity indices indicate that smaller tip may be used particularly for smooth surfaces. Moreover, adequate number of scans should be taken to minimize measurement and estimation errors. It was also found that 7.28μm, 10.89μm, and 12.17μm may be chosen for customized resolution setting; and corresponding cut-off lengths may be set to be 0.32mm, 0.384mm and 0.48mm, respectively, for the examined surfaces. This approach may be applicable for selecting suitable resolution and cut-off settings at micro-scale for suraces produced under various machining processes; however, to include more finer details the measurment of roughness may be extended with finer stylus tip or atomic force microscopy techniques. Since emphasis was given to check the behaviour of roughness parameters with respect to length scale in general, and no restrictions related to any physical application were taken into account, hence results were limited only up to few resolutions available with the stylus profilometer. However, more specific or general analyses may be carried forward to optimize the roughness characterization for any given application.

Acknowledgement

We would like to express our sincere thanks to the Head, Department of Mechanical Engineering, IIT Kharagpur for the necessary support towards utilising laboratory facilities.

References

[1] P. R. Nayak, *Random process model of rough surfaces*, ASME Trans., Journal of Lubrication Technology, July (1971), pp 398-407.

[2] Chin Y. Poon, Bharat Bhushan, Comparison of surface roughness measurements by stylus profiler, AFM and non-contact optical profiler, Elsevier Wear, 190 (1995) 76-88.

[3] D.J. Whitehouse, J.F. Archard, The properties of random surfaces of significance in their contact, Proc. R. Sot. London, Ser. A, 316 (1970). 97-121.

[4] G.W. Stachowiak, A.W. Batchelor, *Engineering Tribology*, Elsevier Butterworth-Heinemann, 2005.

[5] David Necas, Petr Klapetek, Characterization of surface roughness, Greifswald, 2012.

[6] David J. Whitehouse, *Handbook of Surface and Nanometrology*, Institute of Physics, Bristol and Philadelphia, 2003.

[7] Wen Shizhu, Huang Ping, *Principles of Tribology*, John Wiley & Sons, 2012.

[8] R.A. Onions, J.F. Archard, The contact of surfaces having a random structure, J. Phys. D: Appl. Phys., 6 (1973) 289-304.

[9] J.A. Greenwood, J.B.P. Williamson, Contact of nominally flat surfaces, *Proc. R. Soc. Lond. A*, 295 (1966) 300-319.

[10] Petr Klapetek, *Quantitative Data Processing In Scanning Probe Microscopy*, Elsevier, 2013.

Appendices

Appendix A: List of Symbols and Abbreviations

β – Autocorrelation Length

β* – Value of β, where β becomes stable w.r.t. Cutoff length

δ – Plastic deformation

ψ – Plasticity index

σ – RMS

τ – Shift Distance

ν – Poisson's ratio

E – Young's modulus

E' – Effective Young's modulus

H – Brinell hardness

R_a – Center Line Average

R_q – RMS

R_{sk} – Skewness

R_{ku} – Kurtosis

$R_{\Delta q}$ – RMS slope of profile

ACF – Autocorrelation function

H-H – Height-Height correlation function

NOP – Non-contact Optical Profiler

SP – Stylus Profiler

Appendix B: Roughness Parameters

Parameters	Equations
R_a – Center Line Average	$\frac{1}{l}\int_0^l \lvert z(x)\rvert dx = \frac{1}{n}\sum_{i=1}^{n} \lvert z_i\rvert$
$\boldsymbol{R_q}$ – RMS	$\sqrt{\frac{1}{l}\int_0^l \lvert z(x)^2\rvert\, dx} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} z_i^2}$
$\boldsymbol{R_{sk}}$ – Skewness	$\frac{1}{\sigma^3}\int_{-\infty}^{+\infty} z^3 p(z)dz$
$\boldsymbol{R_{ku}}$ – Kurtosis	$\frac{1}{\sigma^4}\int_{-\infty}^{+\infty} z^4 p(z)dz$
$\boldsymbol{R_{\Delta q}}$ – RMS slope of profile	$\frac{1}{L}\int_0^L \theta(x)dx$