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Keywords

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AN APPLICATION OF OPTICAL SURFACE ASSESSMENT TO ENGINE PREPARATION TECHNIQUES

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Abstract

Although the advantages of optical techniques have long been appreciated, the inherent limitations of such methods have meant that stylus techniques remain the accepted "standard" for surface assessment. The study of many engineering processes, such as engine preparation techniques, have been based on stylus methods. Much of this research may be extended to optical techniques for surface assessment if a detailed comparison of results obtained from the two techniques is carried out with respect to the process under investigation. A study of this kind will help to develop optical assessment techniques which, although will initially be limited to specific processes, may prove useful in the production environment.

This paper presents a study of established two dimensional models which have been applied to the characterization of the preparation of engine cylinder liners and bores. These models are extended to three dimensions and quantified using a three dimensional stylus measuring system consisting of a computer controlled Talysurf 5 stylus instrument and a precision linear translation stage. Relocation techniques are then employed and the surface finish is assessed using a computer controlled laser measuring system. With reference to the original models it is shown that engine preparation techniques may be monitored using an optical assessment of this kind. Thus an alternative method of assessing the evolution of engine preparation is proposed for optically based techniques.

It is hoped that studies of this nature will eventually lead to the development of an on line optical surface assessment system for engine preparation techniques with all its associated advantages.

Introduction

The specification of the preparation process of cylinder liners and bores is of fundamental importance to the engine manufacturer. Monitoring the evolution of the surface texture of cylinder liners and bores during preparation processes is usually limited to stylus methods of assessment which involve removing the component from the production line for detailed examination. Although surface texture is of great importance to the engine manufacturer, its inspection, at least by traditional stylus techniques, severely restricts the flow of work in the production environment.

Optical methods of surface assessment offer the basis for an on-line, system for the inspection of cylinder liners and bores. Information obtained from such systems, however, is intrinsically different from that obtained by stylus methods. Thus characterization techniques developed for engine preparation based on stylus methods can only be used as a basis to form analogous techniques for optical assessment.

A method for investigating the optical assessment of cylinder liners and bores may be established as follows.

Investigations have shown that the surface changes which occur as honed engine liners are plateau honed follow a simple truncation wear model. The evolution of parameters such as Rq, skewness and kurtosis, which are used to describe the scale and shape of surface profiles obtained from stylus instruments, may be derived from such models. Wear models of this kind may easily be extended to three dimensions to give a more realistic interpretation of the wear mechanism. This approach is also more analogous with optical assessment which directly provides a information pertaining to a three dimensional area.

Simulation techniques may then be used to assess the effects of light scatter as surface parameters such as Rq, skewness and kurtosis are changed. As the evolution of these parameters may be predicted from the truncation wear model it is then possible to relate these values to surface scatter and so evaluate truncation wear from an optical assessment. In this way it is hoped to study the optical assessment of the evolution of the honing process and so provide an on-line technique for its evaluation.

Review

Two Dimensional Profilometry and Characterization

Traditional stylus methods of assessing surface finish are based on a precision stylus traversing a surface, the vertical movement of the stylus is converted into an electronic signal via a transducer which is then digitized for computation. Thus a two dimensional section, or surface profile of the surface is obtained.

When studying surface profile modification (caused by, for example engine preparation techniques) it is useful to be able to describe the initial distribution of the surface heights and the way in which this distribution is affected by the process. A comprehensive approach to the description of the shape and scale of such distributions involves the specification of the moment coefficients of skewness and kurtosis along with its Rq value [see Appendix and ref.1].

When a surface profile is digitized it is usual to employ a sample spacing small enough to allow investigation of the spatial characteristics as well as its amplitude distribution. This gives information about the form and structure of the surface. Spatial characteristics can be represented in terms of the autocorrelation function or power spectrum [see Appendix].

A complete characterization of a surface profile may specified in terms of distribution of surface heights and the horizontal relationship between neighbouring points.

Engine Preparation Techniques

Presented in this paper is an investigation into the surface and the resultant scatter characteristics from the most common preparation techniques used by engine manufacturers - honing and plateau honing. The topographies imparted onto the surface by the respective processes play a vital role in determining the efficiency and life of the engine.

The honing process produces a cross-hatched topography with peaks and valleys. The cross-hatching or honing marks and the cross angle (the preferred range being 40 to 50 degrees) are primarily to ensure a uniform distribution of lubrication fluid on the cylinder bearing surface. Generally, an Rq value of approximately 1.0 micron is sought from this stage of preparation.

Plateau honing is a finishing technique which cuts off and washes the peaks away leaving a surface which presents a large bearing area to the pistons but the valleys remain for oil retention purposes. This pre-worn topography has good lubrication qualities from the underlying honing and boring processes coupled with good wear characteristics from the plateau honing and is the ideal finish for cylinder bores and liners.

Scanning electron micrographs of typical honed and plateau honed surfaces are shown in figures 1a and 1b respectively. The cross hatched topography is clearly visible in both processes whilst the truncation effect of the plateau honing process is evident in figure 1b.

Two Dimensional Wear Models

The amplitude distribution of honed surfaces may usually be characterized by a statistical distribution of known mathematical form (such as a Pearson or Johnson distribution [refs. 2 and 3]). The plateauing of such a surface may be characterized using a simple wear model as follows.

The initial profile is successively truncated by a plane. The distribution of the surface heights is progressively cut off as wear proceeds and an impulse representing all the observations of the plane is formed at the contacting level. The weight of the impulse is equal to the area of the removed portion of the amplitude distribution. The simple truncation wear model is illustrated in figure 2.

Spedding et.al. [ref. 4] illustrated how this model may be used for the Pearson system of distributions and presented results illustrating the predicted variation of Rq, skewness and kurtosis with truncation wear for a variety of initial unworn surfaces. The simple truncation wear model has the advantage that as long as the initial surface is known the plateau honing process may be monitored by only measuring one suitable roughness parameter such as Rq, as the level of plateauing may be derived from Rq.

Three Dimensional Profilometry

Surfaces produced by manufacturing processes cannot be completely characterized without extending the analysis to three dimensions. With this information the designer is then able to specify a surface for more efficient operation. Three dimensional profilometry offers a more realistic assessment of many of the characteristics and functional properties of engineering surfaces. It has the added advantage over two dimensional assessment of giving a more reliable estimate of surface characteristics by reducing sampling variation.

Using a stylus system, a three dimensional representation of the surface can be obtained as a number of parallel traces provided an exact relationship between individual traces is established.

The stylus system used for the work discussed in this paper is based on the Rank Taylor Hobson Talysurf 5 surface finish measuring instrument and shown in figure 3. For three dimensional work the specimen is positioned on a single axis precision linear translation stage which has its axis of motion set normal to the linear motion axis of the Talysurf pick up. Specimen relocation is achieved using a simple right angle fixture aligned to both axes of movement. The system is controlled by a Data General Series 30 desktop computer.

The work for this paper involved logging data from engine cylinder liner sections in various conditions of manufacture. The curvature of cylinder liners and bores is removed using a least squares parabola so that the truncation wear model may be applied.

Optical Surface Assessment

The experimental system for investigating light scatter is shown schematically in figure 4. A helium neon laser (= 0.6328um) acts as an interrogation source and a proportion of the scatter is detected by a vidicon camera, in which no intervening optics are used. The signal from the camera is digitized in the memory of a 512x512x8-bit framestore which is interfaced to a micro-computer. A computer controlled filtering system is also employed; it comprises a series of neutral density filters of varying transmittance mounted in a circular frame which is driven by a stepper motor. Its purpose is to reduce the intensity of the scattered radiation to within the dynamic measuring range of the vidicon detector thereby eliminating the problem of data "clipping" and increasing the range of surfaces that can be meaningfully examined. The micro computer employed for system control and data analysis is a DEC PDP-11/23.

The results from the optical system are given in terms of the optical density (OD) level used to obtain the scatter measurements. The filters cover a range between 0.1 and 5.5 OD, a filter level of 4.75OD being sufficient to reduce the intensity of scattered light from a high precision optical flat to a level acceptable by the vidicon detector. The measuring scale is constructed in such a manner that the maximum detected intensity from a high precision optical flat yields a corresponding value of 100; all other measurements are normalized with respect to this reference value.

The system geometry for both three dimensional and all subsequent two dimensional investigations is stated below:

incident angle (0i)	45 degrees
scattering angle (0s)	45 degrees
detector size	5mm x 5mm
detector distance from surface	50mm.

This configuration gives the system a "field of view" of 0.105 steradians (equivalent, in the two dimensional case, to a span of 6 degrees).

Discussion

Stylus Analysis

Figure 5a shows a profile of a typical honed surface obtained from a cylinder liner of an internal combustion engine. The profile illustrates the random spatial structure, and negatively skewed height distribution, typical of the honing process. The bearing properties of a honed surface can be enhanced by removing the asperity peaks. This usually occurs as a natural wear mechanism when a honed surface is operated in a frictional environment such as an internal combustion engine. The plateau honing process simulates this preliminary wear process by removing the peaks of the surface to a level where the wear mechanism is stabilized. This is illustrated in figure 5b which shows a typical plateau honed surface profile. The skewness value is more negative and the kurtosis value is higher indicating the surface is asymmetric with a high proportion of valleys. The underlying spatial structure of the honed surface is retained with its enhanced lubrication properties.

A more realistic investigation of the honing process can be obtained by taking stylus measurements in three dimensions using the system discussed previously. Figure 6a shows a 2mm square area of a honed surface. The figure clearly shows the cross hatched topography and peaks and valleys typical of the honing process.

Figure 6b shows a similar area of a plateau honed surface, the underlying cross hatched honed structure still clearly visible. The distribution of the surface heights is obviously more asymmetric than the honed surface, increasing the bearing area whilst retaining the valleys for oil retention.

The simple truncation model previously described was applied to the honed surface, shown in figure 6a as an attempt to simulate the plateau honing process. The results of this modelling are shown in figure 6c. A visual comparison between the actual plateau honed surface and the truncated surface shows close similarities. The cross hatched grooves of the honing process are clearly shown in the truncated surface. The flattening of the peaks to increase the bearing area whilst retaining the valleys is reflected in the simulated surface. The average Rq value of the truncated surface compares well with the Rq value of the plateau honed surface; the skewness and kurtosis results illustrate the similarity in the shape of the distributions of surface heights.

Optical Analysis

The three dimensional detected scatter distributions from a typical honed and plateau honed surface are shown in figure 7a and 7b respectively. A filter level of 2.7 OD was required to obtain the scatter measurements from the honed surface; this value had to be increased to 3.6 OD for the plateau honing scatter. The honing topography with its peaks and valleys and little directionality is a strong scatterer, the resultant scatter distribution being basically diffuse. Any directional properties that might have been expected as a result of the honing marks are smothered by the dominant surface roughness. On the other hand, the scatter distribution from the plateau honed surface possesses very definite scattering properties. The dominant features of the scatter pattern can be related to the scattering surface as follows:

a) the specular scatter is attributable to the plateauing of the surface asperities,
b) the cross-effect is a result of the honing marks from the honing process, and
c) the speckle results from the underlying roughness due to the honing and boring processes.

The salient scatter features may be more clearly illustrated by presenting the data in contour form as in figure 8a and 8b. These diagrams illustrate the transition in scattering properties that occur as a direct result of the plateau honing process. The resultant scatter distribution from the plateau honed surface suggests that characterization of a pattern of this complexity would be very difficult although Fourier transforming the pattern two dimensionally may reveal useful information because of the geometrical format of the pattern. This, however, may not be so for the less geometrical pattern of the scatter from the honed surface.

The results do suggest that because of the very different resultant scattering characteristics a two dimensional optical analysis may be perfectly adequate for monitoring the plateau honing process in order that a surface with the desired functional properties is achieved.

Two dimensional analysis

The two dimensional optical scatter results are compared with stylus profile measurements, the reason being that a general acceptance of any new measuring technique will be more rapid if it can be directly related to the accepted standard. Figures 9a and 9b illustrate the two dimensional scatter distributions obtained from the respective honed and plateau honed surfaces of figures 6a and 6b. These results correspond to plane of incidence scatter (that is, they relate to the central column of the detection system). Previous studies on two dimensional scatter from topographies produced by different engineering machining processes (for example, grinding and lapping) have shown that the parameters of the respective systems that yield the best correlation in terms of comparison are the standard deviation of the scattered intensity (Iq) and the standard deviation of the surface slope distribution (Δq). Comparing the results of figures 9a and 9b with the corresponding profile statistics of figures 5a and 5b, it is found that in general an Iq value of 1.4 OD corresponds to a Δq value of 9.6 degrees (honed) and an Iq value of 7.2 OD relates to a Δq value of 6.6 degrees (plateau honed). A series of profile and two dimensional scatter measurements were taken on a number of different honed and plateau honed specimens to confirm this and a relationship between the two was determined. The average wavelength (λq) of all the measured surface profiles, both honed and plateau honed, was 0.035mm. Knowing this and the Δq value for the profile allows the Rq value of the surface roughness to be obtained from the equation below:

$$R_q = (\Delta a * \lambda q)/2\pi \qquad (1)$$

where, Δ_q is in radians, and λ_q are in microns

Figure 10 represents 100 measurements taken from both the honed and plateau honed surfaces of figures 6a and 6b. This shows not only the difference in statistics of the respective processes but also the inherent sampling variation within each area. The average scatter statistics for the honed surface are Iq(1.45 OD), skewness (Isk)(1.16) and kurtosis (Iku)(4.35); for the plateau honed surface the values are Iq(7.42 OD), Isk(2.3) and Iku(7.52). The greater magnitudes of Iq, Isk and Iku from the latter are indicative of a

weaker, more specularly scattering topography. The standard deviation of Iq for the respective processes are 0.19 OD and 0.80 OD. This apparent smaller variation for the rougher honed surface is attributable primarily to the reduced sensitivity of the measuring system to rougher surfaces. Because of the very different scattering properties of the honed and plateau honed surfaces and consequently the very distinct variation in the scattered intensities, figure 10 highlights Iq, as opposed to the other scatter parameters as the most appropriate for monitoring the process.

The effect of profile truncation on the resultant scatter

A computer simulation [ref. 5] has been developed to study scattering from rough surfaces. It is an algorithmic approach for investigating the "inverse scattering problem" and overcomes many of the limitations imposed by more analytically based approaches. The optical model is based on scalar wave theory and incorporates a variation of the Kirchhoff diffraction integral to determine the scattered intensity distribution in the Fraunhofer region [ref. 6]. The flexibility of this approach allows scattering from both real (data logged on the stylus system) and simulated profiles with varying height and spatial characteristics to be obtained. The scattered field is determined with respect to the "local" surface slopes, however, the surface is assumed perfectly conducting and multiple scattering effects are ignored. The simulation results are normalized, in a similar manner to the experimental results, with respect to the scattered field that would be present if the scattering occurred from a smooth surface.

Figures 11a and 11b represent the simulated scatter results obtained from the profiles given in figures 5a and 5b respectively. Comparing these simulated results with those obtained experimentally (figures 9a and 9b) it can be stated that the simulation values are slightly greater in magnitude but the trend of the results is very similar. Taking into account inherent differences of the respective approaches, these results are very encouraging, especially when studying topographical features at the roughess range under investigation. As stated previously, the action of the plateau honing process can be shown to be adequately described by a simple plane truncation wear model. Having illustrated briefly the validity of the simulation technique to study the scatter from surface profiles of this character, the simulation was used to investigate the effects of profile truncation on the resultant detected scatter statistics. For this investigation the honed profile of figure 5a was used. Successive profile truncation at levels between +/- 3 standard deviations from the mean value and determination of the scatter statistics at each level was conducted. Figure 12 shows the predicted variation of Iq, Isk and Iku with profile truncation level. During the initial stage of truncation, Isk and Iku increase substantially whilst Iq increases rather less dramatically implying that the truncation depth is not yet sufficient; the basic scattering mechanism of the surface remains predominantly diffuse. At a truncation level of +0.5 standard deviations a marked change in the scatter statistics occur. Iq begins to increase rapidly for small increases in truncation depth whereas Isk and Iku, having reached a maximum, begin to decrease slowly. At this point, the detected scatter statistics are indicative of the onset of a dominant specular component suggesting that the surface has reached the desired topographical state. Truncation beyond this point results in the specular component becoming more and more dominant until a stage is reached at a level of about -0.5 standard deviations where the features of the underlying boring and honing processes are completely removed and a "scuffed" topography exists.

Hence, the curves suggest that the surface should be truncated to a level of approximately +0.5 standard deviations for good functional characteristics and optimum wear life. The optical scatter values corresponding to this state are Iq (7.5 OD), Isk (2.70) and Iku (11.5); relating these results to stylus values yields Rq (0.77um), skew (-1.80) and kurtosis (7.12).

Conclusions

It has been shown that modelling techniques developed to assess the evolution of the surface finish of engine preparation processes, which were originally based on stylus assessment may be used to form an optical analysis. Results from this investigation have shown that there is good correlation between the standard deviation of the scatter distribution (Iq) and the degree of plateauing. This implies that monitoring Iq is sufficient to control the final machining operation and subsequent functional characteristics of the cylinder liner surface. It is anticipated that these results will form the basis for an on-line optical measuring system for the assessment of the surface finish of engine cylinder liners and bores.

Acknowledgments

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Appendix

The nth central moment (m_n) for a profile observed at N discrete points is defined as

$$m_n = \frac{1}{N} \sum_{i=0}^{N} (y_i)^n$$

the y values being measured with respect to the mean line.

Rq, skewness and kurtosis may be defined in terms of central moments as follows

$$R_q = m_2^{\frac{1}{2}} \qquad \text{(standard deviation)}$$

$$\sqrt{b_1} = \frac{m_3}{m_2^{1.5}} \qquad \text{(moment coefficient of skewness)}$$

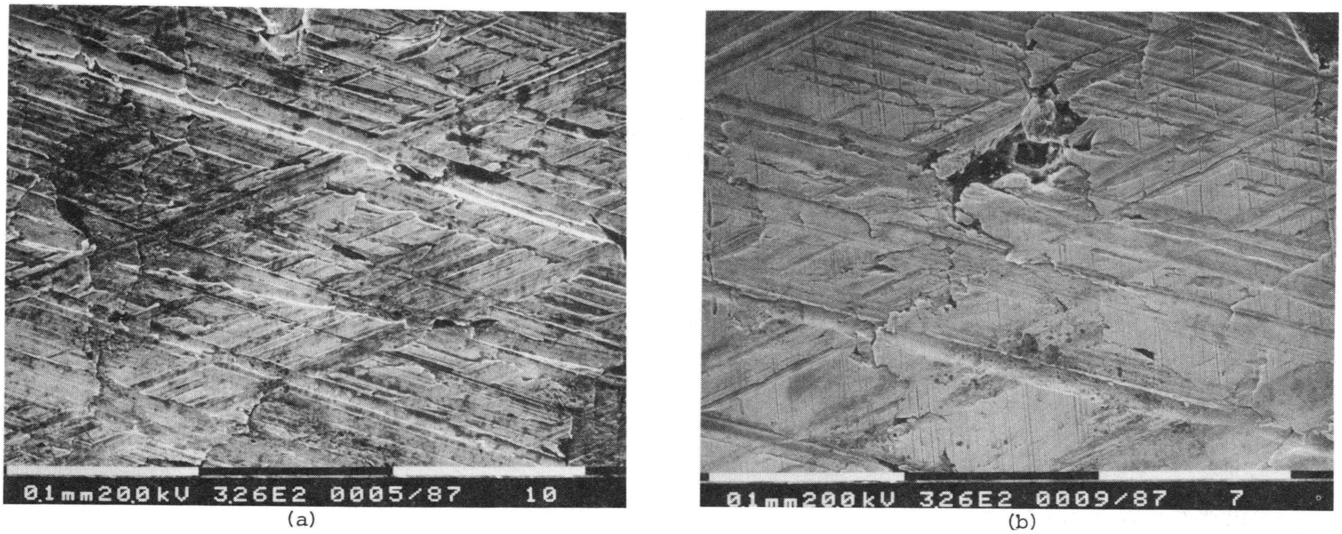
$$b_2 = \frac{m_4}{m_2^2} \qquad \text{(moment coefficient of kurtosis)}$$

Skewness is a measure of the symmetry of a (surface height) distribution about its mean line. Kurtosis is a measure of the spikiness (and/or scratchiness) of the surface profile.

Spatial characteristics can be represented by the sample autocorrelation function defined at lag k for discrete observations by

$$r_k = \frac{1}{r_o(n-k)} \sum_{i=0}^{n-k} y_i \, y_{i+k}$$

where $r_o = m_2$ the sample variance



(a) (b)

FIGURE 1a). S.E.M. of honed surface,
b). S.E.M. of plateau honed surface.

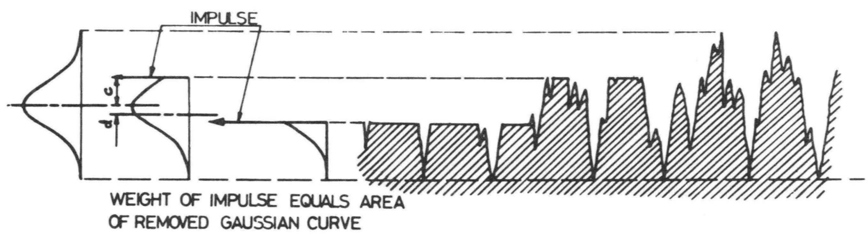


FIGURE 2. Plane truncation wear model.

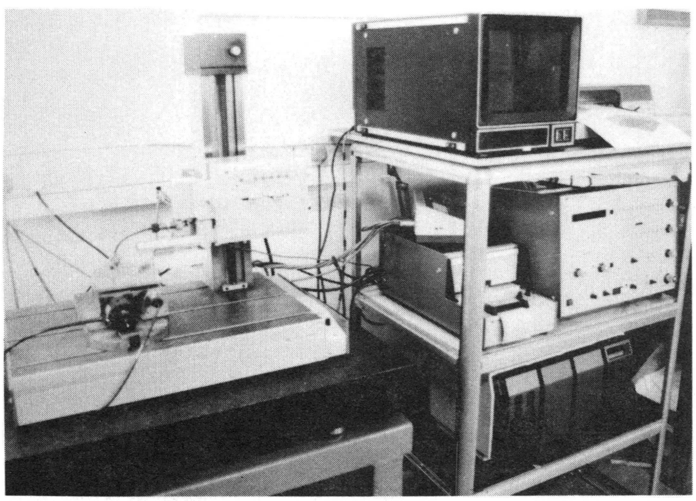


FIGURE 3. Three dimensional stylus measuring system.

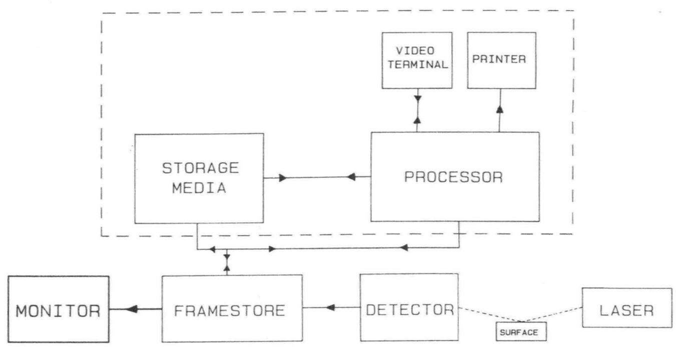
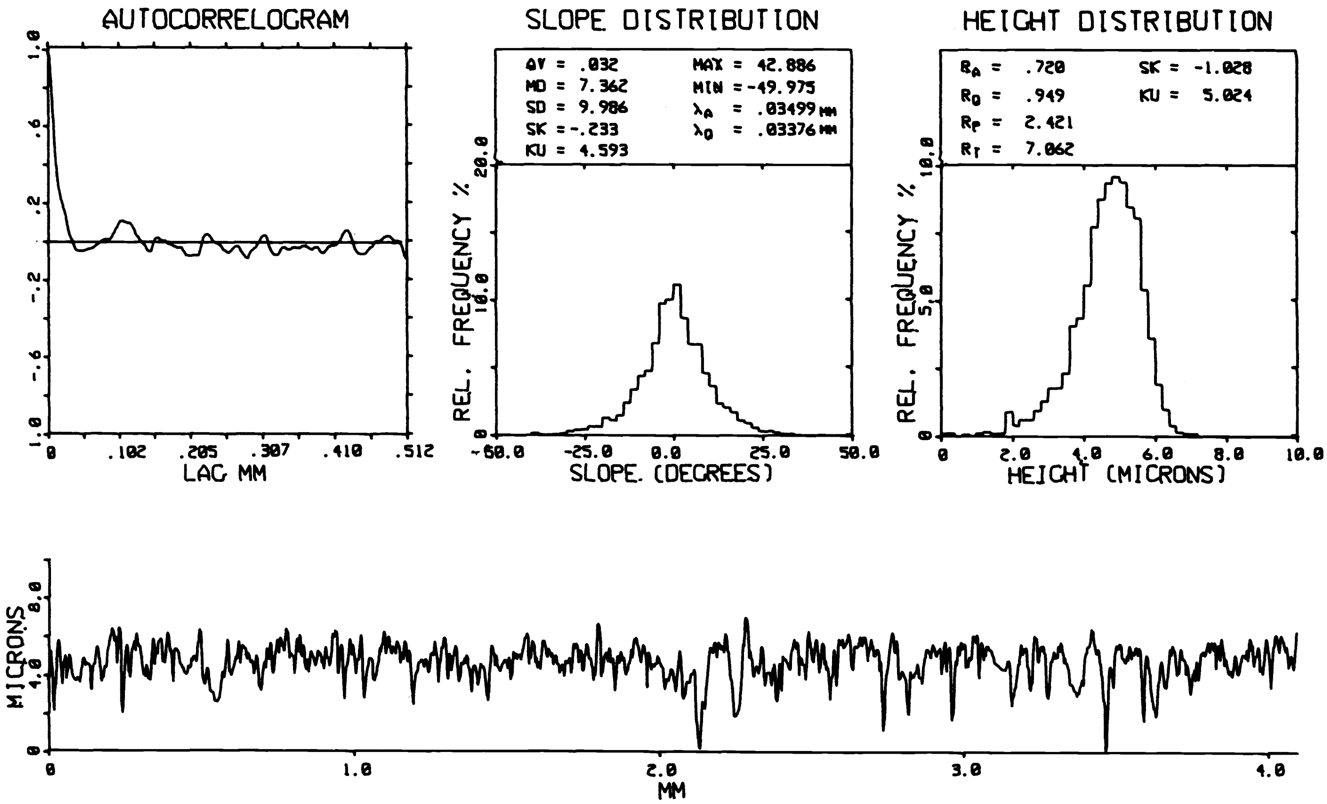
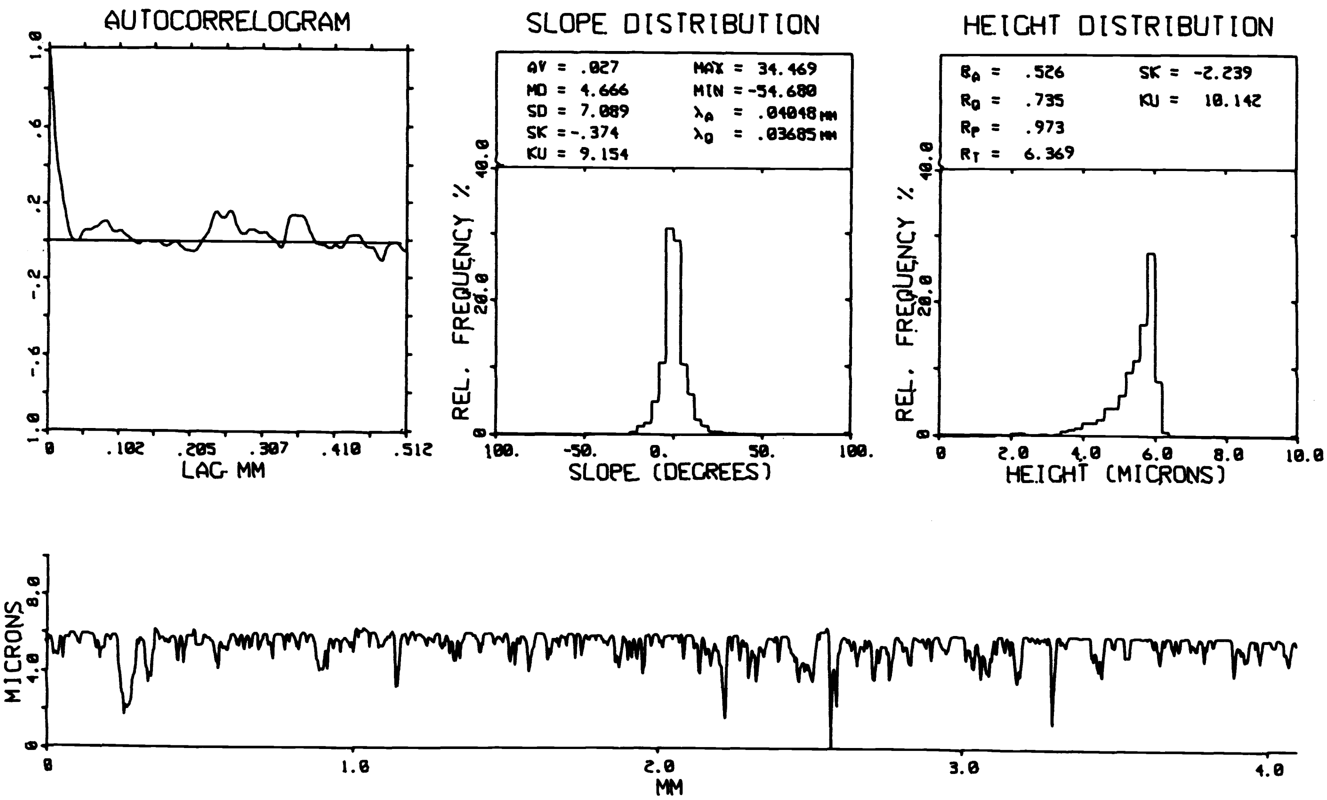


FIGURE 4. Schematic of optical measuring system.

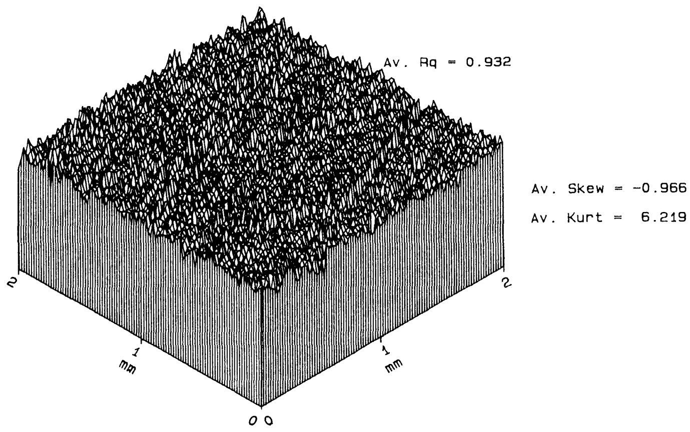


(a)

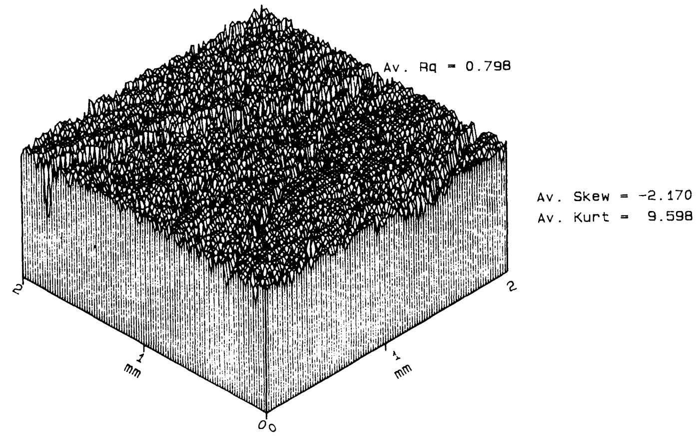


(b)

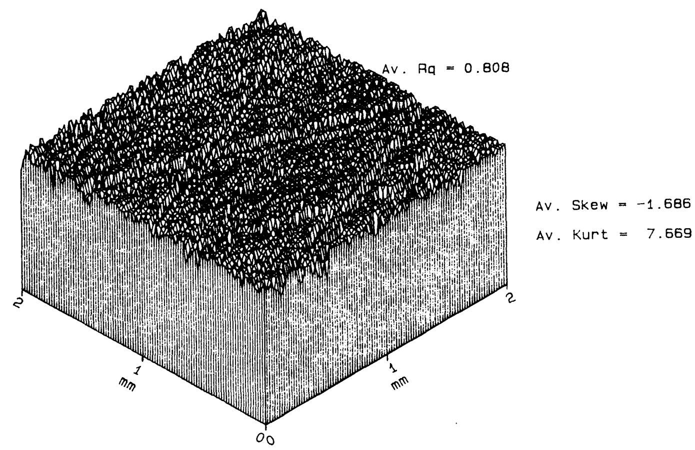
FIGURE 5a). Profile of honed surface with height and spatial parameters.
b). Profile of plateau honed surface with height and spatial parameters.



(a)

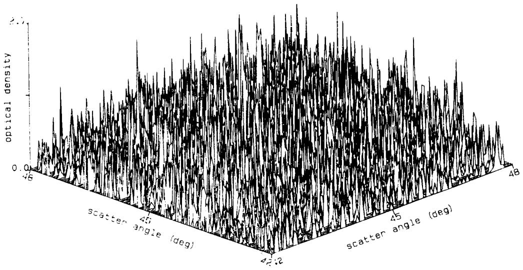


(b)

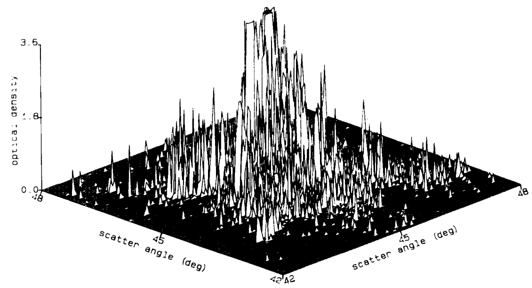


(c)

FIGURE 6a). Area of honed surface.
b). Area of plateau honed surface.
c). Plane truncation of Fig.6a to simulate plateau honing process.

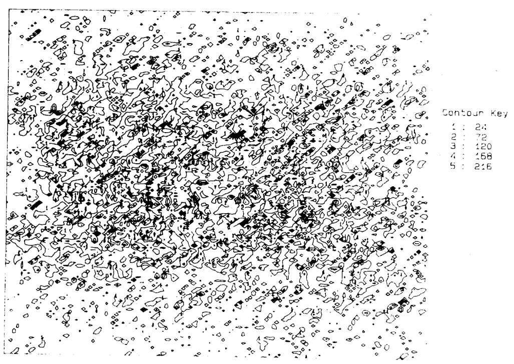


(a)



(b)

FIGURE 7a). Detected scatter from honed surface of Fig.6a.
b). Detected scatter from plateau honed surface of Fig.6b.



(a)

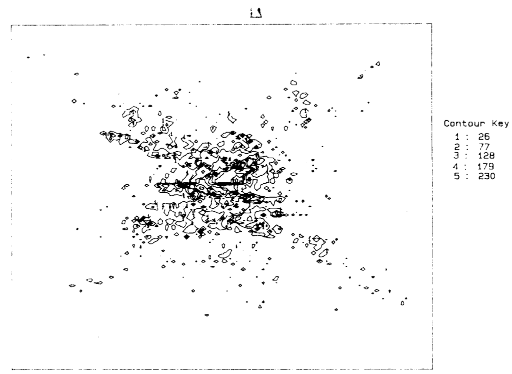


FIGURE 8a). Contour representation of Fig.7a.
b). Contour representation of Fig.7b.

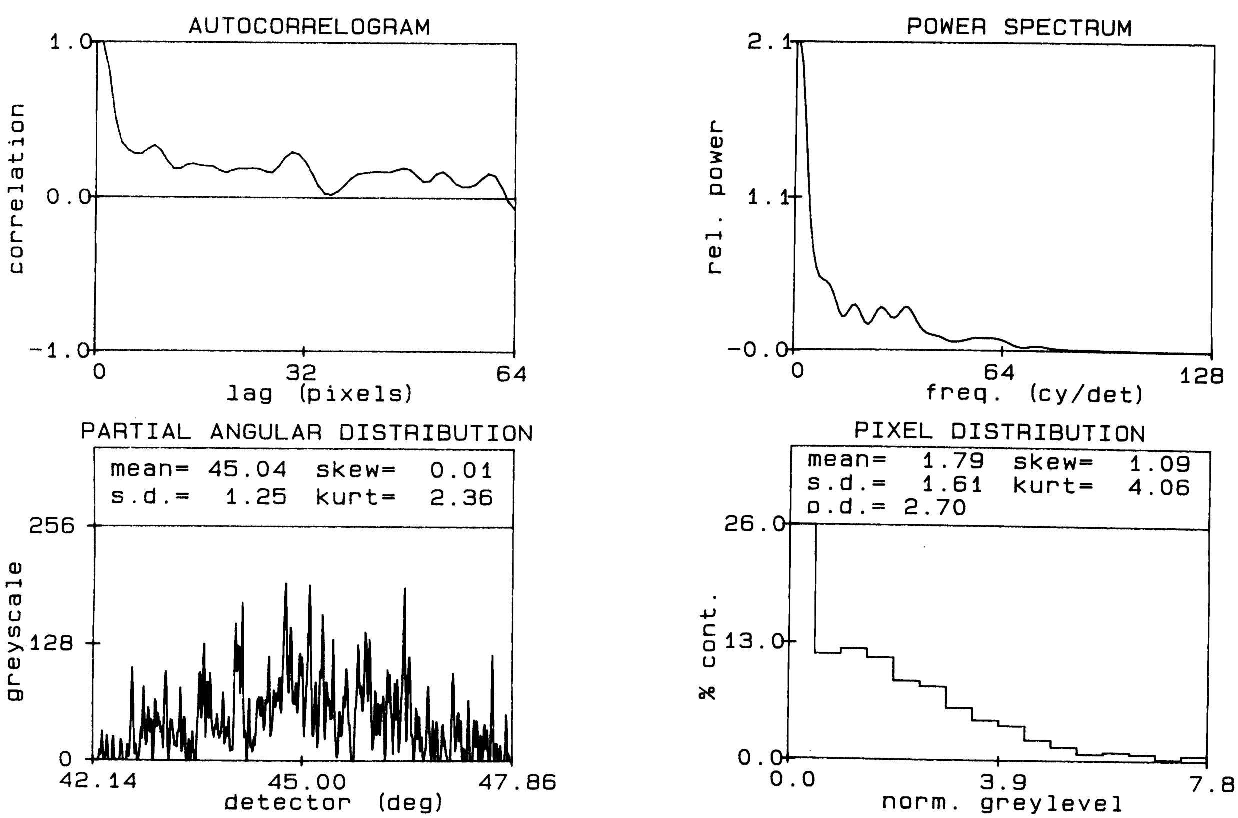


FIGURE 9a). Two dimensional scatter from honed surface.

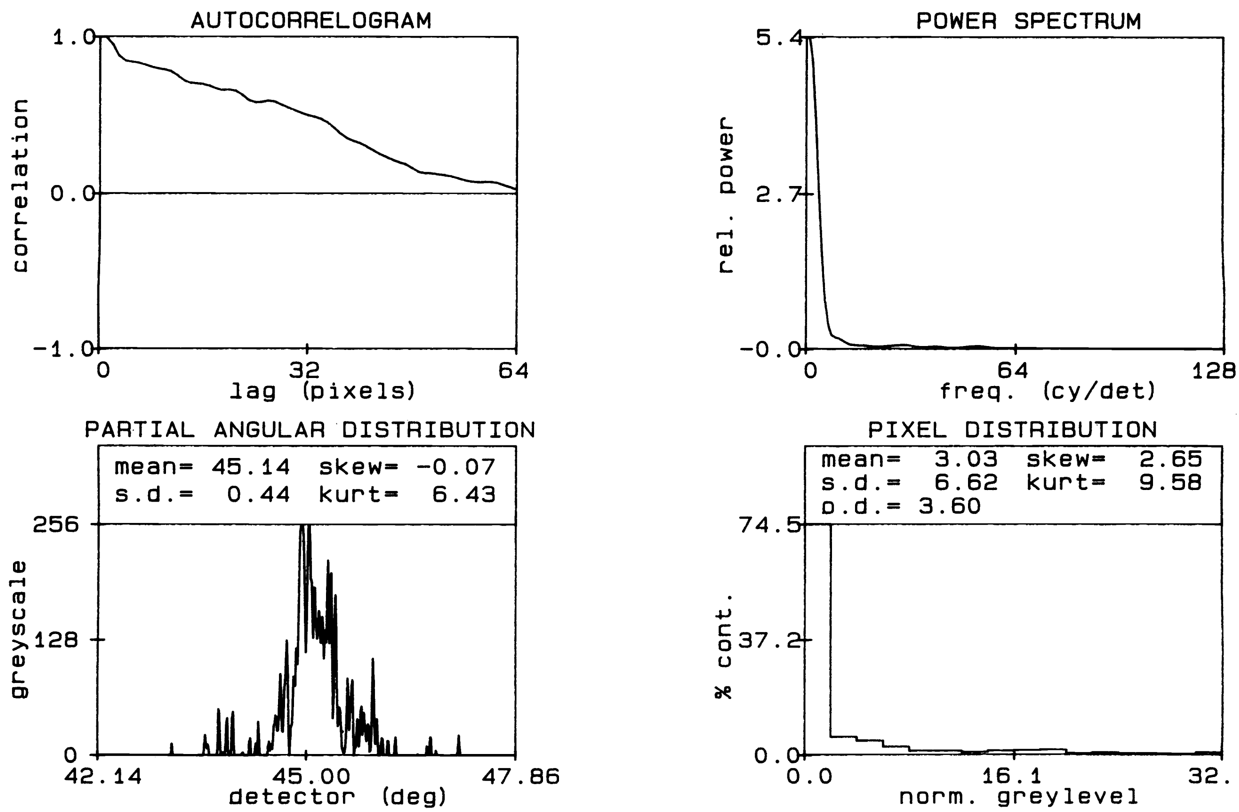


FIGURE 9b). Two dimensional scatter from plateau honed surface.

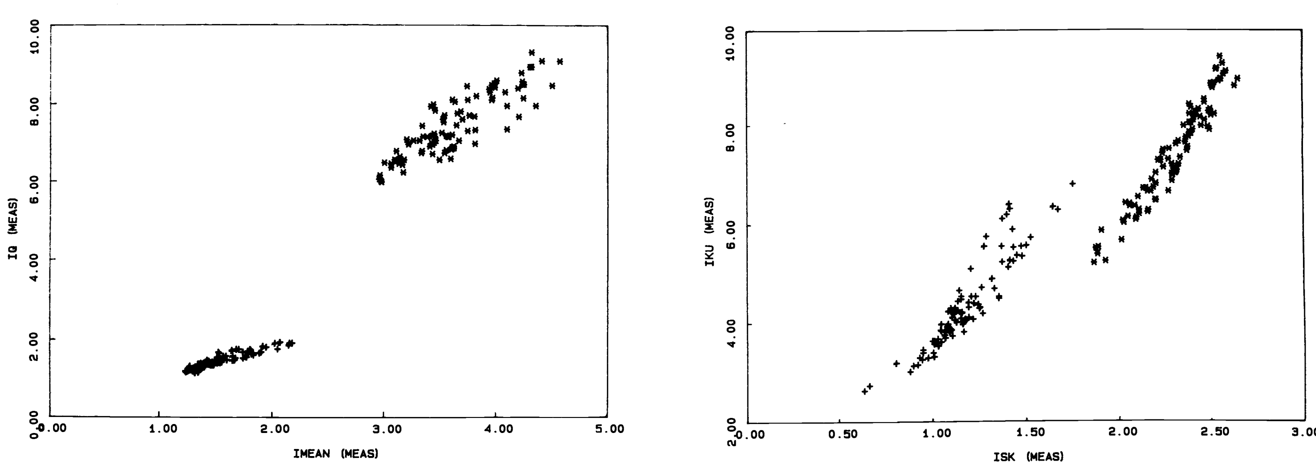


FIGURE lo. Variation of scatter statistics from honed and plateau honed surfaces.

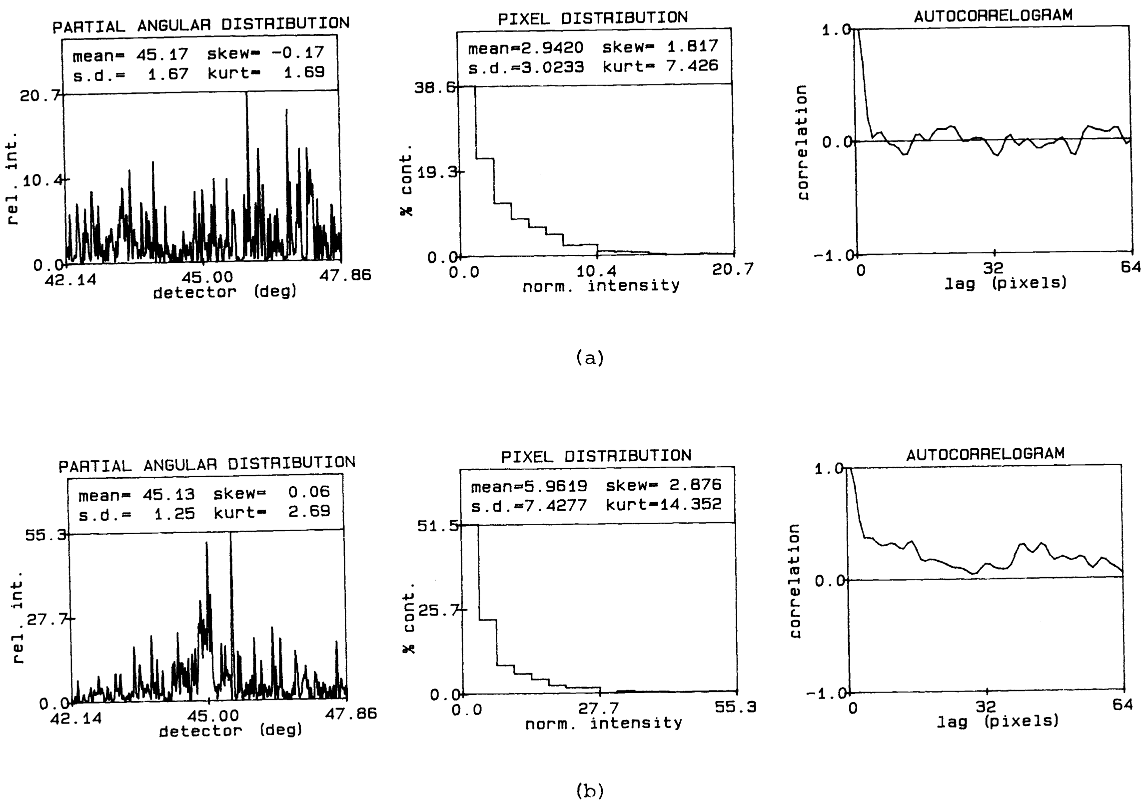


FIGURE 11a). Two dimensional simulated scatter from honed profile of Fig.5a.
b). Two dimensional simulated scatter from plateau honed profile of Fig.5b.

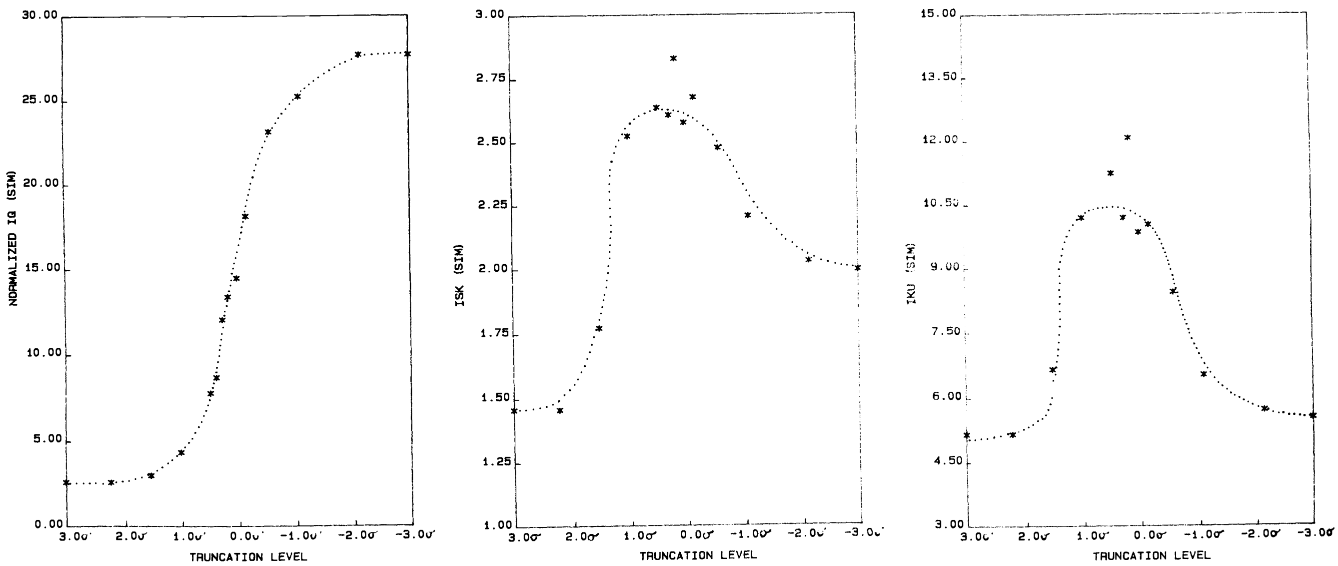


FIGURE 12. Predicted variation of Iq, Isk and Iku with profile truncation.