ATLAS OF MACHINED SURFACES

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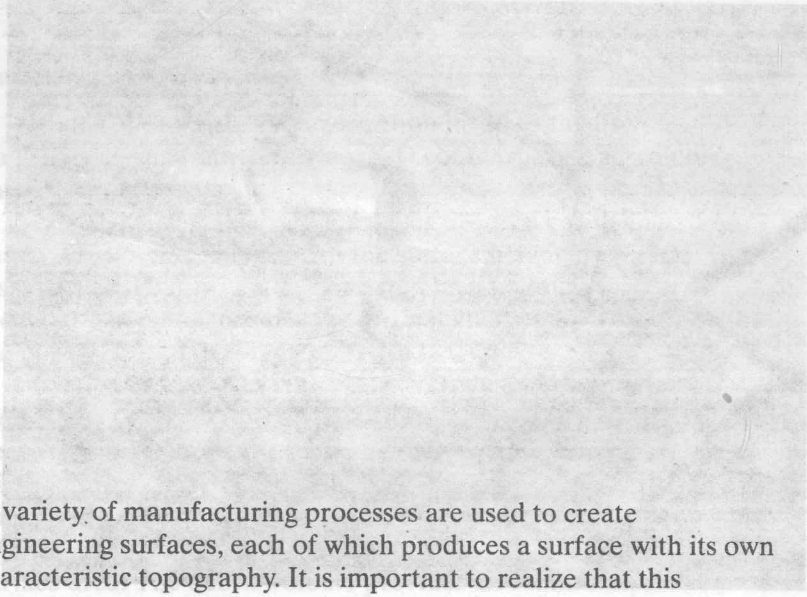
A software package, which is closely similar to the 3-D system offered on Rank Taylor Hobson Form Talysurf series machines, is available containing all the data presented in Part 1 of this atlas. The package allows the user to manipulate the data to produce a full range of projections of the type presented here, together with truncation, inversion and the associated parameters. Additional features available include: zoom, grey-scale imaging and full colour graphics.

The package will run on any IBM AT compatible machine with VGA graphics.

For details of the software package, please apply to:

Whitestone Business Communications
24 Golf Drive
Whitestone
Nuneaton
Warwickshire
CV11 6LY



INTRODUCTION

A variety of manufacturing processes are used to create engineering surfaces, each of which produces a surface with its own characteristic topography. It is important to realize that this topography may affect the suitability of a surface for specific functional applications. Unfortunately, the relationship between surface topography and functional behaviour is not yet fully understood. It is clear, however, that there are two quite distinct issues which need to be addressed: (1) the relationship between manufacture and the resulting surface topography, and (2) the relationship between topography and function. It is also clear that an adequate understanding of these two issues can only be achieved through the use of a suitable technique for characterization of the topography. Such a characterization procedure involves both visual and numerical techniques.

Throughout the manufacturing organization, many groups require an understanding of the surface topography of materials and components if high quality products are to be consistently produced. For example, the designer requires information which will ensure that the surface characteristics specified are suitable for a known function, and must be able to define appropriate parameters and tolerance levels for satisfactory operation. The manufacturing engineer needs to understand the surface structural requirements in order to specify a manufacturing process which will produce a surface having the necessary characteristics. The quality engineer needs to have a system which will provide sufficiently detailed information, relative to the specified characteristics, to ensure that surfaces have been produced within the pre-determined tolerance levels.

SURFACE CHARACTERIZATION

The most common method of determining surface characteristics is through the use of a stylus-based measuring instrument. The stylus is drawn across the surface at near constant velocity for a pre-determined distance. The vertical excursions of the stylus, relative to a datum, when suitably magnified, are a measure of the deviations of the real surface and within the calibrated tolerance range of the instrument.

In recent years metrologists and engineers have begun to realize that surfaces cannot be adequately characterized in two dimensions (2-D) and consequently emphasis has been given to three-dimensional (3-D) analysis. Since conventional stylus instruments are constrained to move in a straight line, a scanning technique may be implemented in order to accomplish 3-D assessment. The technique of recording or presenting data as a series of parallel traced lines is referred to as a 'raster' scan and can be achieved through the use of a stylus measuring instrument, employing a linear translation stage to move the work normal to the line of traverse.

As with conventional 2-D profilometry, a visual image of the logged area is desirable, if only to verify the system operation. More importantly, since 3-D quantitative analysis and modelling has only been investigated beyond its preliminary stages by some statisticians, qualitative analysis provides useful comparative information for the engineer. Thus, 2-D projections of the 3-D data, in the form of an axonometric plot and a contour map, accompanied by suitable numerical analysis are essential features of a surface characterization system.

THE 3-D DATA COLLECTION SYSTEM

The 3-D logging system used to obtain the data for the surfaces shown in this atlas is based on a modified Rank Taylor Hobson (RTH) Talysurf 5 surface measuring instrument incorporating a linear translation stage (Plate 1). In this system, area maps are logged by specifying sample spacing, trace spacing, number of data points per trace and number of traces. The specimen is moved normal to the line of traverse of the stylus by means of a linear translation stage. A raster scan of surface areas is achieved by indexing the stage a pre-programmed distance (trace spacing) before the start of each trace. The logged areas for each surface presented in Part I were square with sides measuring 1.304 mm. The grid spacing on both axes was 8μm, giving a total of 26 896 data points for each sample. The material used in all machining processes was a free cutting mild steel.

The datum plane in the direction of traverse can be accurately defined using a straight line datum attachment. Backlash problems have been eliminated by moving the work surface in only one direction for each profile. It should be noted that the stage is stationary during data logging, thus eliminating vibration problems and the need to accurately control the velocity of table movement.

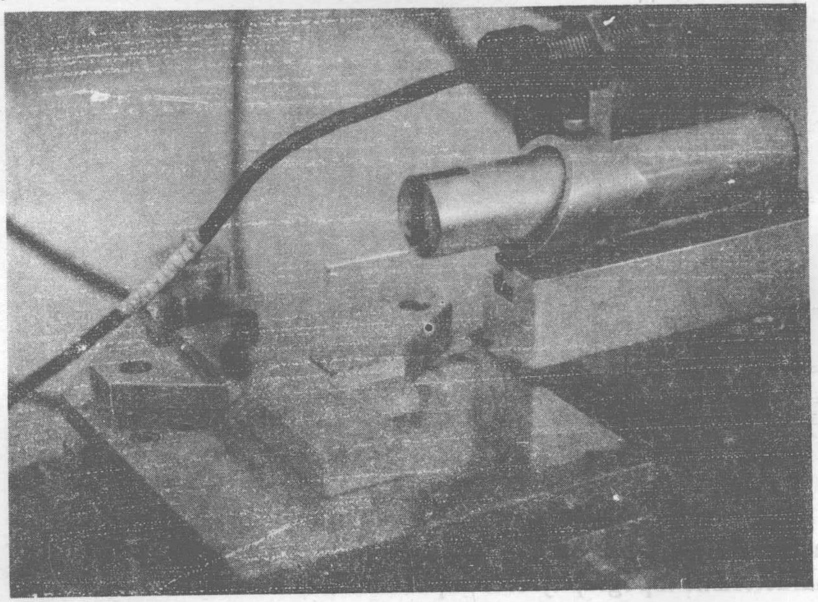


Plate 1

THE 3-D DATA ANALYSIS SYSTEM

When analysing data in three dimensions it is necessary to determine a suitable datum, such as that specified by the least squares mean plane. This plane is defined as the mean true plane, for which the sum of the squares of the errors yields a minimum value. When examining surfaces which are curved, such as those produced by turning, it is often beneficial to remove the curvature mathematically from the data. This process assists data manipulation and surface visualization. The best fitting curve which approximates to a given data set is that for which the sum of the residual squares is a minimum. For this work the least squares parabola was found to fit the data best and, where appropriate, this curve is subtracted from the original data prior to further manipulation.

As previously stated, 3-D data characterization is accomplished through the use of both visual and numerical techniques. In addition, specially developed numerical routines are used to manipulate the data for further analysis.

Numerical characterization

In this atlas numerical characterization involves the use of traditional 2-D parameters, their 3-D counterparts and volume-based measurements.

The most readily accepted measures of surface roughness characteristics are contained in the surface height amplitude distribution. Thus, when defining roughness parameters for an area, it is logical to consider the ordinate height distribution of the area as a measure of roughness.

Numerical integration techniques have been used to calculate the material volume of the logged area. By computing this volume before and after truncation (see below), two further parameters of tribological interest can be obtained – void volume and debris volume. The void volume parameter provides an estimation of the lubrication capacity of the surface in cubic mm per square mm of surface area. The debris volume provides an estimation of the expected volume of truncated material in the surface lubricant. The value is obtained as the volume difference between successive truncation levels in cubic mm per square mm of surface area.

To investigate directional properties of the surfaces we have presented graphs showing the distribution of single profile values in two orthogonal directions. The calculations of the profile parameters, *Ra*', and *Rq*', skew and kurtosis, are based upon the definitions given in ISO R468.

The following parameters are used in the atlas.

Area parameters

The following definitions are given for a set of data points Z_i where $1 \leqslant i \leqslant T$. T is the total number of data points (i.e., the product of the number of points per trace and the number of traces).

Mean = area mean height, $\bar{z}_a$

$$\bar{z}_a = \sum_{i=1}^{T} \frac{z_i}{T}$$

Ra = average roughness of area

$$Ra = \sum_{i=1}^{T} \left| \frac{z_i - \bar{z}_a}{T} \right|$$

Va = average variance

$$Va = \sum_{i=1}^{T} \frac{(z_i - \bar{z}_a)^2}{T}$$

Rq = root mean square roughness of area

$$Rq = \sqrt{Va}$$

Rsk = skewness of the area about the mean

$$Rsk = \sum_{i=1}^{T} \frac{(z_i - \bar{z}_a)^3}{TVa^{3/2}}$$

Rku = kurtosis of the area about the mean

$$Rku = \sum_{i=1}^{T} \frac{(z_i - \bar{z}_a)^4}{TVa^2}$$

Rt = the vertical height between the highest and lowest points of the area

Rp = distance from mean to highest peak

Rv = distance from mean to lowest valley

Volume parameters

Material volume ($mm^3 mm^{-2}$)

Void volume ($mm^3 mm^{-2}$)

Debris volume ($mm^3 mm^{-2}$)

Graphical characterization

Various graphical techniques have been incorporated to enhance visualization of the 3-D data. These include the following.

Axonometric plotting

This feature produces scaled 2-D projections of the 3-D data, including complete hidden line removal. The projections presented here use differential magnification to enhance visualization of asperity characteristics. This feature is consistent with 2-D analysis but the observer must always recognize the distortions which are inherent in the technique. Scale values on the *z* axis have the units of micrometers.

Contour plotting

This feature produces a surface map of equivalent height contours. The number of contour levels can be selected so as to produce a clear view of surface characteristics. The feature enhances qualitative analysis of surface details such as directionality and extends the use of surface topography data to include surface flaws or wear scars.

Data manipulation

In addition to the data visualization features of the package, the data can be manipulated to produce quantitative information, with particular reference to tribological functions and surface flaw analysis. The data manipulation features include the following.

Inversion

This provides a detailed view of the surface valleys in the inverted form. The feature is of particular use in revealing features in lubrication and wear analysis where the extent of the surface structure is important.

Truncation

The truncation feature is used both to predict controlled wear behaviour of surfaces in a tribological environment and to examine sub-surface features. The surface can be truncated to any pre-determined level and then analysed in any of the previously mentioned modes. The truncated data is used to compute a percentage area of contact parameter (contact %).

The truncation feature is used in combination with parameter calculation routines to allow the development of certain parameters to be analysed throughout the life (i.e., 1% to 100% truncation) of the surface. The results of this 'progressive truncation model' are presented in the form of composite graphs. For this atlas the development and interpretation of the following parameters are presented: contact %; material volume; void volume; debris volume; *Rsk* and *Rku*.

THE FIGURES

The figures presented in sections 1–14 of Part 1 of the atlas, are arranged in a standard sequence with some supplementary figures being added where appropriate.

Firstly, information is presented regarding the original unmodified surface in the form of an axonometric projection, height distribution with associated parameters and 5-level contour map. Height distribution information is presented as relative frequency (percentage of total data points) against height value (μm).

In order to investigate the directional properties of the surface and the variability of single trace parameters, four graphs are given which characterize trace values in two orthogonal directions. The relative frequency (percentage of total number of traces) of four parameters (*Ra*', *Rq*', skewness and kurtosis) are given.

In order to investigate the predicted behaviour of the surfaces in a tribological wear environment, they are subjected to a 30% and 70% truncation process. Figures included to indicate the effects of 30% truncation are an axonometric projection of the modified surface, a 5-level contour map, an axonometric projection of the debris removed, and the height distribution and associated area parameters for the modified surface.

To reveal the effects of 70% truncation the following figures are included: an axonometric projection of the modified surface, a 5-level contour map, an axonometric projection of the inverted surface to reveal the shape of the remaining valleys, and the height distribution and associated area parameters of the modified surface.

Finally, a list of figures is included to show the behaviour of surface parameters when subject to progressive truncation.

SUMMARY

The objective of the atlas is to provide a reference document of engineering surfaces so that the character of these surfaces may be understood in a 3-D sense.

Part 1 considers typical surfaces generated by 14 machining processes and describes the character of each in relation to the process by which it has been generated.

Part 2 provides an investigation that relates a machined surface's topographical features to its functional behaviour in a wear environment.

The Appendix provides information on relevant international standards for surface finish to provide the user with a reference source of useful literature.

CONTENTS

PART 1

MACHINED SURFACES

The figures presented in this section relate to a surface typical of those produced by the turning process. In this case, for ease of instrumentation, a face-turned surface has been selected, but the characteristics would be similar for any turned surface. Figures 1.1 and 1.3 show that such a surface has a highly regular structure generated by the single point of the cutting tool moving across the surface at a constant feed-rate during machining. Note that the structure generated is slightly curved, the rate of curvature being dependent upon the distance of the tool point from the centre of the workpiece. The structure of the surface is therefore a combination of a waviness component, generated by the feed process associated with the cutting point, and a random component of micro-roughness, caused by the action associated with chip removal. The randomness is due to the built-up edge on the cutting tool being continuously generated and removed during machining; the rate at which this occurs is partly determined by non-homogeneity within the body of the material itself.

As is evident from Figure 1.15, in a tribological situation this surface will yield rapid asperity removal until approximately 50% of the original *Rt* value has been lost; after this stage has been reached the rate of debris removal becomes more or less constant. In general, the turned surface appears to have potential as a tribological ssurface since the valleys provide the lubricant retention features needed in any surface. To improve the surface characteristics it is essential to pay considerable attention to the shape of the tip of the surface-generating cutting tool.

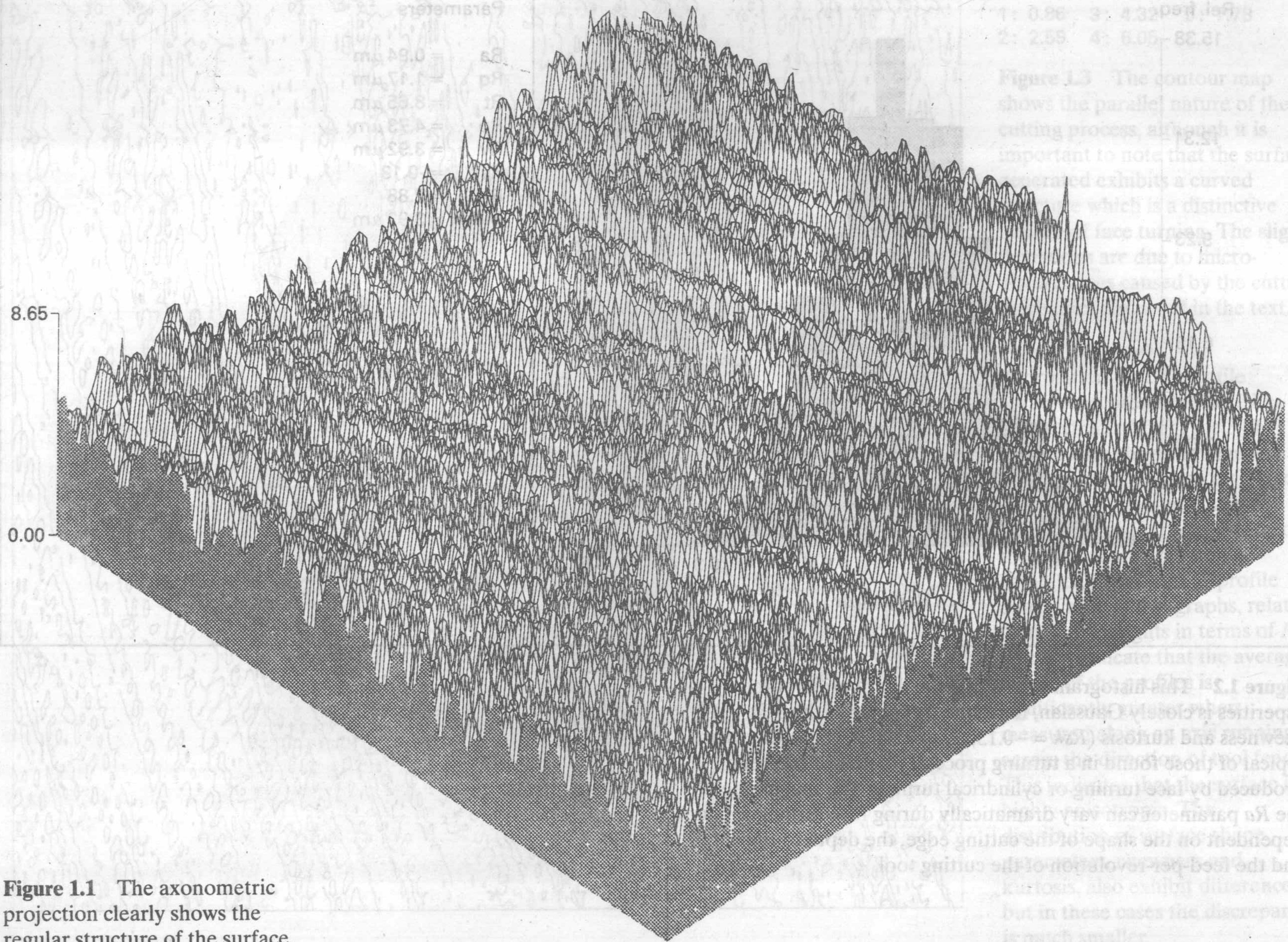


Figure 1.1 The axonometric projection clearly shows the regular structure of the surface.

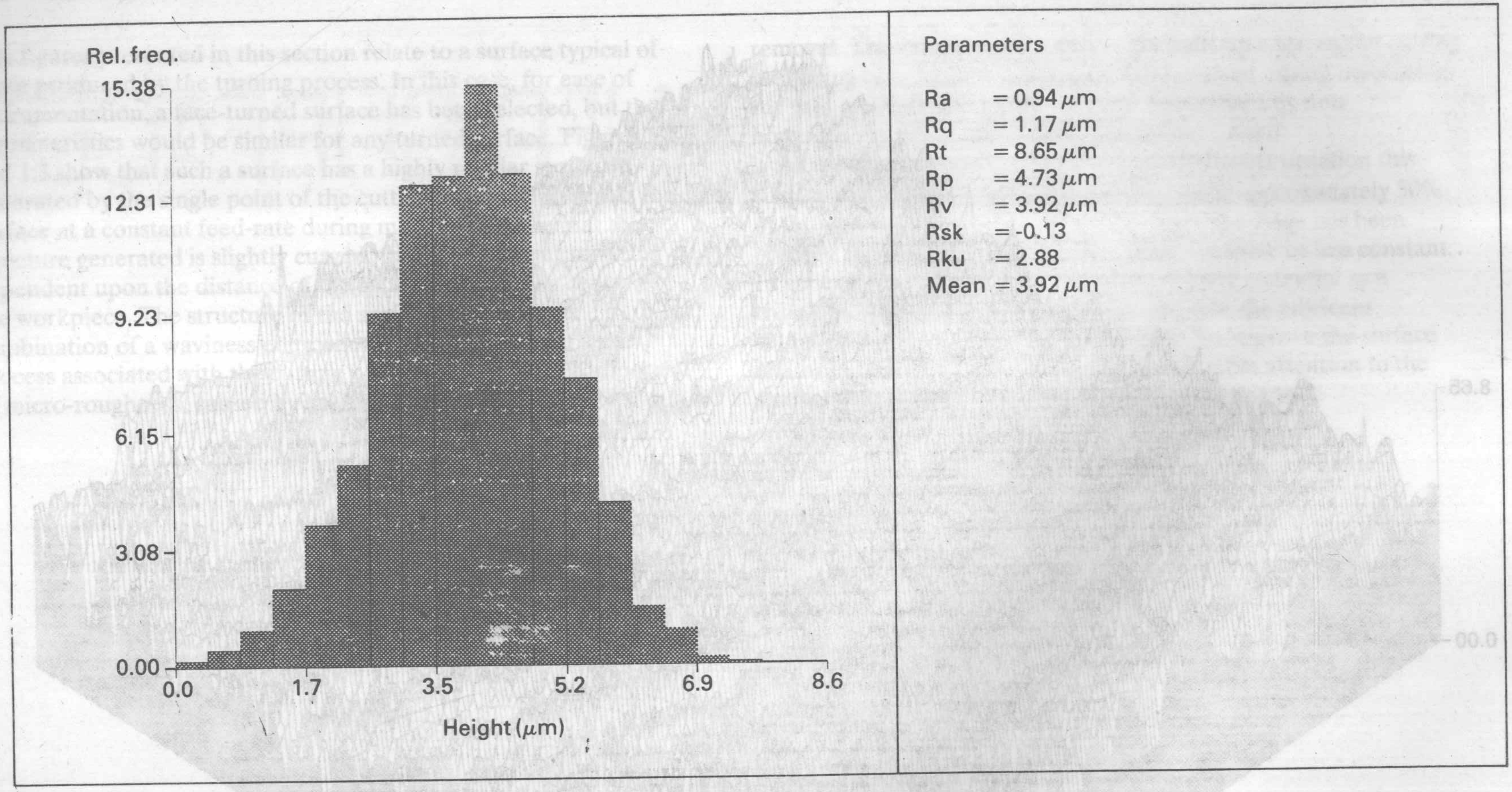
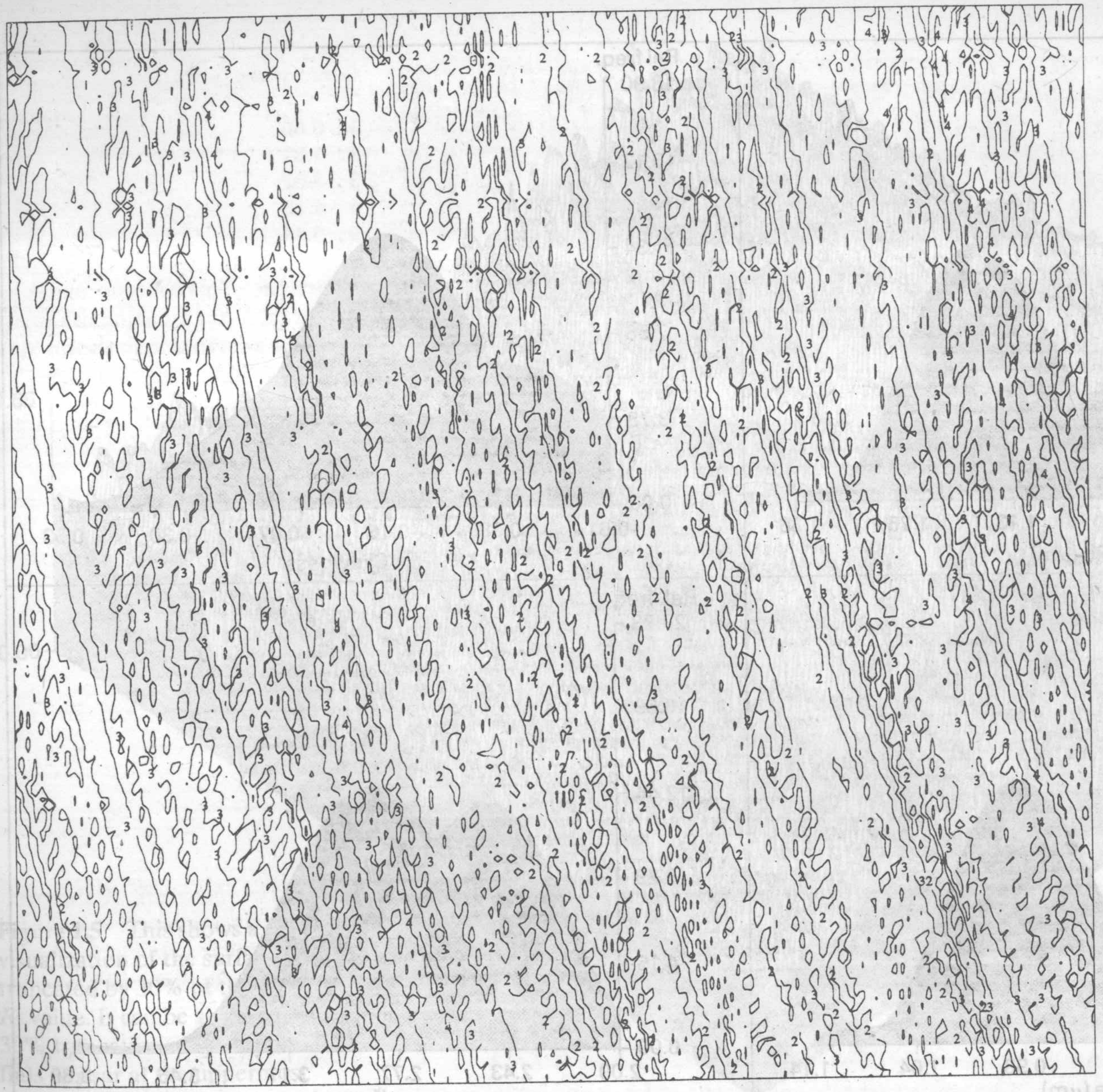


Figure 1.2 This histogram shows that the distribution of the asperities is closely Gaussian, indicated by values of the 3-D skewness and kurtosis (*Rsk* = −0.13; *Rku* = 2.88). These values are typical of those found in a turning process, whether it has been produced by face turning or cylindrical turning. The magnitude of the *Ra* parameter can vary dramatically during face turning as it is dependent on the shape of the cutting edge, the depth of the cut and the feed-per-revolution of the cutting tool.

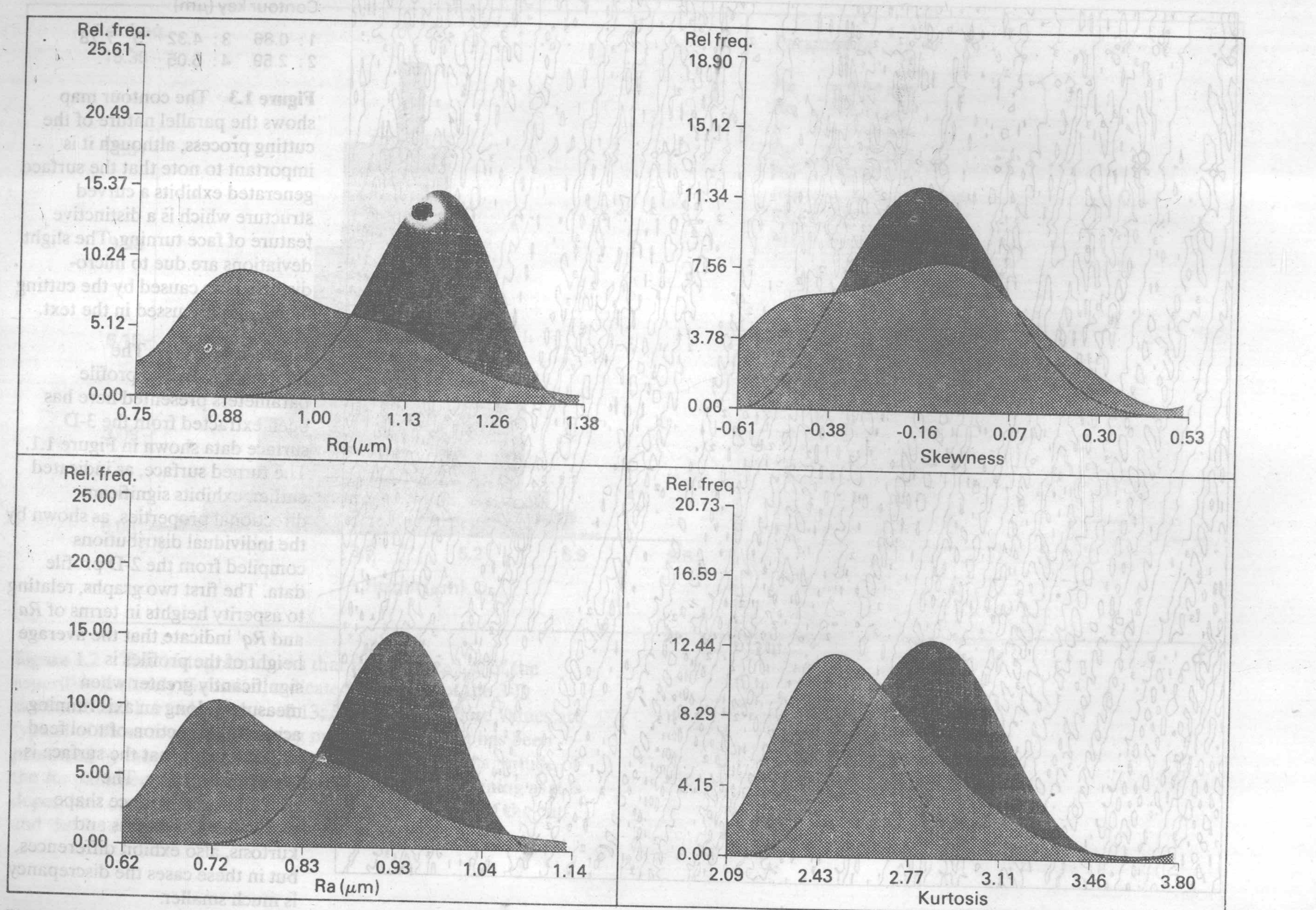


Contour key (μm)

1: 0.86	3: 4.32	5: 7.78
2: 2.59	4: 6.05	

Figure 1.3 The contour map shows the parallel nature of the cutting process, although it is important to note that the surface generated exhibits a curved structure which is a distinctive feature of face turning. The slight deviations are due to micro-disturbances caused by the cutting mechanics discussed in the text.

Figure 1.4 (over) The information on 2-D profile parameters presented here has been extracted from the 3-D surface data shown in Figure 1.1. The turned surface, as indicated earlier, exhibits significant directional properties, as shown by the individual distributions compiled from the 2-D profile data. The first two graphs, relating to asperity heights in terms of *Ra*' and *Rq*' indicate that the average height of the profiles is significantly greater when measured along an axis running across the direction of tool feed. This indicates that the surface is highly anisotropic. The distribution of surface shape parameters, skewness and kurtosis, also exhibit differences, but in these cases the discrepancy is much smaller.



Rel. freq.
25.61
20.49
15.37
10.24
5.12
0.00
0.75 0.88 1.00 1.13 1.26 1.38
Rq (μm)
Rel freq.
18.90
15.12
11.34
7.56
3.78
0.00
-0.61 -0.38 -0.16 0.07 0.30 0.53
Skewness
Rel. freq.
25.00
20.00
15.00
10.00
5.00
0.00
0.62 0.72 0.83 0.93 1.04 1.14
Ra (μm)
Rel. freq
20.73
16.59
12.44
8.29
4.15
0.00
2.09 2.43 2.77 3.11 3.46 3.80
Kurtosis

Figure 1.4

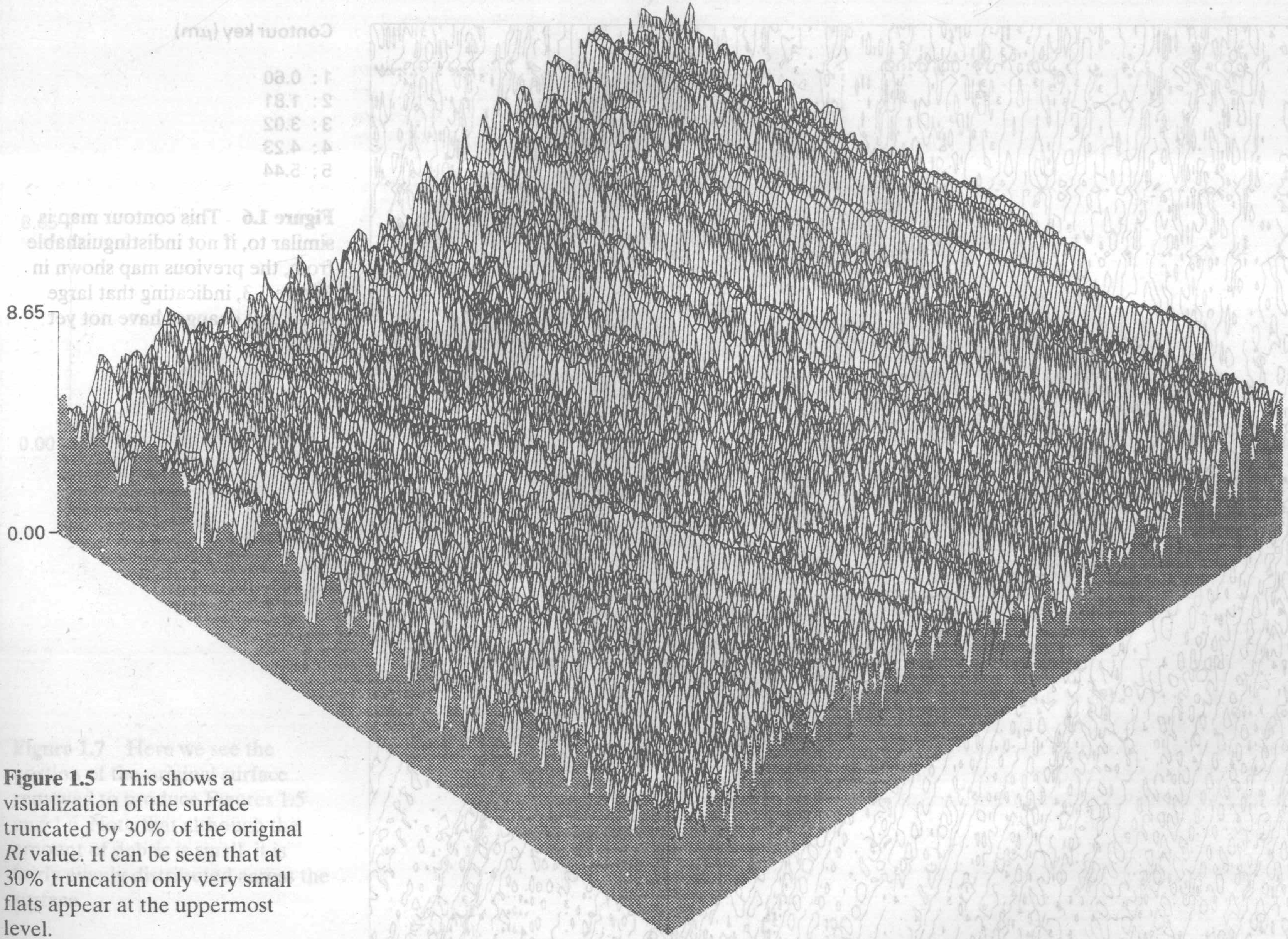
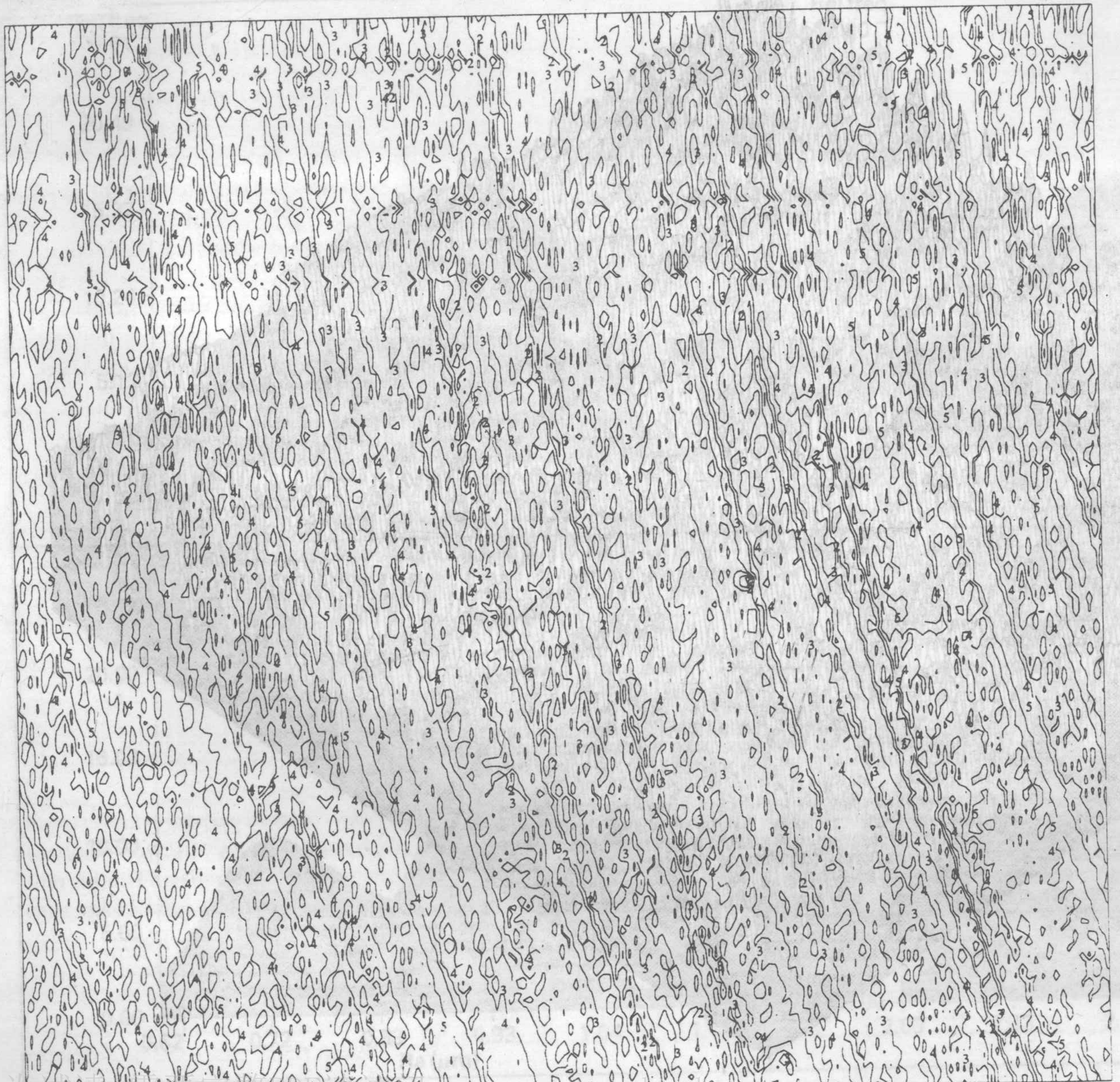


Figure 1.5 This shows a visualization of the surface truncated by 30% of the original *Rt* value. It can be seen that at 30% truncation only very small flats appear at the uppermost level.



Contour key (μm)

1 : 0.60
2 : 1.81
3 : 3.02
4 : 4.23
5 : 5.44

Figure 1.6 This contour map is similar to, if not indistinguishable from, the previous map shown in Figure 1.3, indicating that large structural changes have not yet occurred.