The Loaded Surface Profile: A new technique for the investigation of contact surfaces.

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Summary
Contact between rough surfaces produces a complex contact profile. The contact area is usually estimated according to roughness statistics in conjunction with surface models or by examining the surfaces before and after contact. Most of the existing literature on loaded surface profiles is theoretical or numerical in nature.
This paper presents a methodology for a new system to measure the loaded surface profile, based on a non-contact 3D laser profiler. The system allows the measurement of contact area, deformation and contact resistance in terms of the contact force and plane displacement, all whilst the surfaces are actually in contact. This paper presents the initial study of the methodology and focuses on the method for determining the real contact area.
The laser performs the scan through a transparent flat slide supported in a fixed position above the base. A test contact is mounted on a force sensor on an adjustable screw support such that this sub-assembly can move into contact with the fixed transparent surface.
The main results are in the demonstration of the measurement method and in the initial study of contact force and contact area on a hemispherical Ag/SnO electrical contact surface.

Key words:
Contact Area Measurement, Contact Force

1. Introduction

Contact between rough surfaces produces a complex contact profile. The real contact area, shapes, sizes, number and distribution of points of contact (a-spots) is relevant to many topics concerning surfaces, including electrical contacts. The contact area is usually estimated according to roughness statistics in conjunction with surface models, or by examining the surfaces before and after contact.
A new system is presented that allows the measurement of contact area, deformation and potentially contact resistance in terms of the contact force and plane displacement, all whilst the surfaces are actually in contact. This study considers low contact force, below 1N; and is applicable to many contact systems, including MEMS devices.

Conventionally a contact surface is assumed to be governed by random process and the associated statistical analysis of such surfaces is well documented, [1-3]. The statistical approach is limited on the dependence of the sampling length and the resolution of the measurement instrument. For this reason Fractal models of the interaction between surfaces have been developed. [4,5]. In all of the above theories there is little evidence on the measurements of actual contact surfaces, other than the conventional 2D scans of surfaces associated with stylus based instruments.
The link to contact resistance is generally stated in the Holm equation [6], where the ‘a’ spot, (point of electrical contacts) is assumed to be circular and a single point contact. This equation can be modified to account for non-circular, for example elliptical form factors. To account for a number of these ideal contact points within a single cluster, the following equation is used, [7];

$$R_C = \rho\left(\frac{1}{2na} + \frac{1}{2\alpha}\right) \tag{1}$$

Where a is the mean a-spot radius, n is the number of circular a-spots in the cluster and α is the radius of the cluster, (sometimes defined as the Holm radius). The conclusion drawn from the application of this equation is that “ the details of the number and spatial distribution of an a—spot are unimportant to the evaluation of the contact resistance in many practical applications”, [8]. This is however based on the assumption that n is large, n=76, was used in the application of Eq(1), [7].
Some previous studies of the points of actual contact area seem to support the hypothesis of n being a large number, for example optical micrographs have been used to detect the points of contact on a sand blasted steel surface with an optical flat, [8]. Although in this case the force levels are in kN.
The similarity between the electrical conduction problem and the thermal conduction problem has been addressed by Barber [9] who has shown that the conductance of a rough contact is the derivative of the force indentation curve. The evaluation of the force-indentation curve requires the analysis of a 3D contact problem. The direct algorithms available cannot be applied to rough surfaces due to cumbersome numerical analysis required, and as such the contact with a rough surface is still an open problem, [10].

The relationship with the applied force is based on the assumption that the asperities and the associated a-spots deform plastically, and as such can be related to the Hardness of the softer material (H). This observation underlies the physics of friction between sliding bodies. The relationship between the applied force (F) and the actual area of contact (A_C) is then simply;

$$F = A_C H \quad (2)$$

If we then assume that the contact resistance can be approximated from Eq (1) to be;

$$R_C \approx \frac{\rho}{2\alpha} \quad (3)$$

And where the area of contact A_C is again considered to be circular, and where η is an empirical coefficient to account for surface films (1 for a film free surface).

$$A_C = \eta\pi\alpha^2 \quad (4)$$

Then;

$$R_C = \left(\frac{\rho^2\eta\pi H}{4F}\right)^{\frac{1}{2}} \quad (5)$$

For numerous studies of the contact resistance with force relationship for new surfaces, the relationship shown in Eq. (5) has been shown to hold, for example [11]. However if the deformations were elastic then based on the Hertzian analysis;

$$R_C = \left(\frac{k}{F}\right)^{\frac{1}{3}} \quad (6)$$

The study presented here allows for the investigation of the relationship between the contact force and the area of contact. The common experimental evaluation of the "contact problem" is usually presented as the direct measurement of contact resistance with the applied force, as shown in Eq's (5) and (6). In these experiments the contact resistance is usually evaluated at some distance from the area of contact and therefore always includes an element of the bulk material resistance unless a non-linear contact resistance measurement is used.

2. Experimental Methods

The system used for this study is the XYRIS 4000LT, using a con-focal laser source (650nm) for the measurement of the contact surface. [12,13]. The outline of the system is shown schematically in Fig.1, with table 1 providing the specification for the system. The light spot size and the sensor resolution are critical features for this study. The system is characterized with the sensor in the vertical (Z) axis and a sample being scanned in the X,Y plane. The sensor selected for this application has the critical ability to measure features below the light spot size, and through a transparent medium. This is achieved by moving the sensor with sub micron resolution in the X,Y plane, and the sensor returning a value which is the average height at that particular position, [11,12].

Laser Sensor range	0.6mm
Sensor Resolution	10nm
Light spot size	2μm
X,Y system Resolution	0.1μm
Optical Flat R_a	30nm
Force Resolution	10mN

Table 1.System specification.

With reference to Fig.1, the electrical contact surface is mounted upon a spring which is connected to a force sensor. The force sensor is calibrated and can be related to the displacement of the electrical contact surface, as shown in Fig.2. The electrical contact is constrained such that it can only move in the vertical (Z) direction. The contact force is applied by a glass surface which acts upon the electrical contact surface. The force ise controlled by the positioning of the glass plane. The system is limited to low forces below 1N, as shown in Fig.2. The data in Fig.2 shows the position of a single point on the contact surface as the glass plane is moved, and the corresponding output of the contact force. It shows that the system is linear over most of the operational range, up to the higher levels of force above 0.8N, where the contact support reaches the end stop preventing further movement.

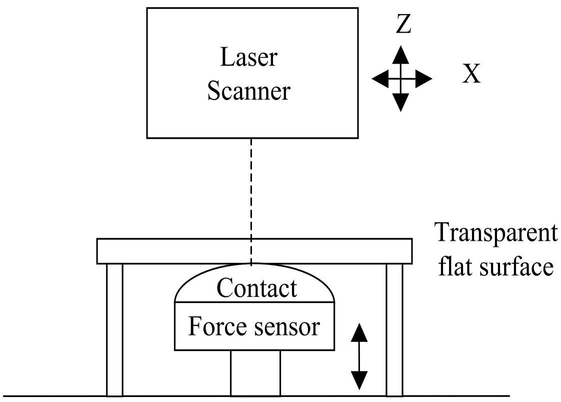

Fig. 1. Schematic of the measurement system.

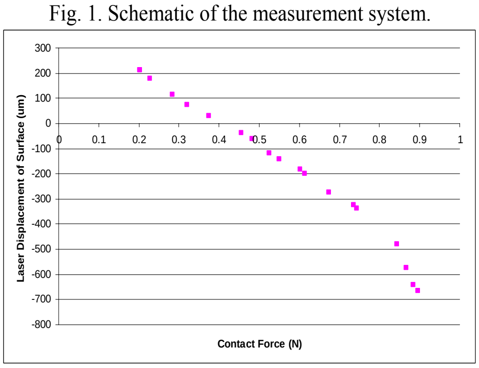

Fig.2 Calibration of sensor output with the surface displacement.

The optical method used allows the surface of the contact to be measured through the glass surface. With a force applied to the glass surface, the surface deformation can be determined with data sets representing the full 3D surface. For most of the data presented the position of the sensor head is fixed (Z axis) and the motion system used to scan (X,Y axis) the electrical contact surface.

2.1 Methodology.

The contact surface selected is a hemispherical Ag/SnO contact rivet, with a nominal radius of 6.422mm. All surfaces were cleaned prior to testing. The system is mounted upon a anti-vibration work station in a temperature controlled clean room (20°C +/- 0.5°C). The results are presented in a 3 stage process.

- Stage 1. Initial tests without the glass surface. To determine the nature of the contact surface a series of scans were conducted on the electrical contact surface without the glass.
- Stage 2. Initial study of the surface under a fixed contact force, to identify the contact areas.
- Stage 3. The study of the contact areas as a function of the contact force.

3. Results

3.1 Stage 1. Initial tests without the glass surface.

The profile of the surface is shown in Fig.3 to be nominally spherical with a radius of 6.4mm and with a surface roughness of 172nm, and with a 2µm level deviation from the sphere. To determine the surface area in contact it is essential to define a measurement grid where the spacing is sub micron. Fig 3 shows an example image of the surface over and area of 0.21mm x0.21, with a grid spacing of 0.7µm. The small square at the centre of Fig 2, is the corresponding area. This is shown in both plan view and in profile. This shows that the surface selected for the study has a number of high peaks which stand above the normal surface. This is ideal for the initial study in that it allows for the ease of identification of the points of contact between the surfaces.

3.2 Stage 2. Initial study of the surface under a fixed contact force, to identify the contact areas.

3.2.1 Positioning of the sample

Fig.5 shows the central region of the contact area with the glass surface in contact, with the line on the surface corresponding to the 2D section also shown in Fig.5.

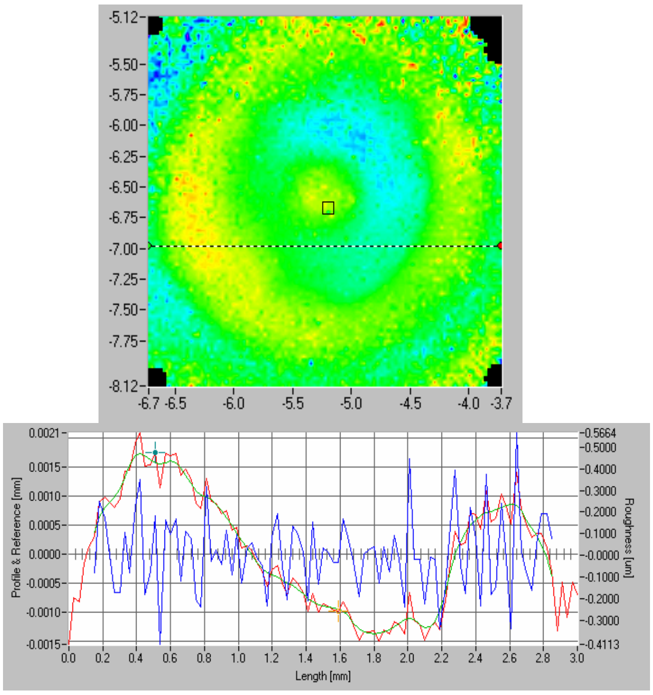

Fig.3. The upper figure shows the 3mmx3mm (30µm grid spacing) contact surface with the spherical form removed. The line is the 2D section in the lower figure. With sphere removed. R=6.422mm. Pa = 0.992um (Red Line), with Ra = 0.172um (Blue Line) with 0.25 Gauss filter (Green)

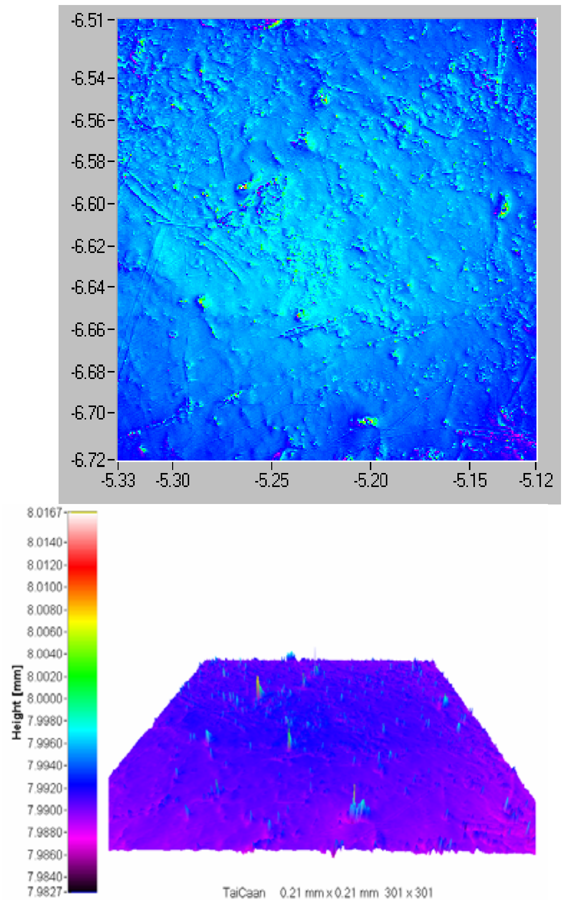

Fig 4 Details of the surface of the contact, 0.21mm x0.21mm (301x301) grid 0.7µm

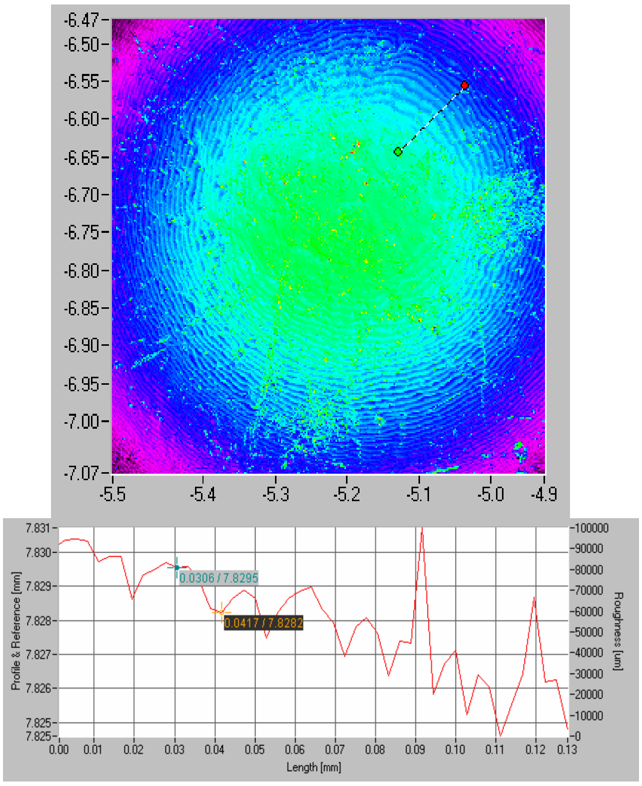

Fig 5, Ring pattern, with the glass in contact with the surface. With cross section through the data 1.32um. Data is 0.6mm x0,.6mm with 301 x 301 data (grid size 2µm).

The results in Fig 5 show an interesting consequence of the measurement method, where rings appear on the surface with a spacing related to the distance between the glass and the metal surface. These are not conventional interference fringes as the interference pattern is a consequence of the light interactions between the reflection from different surfaces, and as such affects the light intensity. In the data presented the light intensity is unaffected, but there appears to be an influence on the height measurement shown in the lower figure, (based on the line section in the upper figure) with typical peaks to valley of above 1µm. This affect has the benefit that it allows the alignment of the surface, as the concentricity of the rings point to the central area. This is important as the contact surface can tilt very slightly with the application of different force levels.

3.2.2 The Resolution of the Data for the Evaluation of the Contact Area.

Consideration is given here to one experimental condition, with 0.35N force. The data is considered at 3 resolution levels.

- Res 1 = 0.6mm x0.6mm, 2µm grid. As shown in Fig.5, to allow for the centering of the measurement, based on the ring structure identified in Fig.5.
- Res 2 = 0.3mm x 0.3mm, 1µm grid, to identify the structure of the peaks within the contact region.
- Res 3 = 0.21mm x 0.21mm, 0.7µm, for the evaluation of the surface area, shown in Fig.6.
- Res 4 = 0.02mmx0.02mm, 0.2µm grid, for the evaluation of a single asperity, shown in Fig.7.

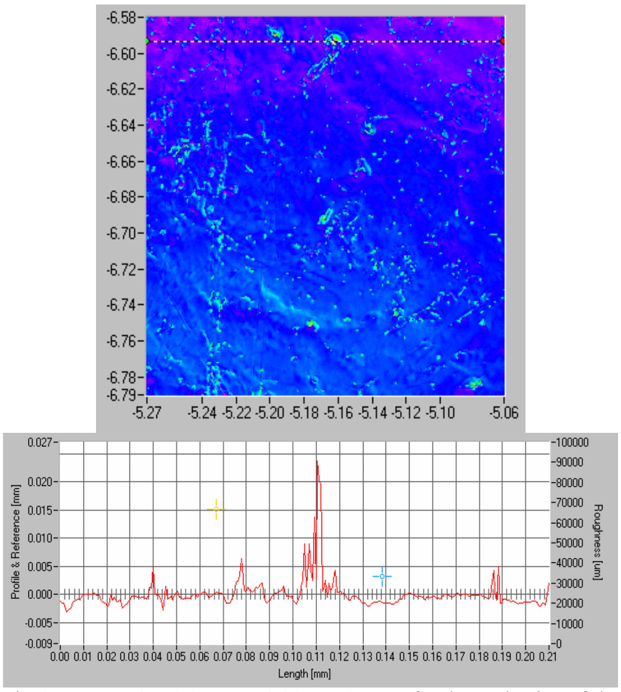

Fig.6, Res Res 3 = 0.21mm x 0.21mm, 0.7µm, for the evaluation of the surface area. Close up of the surface in Fig 6, with 0.21mm x0.21mm and 0.7µm grid spacing.

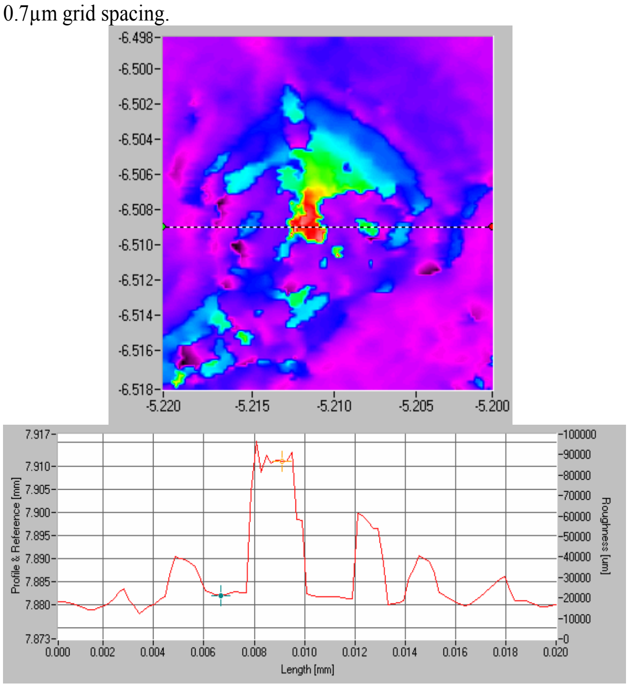

Fig 7. Res 4, The profile of a single asperity 20µm x 20µm, with a grid spacing of 0.2µm.

The data presented in Fig's 4-7 show increasing magnification of the surface features. Fig 6 shows the central region of the contact area, and presents a cross section through one of the peaks, with the peak 20µm above the normal surface. A further increase in magnification leads to the surface in Fig.7 where the grid spacing is reduced to 0.2µm. This shows the details of a single peak, and the very clear leveling of the surface due to the interaction with the glass plane.
It can be concluded for the resolution of the data that Res 3 has sufficient detail to resolve the peaks in the contact surface, where Res 2 and Res 1 are used initially to align the measurement for a given contact force.

3.1.3 Determining the contact area

The problem to be addressed is how to define the measurement of the area in contact with the glass plane. It is clear from the data in Fig.7 that there is a flattening of the asperity, but this flattening appears to be a localized phenomena, and also appears to be elastic. It should be noted here that the contact surface selected has undergone a number of loading and unloading cycles prior to the experiment. To determine the surface area as a function of force it is necessary to consider the statistical properties of the surface under consideration.
The data shown in Fig 8, is the z data distribution for the data in Fig.6. It shows that the surface has a number of peaks at 10-20µm above the datum level.

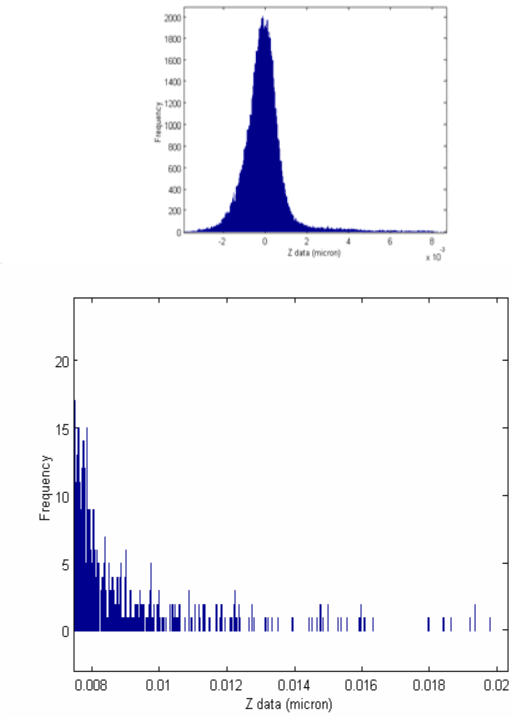

Fig 8. Histogram of loaded contact surface in Fig 6, with RES 3. The lower figure is a magnified section of the peaks where there are clearly low number of peaks above the 10 micron level.

The two histograms show that the surface under consideration here has a low number of surface peaks which appear to be carrying the contact load. The problem is determine a method for the evaluation of the area of the surface. Clearly any arbitrary value of the level above the datum surface will yield a different result for the area. To identify the peaks in the selected area a cell counting program has been used [12]. The software allows the user to define a plan relative to the histogram of the surface data. An example is shown in Fig's 9 and 10, applied to the RES 3 data shown in Fig 6 and Fig 8. Fig 9 is used to define the slice level, and present the data below this level. The remaining data is presented as cells, in Fig 10, where the number of cells and the average area is calculated.

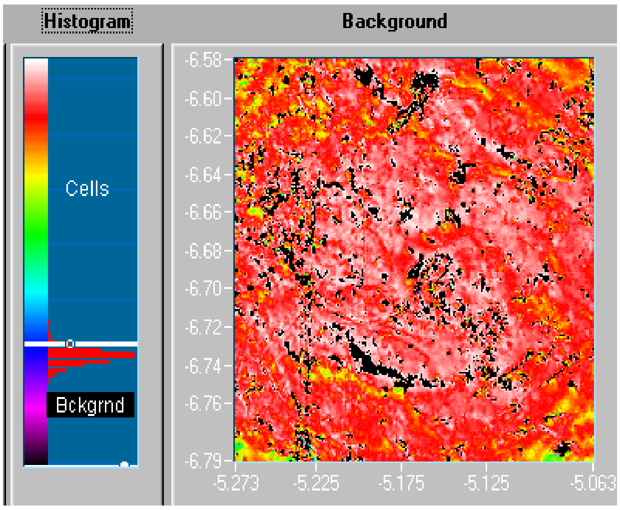

Fig 9, The definition of the slice level and the data below the level.

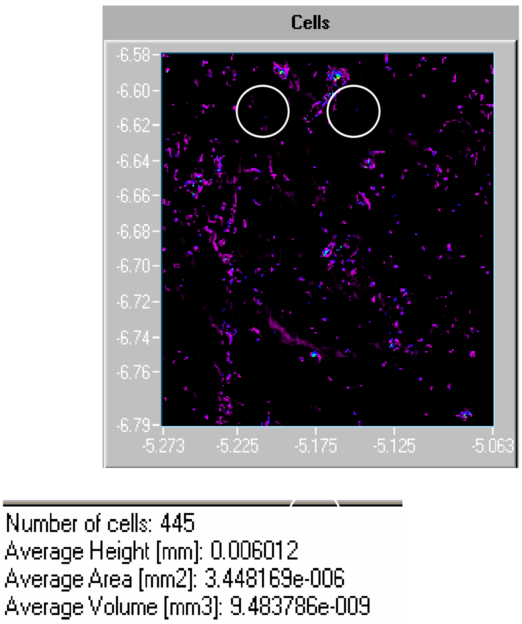

Fig 10, The evaluation of the number of cells, and the area of the cells above the slice level. With the 3 highest peaks circled.

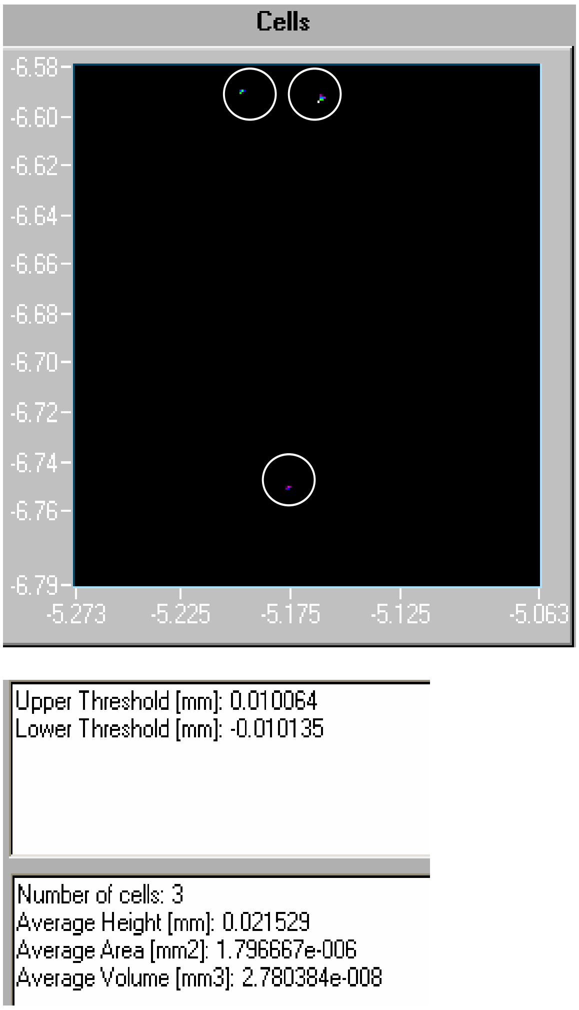

Fig 11 The area of contact over 3 cells which are not located within the same local area. The peaks are the same as those highlighted in Fig 11, and are circled here. The contact area is 5.388 μm^2

To determine the area in contact with the glass requires a definition for the slice level used.

Slice level definition: To determine the surface area in contact with the glass, the slice level is defined as that level at which there are a minimum of 3 clearly defined areas of contact, which are separated by a reasonable distance.

The rationale behind the definition is that for the contact surface to be stable there must be a minimum of 3 contact points, and that these contact points cannot lie within the same peak. There are a number of cases where the peak of the asperity is not uniform, and where there can be local peaks within the asperity. In the case of the peak shown in Fig 7, the other peaks would be outside the field of view presented. In some cases in the data presented the number of peaks (referred to as cells) can exceed 3, where there are 2 or more local peaks.

For the data shown in Fig.11, there are 3 cells, circled, which are independent asperities. The total area in contact is then the number of cells, multiplied by the average area.

3.3 Stage 3. The study of the contact area as a function of the contact force.

In the data presented here the contact surface is un-loaded in the same direction, from high load to low load, to prevent system influences. The data is scanned at 3 resolutions, with the system centered after each scan to make sure the contact region is covered.

Contact Force (N)	Number of Cells	Area above the slice level x μm^2	Slice level above the datum surface.(μm)
0.43	4	8.33	13.58
0.35	3	6.45	9.44
0.27	5	4.4	15.36
0.12	3	4.16	14.6
0.047	3	2.94	17.56

Table 2. Results of the area in contact with the glass as a function of the contact force.

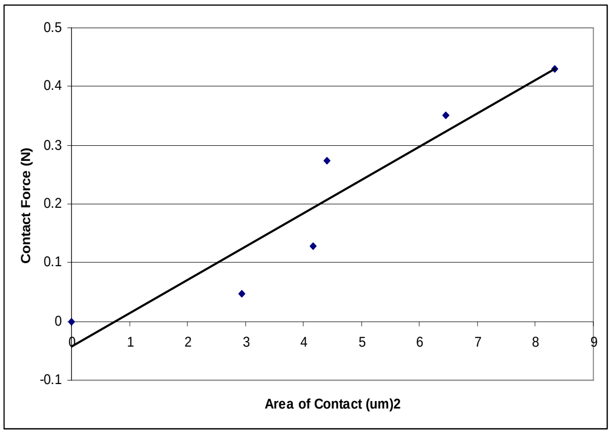

Fig 12. The relationship between the contact Contact Force and the Area of Contact.

4. Discussion

The results presented here provide a unique insight into to events affecting real contact surfaces. It should be stated that the results presented here are mainly focused on the methodology used in determining the actual area of contact.

The study of the grid resolution required to provide data on the area of contact, has shown that the 0.7µm grid is best suited for the surface under consideration. It is likely to be the case that a more refined surface would require a different grid resolution.

The surface selected for this study was a common electrical contact hemispherical surface, which shows a small number of peaks in the region of the contact area. Such a surface would not fit with the approximation provided by Eq. 3. It is more likely to be the case that each contact area will act alone as a conducting interface, with the combined contact resistance would be given by the combined 3 independent constriction resistances associated with the 3 cells identified.

The resulting application of the method for measurement of the contact area with the applied contact force shown in Table 2, and Fig 12, shows that there is a near linear relationship between the force and the area of contact, implying that the process measured is plastic, however it should be noted here that;

(i) the surface under investigation had undergone a number of loading cycles and the expectation is that the process measured is elastic;

(ii) the results presented are preliminary, and more data will be accumulated for a range of surfaces, before linkage to the theory outlines in this paper.

5. Conclusions

The results presented here provide a unique insight into to events affecting real contact surfaces. The system and the methodology developed allows for the evaluation of the areas of contact between a metallic and a glass/transparent surface. In determining the area of contact the main observation is that the resolution of the data collected and slice level used needs to be clearly defined.

The X,Y grid resolution for the data presented in this paper is 0.7µm over a measurement area of 0.21mm x 0.21mm.

The slice level used is defined as follows;

Slice level definition: To determine the surface area in contact with the glass, the slice level is defined as that level at which there are a minimum of 3 clearly defined areas of contact, which are separated by a reasonable distance.

The evaluation of the reasonable distance between the regions of contact are to ensure that the areas measured are not within a single asperity peak.

The initial results presented show that there is a near linear relationship between the area of contact measured and the contact force.

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