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ULTRASOUND AS AN EXPERIMENTAL TOOL FOR INVESTIGATING ENGINEERING CONTACTS

ABSTRACT

Within the science of Tribology, there are few tools which practically and effectively allow the measurement of conditions at an interface. This paper describes an ultrasonic technique for measuring interface parameters. Ultrasound is an ideal measurement medium, as it has good transmission through most solids, is unaffected by surface oxide layers, is non-destructive, safe and portable.

If an interface is modelled as a stiff spring, an equation can be derived which predicts the frequency profile of the reflected ultrasound. By performing a Fourier transform upon the ultrasonic echo from the interface, the stiffness of that interface can be calculated. The stiffness can be used to infer the behaviour of asperity contacts within the interface.

In this work the stiffness of a metal interface over 10 loading cycles was measured, showing the effects of plasticity and adhesion. Results are also presented showing how first plastic loading cycles exhibit asperity creep and how over a number of cycles shakedown is achieved. Finally, a Hertzian ball-on-flat contact was scanned and the ultrasonic reflection profile obtained.

INTRODUCTION

Ultrasound is sound with a frequency above the range of human hearing (>20kHz). The use of ultrasound is well established as a NDT tool. for detecting cracks, voids, porosity and other defects within a material.

This technique uses ultrasound to measure tribological parameters at the interface between two surfaces. The method is unique in that it can non-destructively measure contact parameters inside a real assembled component. These measurements can be made through many millimetres of solid, in a variety of materials; as ultrasonic propagation is independent of electrical, magnetic or optical properties.

When any two real surfaces are loaded together, they will contact at a few asperities. The real area of contact is consequently small, and the real pressure at the contacting asperities is high. The nominal contact area is therefore composed mainly of air gaps. As an ultrasonic wave has negligible transmission from solid into air it is almost 100% reflected by the air gaps.

At the contacting asperities the ultrasound passes through with almost no reflection. As the load on the interface is increased, the real area of contact increases, and the proportion of air gap decreases. Therefore an increase in pressure at the interface causes less ultrasound to be reflected.

As load is applied to the interface, the surfaces approach, and the interface has a given deflection for an applied pressure, i.e. the interface has a quantifiable stiffness. (See Fig.1) Therefore the interface can be modelled as a very stiff spring. Furthermore, ultrasound is a mechanical vibration wave within the material, which means that an interface subject to ultrasonic investigation behaves like a spring under forced vibration, and is governed by similar laws. This 'spring-model' implies that different frequency ultrasound is reflected from the interface by differing amounts, and the magnitude of the reflected wave is frequency dependent. By using a broadband ultrasonic transducer this frequency dependence can be measured, and used to calculate the interfacial stiffness.

Tattersall [1] derived an equation relating ultrasonic reflection, frequency and stiffness, from an equation of forced oscillation. From this equation, Drinkwater et al [2] derived the following equation which is used throughout this work to convert measured reflection coefficients into interfacial stiffness values:

$$K = zf\pi\sqrt{\frac{1}{R^2} - 1} \qquad (1)$$

Where f= frequency, z= acoustic impedance and R= ultrasonic reflection. (acoustic impedance is the product of the wave speed and the density).

The stiffness K of an interface is defined as the change in nominal contact pressure, P_{nom} required to cause a unit approach, u of the mean lines of the rough surface, (see Figure 1.)

$$K = -\frac{\mathrm{d}p_{nom}}{\mathrm{d}u} \qquad (2)$$

The stiffness of an interface increases as the surface roughness becomes more conformal. The stiffness will vary from zero to infinity as the real area of contact varies from 0% to 100%. However, the relationship between stiffness and real area of contact is not simple, and depends upon the number, size and distribution of the contacting asperities[3].

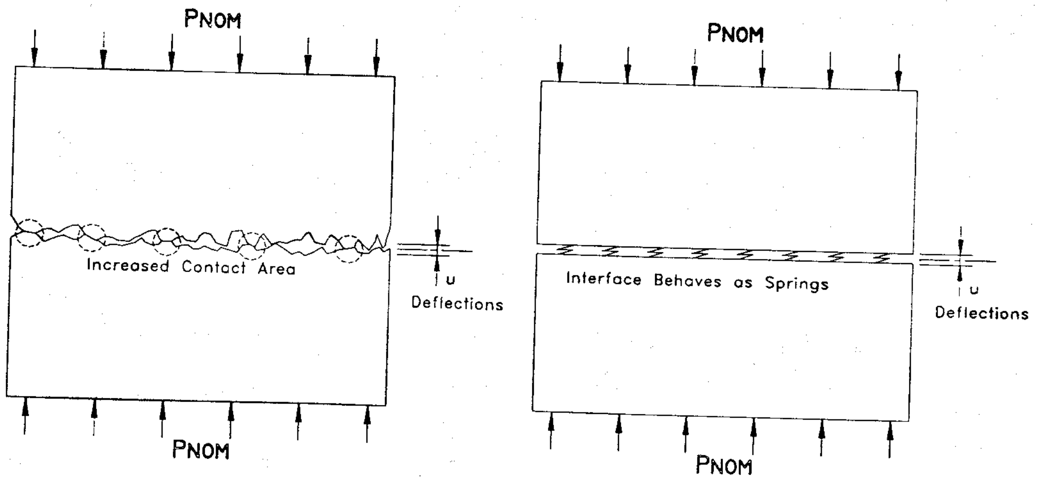

Figure 1. Asperity contact at a loaded interface, shown as a schematic, and using the spring analogy.

DATA CAPTURE & PROCESSING

Conventional ultrasonic techniques measure only the amplitude of the reflected signal, and commercially available systems, exist to make rapid analysis of amplitude-based data. Amplitude based data is suitable for flaw detection, but lacks the necessary detailed information for calculating contact parameters. In order to use frequency dependence to calculate interfacial stiffness, data must be readily available in the frequency domain. To obtain a full frequency spectrum of the interface echo, digital data capture and processing methods have to be employed.

An ultrasonic pulser-receiver (UPR) sends a voltage pulse to a focussed ultrasonic transducer, causing it to generate ultrasound in the frequency range of approximately 2 to 15MHz. A water bath is used to couple the transducer to the test specimen, as ultrasound has almost zero transmittance in air. The ultrasonic wave then propagates through the test specimen to the interface, where it is partially reflected back to the transducer. The same transducer converts the sound energy back into an electrical signal, which is amplified by the pulser-receiver.

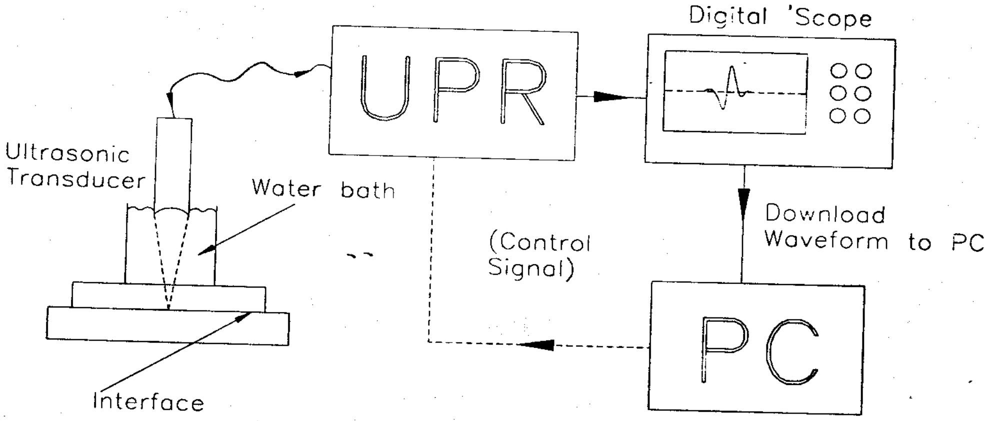

Figure 2. A schematic showing the hardware used to generate, receive and capture the ultrasonic echo from an interface.

A digital oscilloscope captures the signal from the UPR, and isolates the required interface echo from other echoes and signals. This is then transferred to a PC where the signal is converted to the frequency domain, the reflection coefficient is calculated by dividing by a zero-load reference trace, and finally the spring model stiffness equation is applied. The frequency profile of the interface echo is then stored for later analysis. This data capture and analysis has been custom written using 'Labview' software, this incorporates a graphical user interface displaying the waveform in both time and frequency domain, reflection coefficient, and interfacial stiffness (see figure 3.)

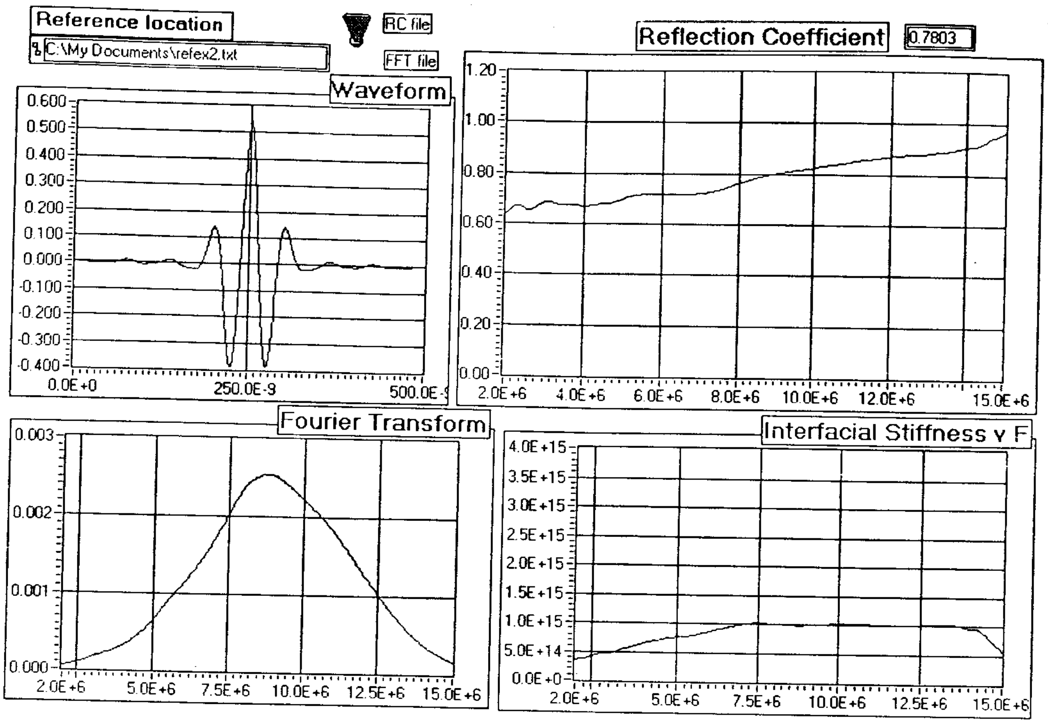

Figure 3. A screen print, showing a typical signal, and its subsequent processing, as displayed in the graphical user interface.

EXPERIMENTS TO MEASURE THE STIFFNESS OF AN ALUMINIUM – ALUMINIUM INTERFACE

This section details the results of an experiment, during which the interface between two aluminium specimens was subject to a series of loading cycles. Both upper and lower specimens were highly polished, providing a very flat and therefore very stiff interface. A 10MHz broadband focussed transducer was used, and positioned so that it focussed exactly on the interface. The ultrasonic echo from this interface was processed to provide a measured stiffness value for the interface.

The load across the interface was cycled 10 times, between 2MPa and 17MPa. The residual 2MPa pressure was to ensure that the surfaces could not separate, allowing new asperities to come into contact. Ultrasonic readings were taken at regular intervals throughout.

As shown in Figure 4, the first cycle loading line lies well below all subsequent lines. During the first load cycle the asperities are deforming plastically. As the load is removed the elastic deformation recovers. However, since the surfaces are left in a more conformal state, the contact stiffness has increased.

Subsequent loading cycles show increasingly smaller levels of plasticity, and from around the 5th cycle , it is difficult to identify the individual loading cycles. The end point of each loading cycle also progressively increases, showing stiffening of the interface as shakedown occurs. Even after many cycles, load and unload lines for the same cycle do not become convergent, (i.e. the dotted unload line falls above the solid load line.) This indicates that even when a steady state is achieved, the process does not become fully elastic. This residual hysteresis is thought to be caused by plastic adhesion at the interface. During the loading some local bonding at the asperity contacts may occur. When the same contact is unloaded these bonds act to attract the surfaces. The contact area, and thus stiffness, is greater, at a given pressure, during the unloading part of a cycle.

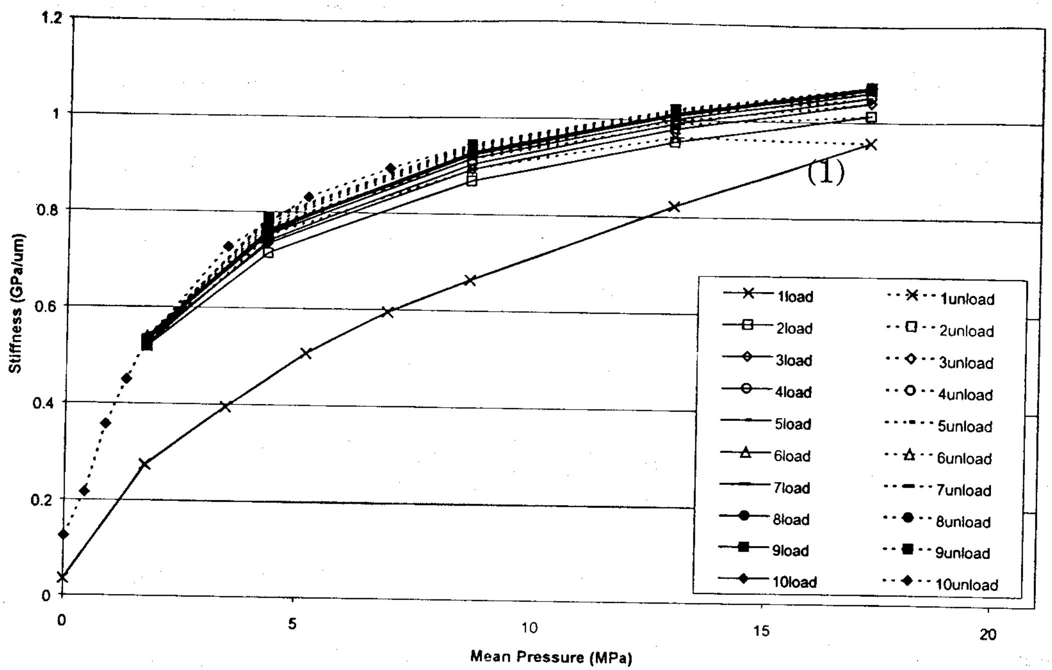

Figure 4. Stiffness plotted against mean pressure for 10 load – unload cycles.

RATE DEPENDENT EFFECTS IN METAL-METAL CONTACT LOADING

Plastic contacts in metals are known to exhibit rate dependent effects[4]. A hardness indentation will relax with time of application of the loading. An experiment was performed to investigate whether this effect would also occur in a rough surface contact.

Five identical aluminium specimens were produced with shot blasted contact surfaces, and loaded against a ground hard steel disc. Each specimen was rapidly loaded from zero and held at a given load of 2, 4, 6, 10 or 14kN. A series of measurements were taken during this constant load period. The specimens were then loaded to 16kN, then partially unloaded and held again at the given load. A further series of results were taken, before unloading the specimen to zero.

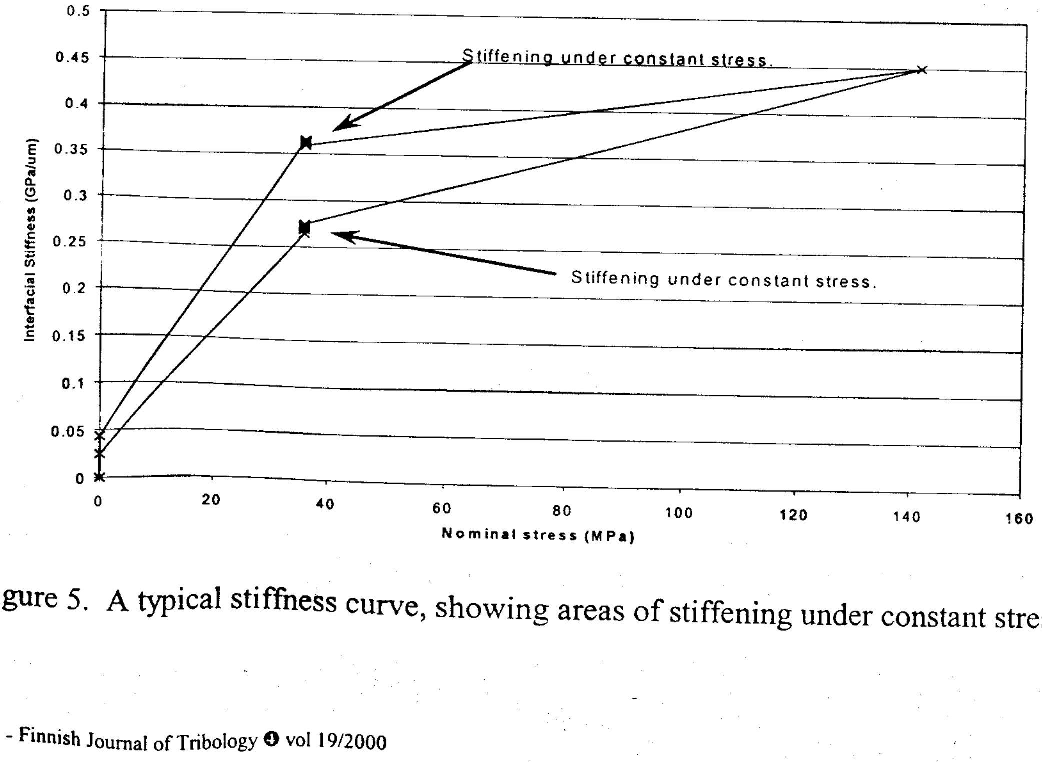

Figure 5. A typical stiffness curve, showing areas of stiffening under constant stress.

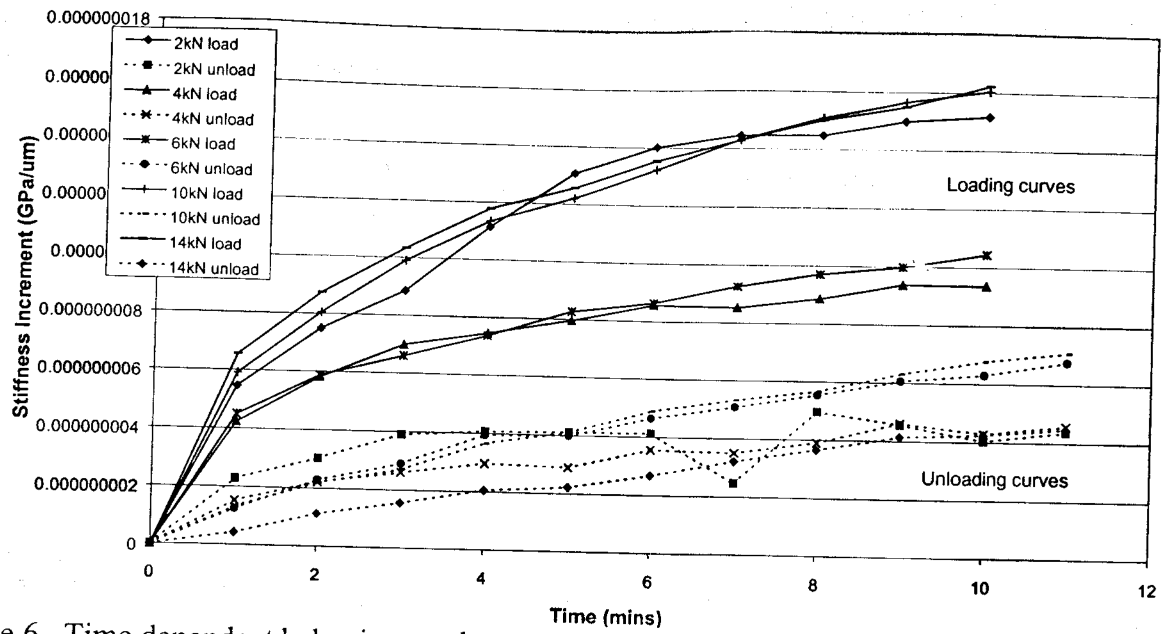

Figure 6. Time dependent behaviour under constant load, or 'asperity creep'. Each curve shows the stiffening of the interface with time, under a given constant load.

The data taken from the experiments is initially plotted as five separate stiffness loading curves (a typical curve is shown in figure 5), these are then combined and replotted to show how the stiffness of the interface held under a particular load varies with time (figure 6.) It would not be expected to see bulk creep occurring in aluminium at this pressure and room temperature. However, as the real area of contact is much lower than the nominal area of contact, the real contact pressure will be proportionally higher than the nominal pressure. This pressure is sufficient to allow time dependent stiffening of the interface to be observed.

When maintaining constant stress during the loading cycle, the measured interface stiffness increases significantly with time (the five solid lines). It is interesting to note that the nominal stress level (applied load) at which the contact was held has little effect on the rate of increase of stiffness.

Rate dependence in metal is usually expressed in a relationship of the form $\dot{\varepsilon} = C\sigma^n$. The strain rate is proportional to the applied stress raised to some power n. The included data shows that the strain rate is relatively insensitive to the nominal contact stress. From this we can infer that whilst the nominal stress has been changed significantly within these experiments the real stress at the asperities has not varied by a large amount. The increased load has been supported, not by an increase in real contact pressure, but by an increase in the number of asperities coming into contact and the size of individual contact regions.

The data in figure 6 also shows the same experiment, this time carried out during the unloading phase of the load cycle (the five dashed lines). Here the stiffening effect over time is lower, due to the previous plastic deformation which has occurred during the loading part of the cycle.

ULTRASONIC PROFILES OF HERTZIAN CONTACTS

A logical extension of taking measurements with a fixed transducer position, is to move the transducer across the contact area, with the ultimate aim of determining the area and magnitude of the contact stresses. Commercial ultrasonic scanning tanks are commonly used to obtain 2-dimensional scans of components, however the software that drives scanning equipment is restricted in that it usually records the amplitude of the returned signal, and not the entire waveform. Without the complete waveform data, the signal cannot be transformed into discrete frequencies for stiffness calculation.

The major difficulty with the scanning technique is the finite focal diameter of the transducer. In previous experiments the entire focal area was subject to a virtually uniform pressure field. However, in the general case the focal area will often be located within non-uniform pressure fields, such as that at the edge of a contact. This means that the transducer will tend to 'blur' step changes in stiffness, as it records a mean stiffness over the entire focal spot.

The focal diameter of a focussed ultrasonic probe decreases with increasing frequency. The *nominal* focal diameter of the 25MHz probe used was 0.52mm at 25MHz. However, as the broadband transducer emits useful energy between 5 and 35MHz, the focal diameter will vary; from 2.6mm (at 5MHz), to 0.37mm (at 35MHz). Therefore the higher frequencies, with small focal diameters, will provide higher resolution than the lower frequencies with large focal diameters. Higher frequencies will record lower minimum reflection coefficients and narrower contact patches than the lower frequencies, which will average or 'blur' the measured reflection coefficient over a larger focal diameter. This emphasises the importance of analysing the frequency spectrum, and not just the echo amplitude.

In the following experiment a 25mm diameter ball bearing was pressed against a hard steel flat using a hydraulic cylinder. The applied load was 2000N, which according to Hertzian theory should produce a 0.55mm radius contact patch, with a maximum pressure of 3.3GPa. It was not intended to yield either specimen, and no plastic deformation was observed after the experiment. A 25MHz focussed transducer was positioned above the upper specimen, in a water bath. Micrometer screws were used to scan the transducer across the contact area.

Figure 7 shows the recorded reflection from the ball loaded on the flat plate. The indicated diameter of the contact is greater than that predicted by Hertz, due to the 'blurring' of the finite focal area. The results are very clear, especially considering that the nominal focal diameter of the probe is only half that of the contact diameter. By considering the individual frequency lines, it is seen that the lower frequencies record higher reflection coefficients and a wider contact area, as predicted at the start of the chapter.

It is no longer possible at this stage to use the spring model (equation 1) to determine the stiffness of this interface. Each frequency of wave is reflected back from a different size region, over which the pressure is non-uniform. Work is currently underway to develop a model to discretise the spring model across any given interface with non-uniform pressure variation.

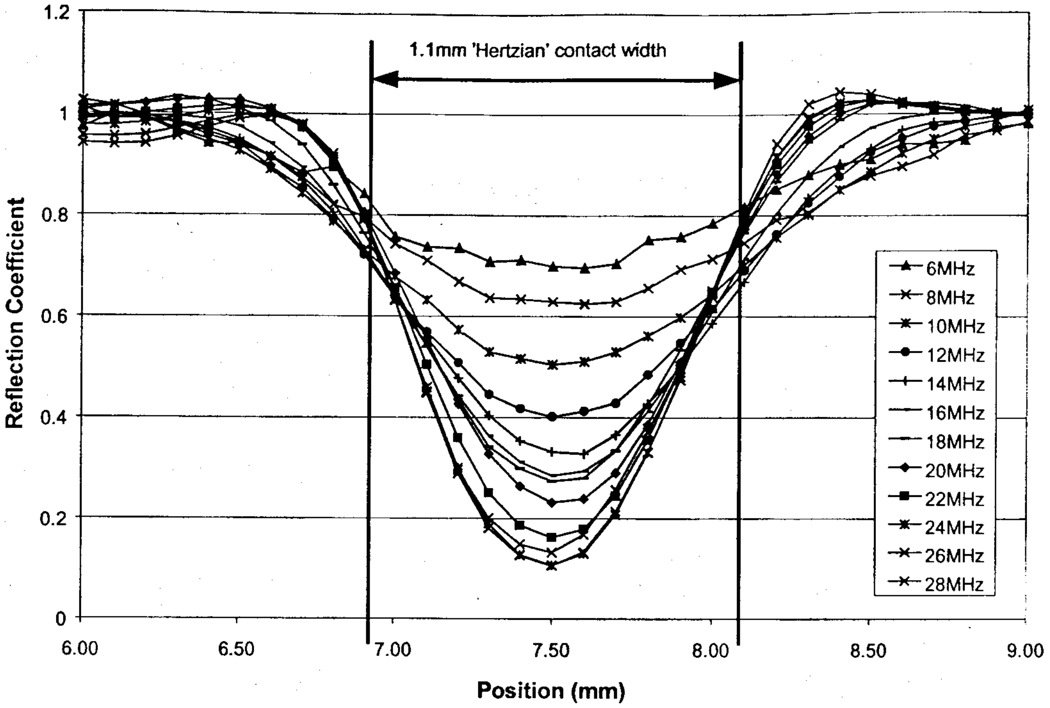

Figure 7. The variation of ultrasonic reflection across a ball-on-flat contact patch.

DISCUSSION

During ultrasonic measurement of contact stiffness, the first loading cycle indicates predominantly plastic behaviour, despite the nominal stress being well below the bulk plastic limit. If the asperity contact of two rough surfaces is considered, then it can be expected that asperity tip pressures will lie well within the plastic regime for the material. If this is taken one step further, and the asperity contact considered to be fully plastic, then the real contact pressure will be equal to the hardness of the material.

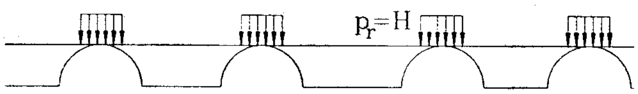

Figure 8. Schematic of fully plastic asperity tips. p_r=real pressure, H=Hardness.

p_{nom} is defined as the nominal contact pressure, and A_{nom}, A_r and A as the nominal, real and proportion of real (A_r / A_{nom}) contact respectively.

Therefore the real area of contact can be estimated by assuming full plasticity:

$$A_r = \frac{Load}{Hardness} = \frac{p_{nom}\cdot A_{nom}}{H} \qquad (3)$$

$$\text{or}\quad A = \frac{p_{nom}}{H} \qquad (4)$$

If this real area of contact is considered to be composed of n regions of radius a then:

$$A_r = n\cdot\pi a^2 \quad \text{or} \quad A = \eta\cdot\pi a^2 \qquad (5)$$

(where η equals the contact density per square metre.)

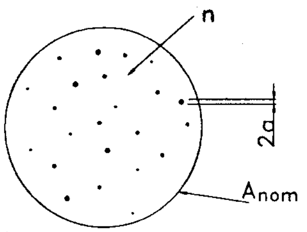

Figure 9. Schematic of n contact points with mean radius a, within the nominal contact area A_{nom}.

The stiffness of a single asperity contact can be deduced by assuming a shape (spherical, flat punch) and using elastic* solutions for the load displacement relationship. Kendall & Tabor [3] propose that the stiffness of a single asperity contact is given by

$$\frac{\pi}{2(1-\nu^2)} Ea < S < \frac{2}{1-\upsilon^2} Ea \qquad (6)$$

The lower bound corresponds to a spherical capped asperity, the upper to a punch type asperity. Since in the present work considerable plastic flattening has occurred, the punch shape is considered more appropriate.

When the individual contacts are widely spaced, so as not to interfere with one another, the total stiffness per unit area of the interface is given by:

$$K = \frac{n \cdot S}{A_{nom}} \quad \text{or} \quad K = \eta \cdot S \qquad (7)$$

which is the parameter measured by the ultrasonic technique. By combining equations 6 and 7 we get:

$$K = \eta \frac{\pi}{2(1-\nu^2)} Ea \qquad (8)$$

Equations 8 and 5 are solved simultaneously to give solutions for the dimension, a and the density, η of the contact regions. We find for p_{nom} and K taken at the end of the load cycle (point 1, figure 4), A=1.5%, a=0.7μm and η=9800mm^{-2}.

*(note) Here we consider the elastic stiffness of the asperity contact. Although the bulk loading is plastic, the passage of the ultrasonic wave is elastic, and thus the reflection is controlled by elastic stiffness.

CONCLUSIONS

A technique has been developed which allows the stiffness of an interface to be measured using ultrasonic reflection. The technique has been applied in two different modes. In the first technique, the ultrasonic transducer is fixed at a single point on the interface, and the load applied across the interface is varied. This allows surface plasticity effects such as asperity creep, adhesion and shakedown to be investigated.

The second type of experiment involves moving the transducer relative to the contact area, while keeping the load constant. This allows the contact pressure profile to be investigated. With further mathematical analysis it should be possible to determine the actual contact area and pressure within various contact geometries.

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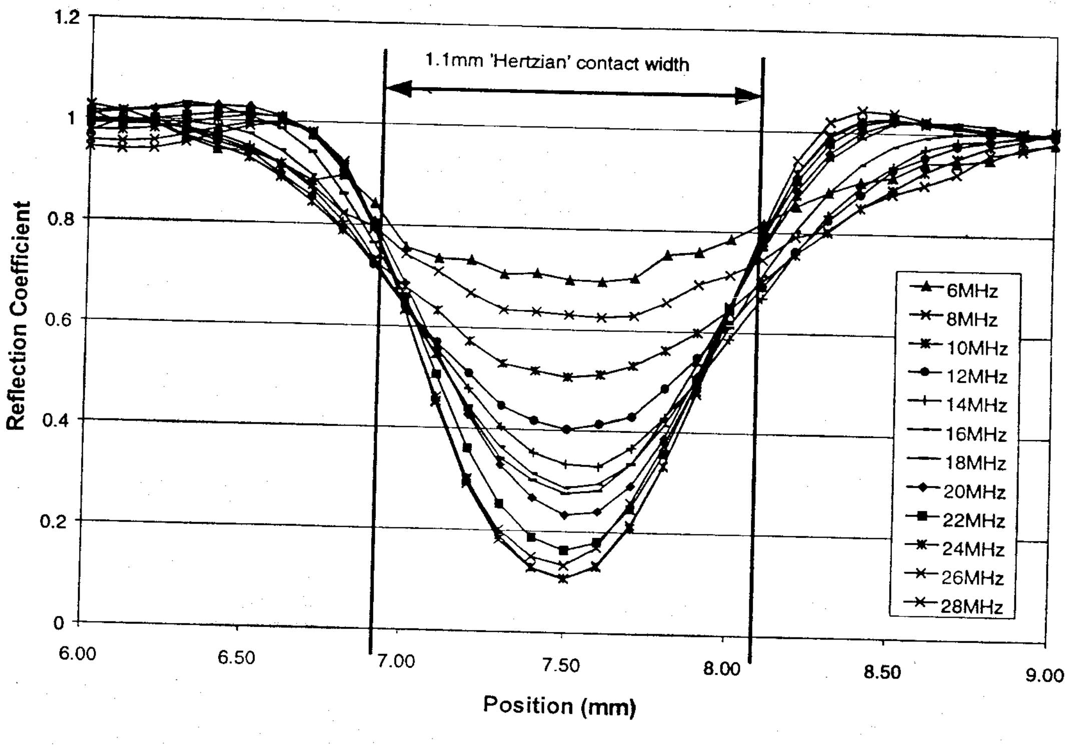

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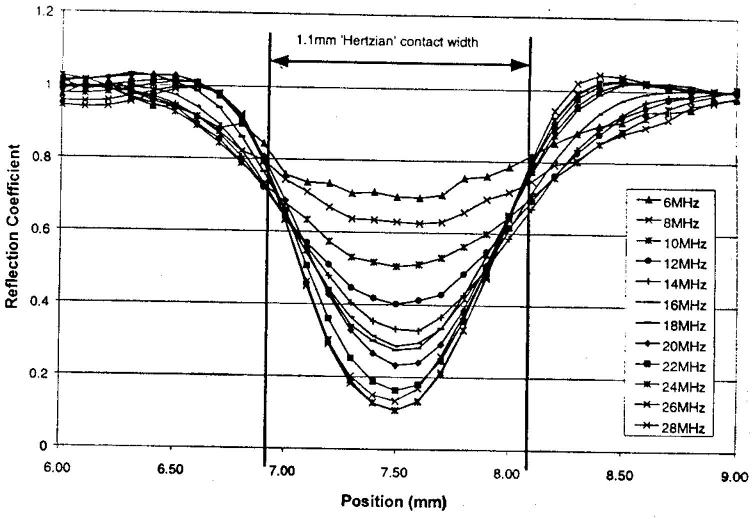

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