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# THE INTERACTION OF ULTRASOUND WITH A PARTIALLY CONTACTING SOLID-SOLID INTERFACE IN THE LOW FREQUENCY REGIME

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## INTRODUCTION

When real engineering surfaces touch, contact occurs between the asperities of the surface roughness. For this reason the true area of contact between components can be significantly less than the apparent contact area and the stresses at the asperities are considerably higher than the average (nominal) contact pressure. Measurement of the degree of contact between solids is important in a number of applications such as the design of contacting elements (e.g. gears and bearings) [1] and the detection of 'kissing' bonds [2].

The proportion of the amplitude of the incident ultrasonic wave reflected at a solid-solid interface is dependent on, amongst other things, the degree of contact between the two surfaces. This is because where asperity contact occurs the ultrasonic wave is transmitted across the interface and where the asperities are not in contact (i.e. an air gap exists) negligible energy is transmitted. When no load is applied across the interface the percentage contact will be low and so the energy transmitted across the interface will be low. As the applied load is increased, the transmission of ultrasound across the interface will increase as the percentage contact increases. The proportion of the amplitude of the ultrasonic wave which is reflected, termed the reflection coefficient, can therefore be used to interrogate a partially contacting interface and to extract some information about the degree of contact.

This paper describes the use of low frequency longitudinal ultrasonic waves to interrogate the partially contacting interface between two rough aluminium specimens. Firstly, experiments will be described which were performed to validate the use of spring models to describe the interaction of ultrasound with partially contacting solid-solid interfaces. Secondly, contact models will be described which allow the interfaceial stiffness of a solid-solid interface to be predicted. The predictions obtained using this model are then compared to experiment.

Apparatus

Figure 1 shows the experimental set-up used to measure the reflection coefficient from an aluminium-aluminium interface under pressure. The contact specimens consisted of a 12.5mm diameter aluminium cylinder of length 20mm and a flat aluminium plate of thickness 15mm. Both contact surfaces were machined flat and surface treated by grit blasting. In this way a rough surface was created whose profile had no form error (waviness). The surface finish was measured using a stylus profilometer, and specimens with excessive waviness were re-machined. A 10MHz centre frequency, broadband, focused, longitudinal wave ultrasonic transducer was mounted below the specimens in a bath of water which enabled good coupling to be achieved between the transducer and the underside of the aluminium test plate. The ultrasonic transducer was used as both the transmitter and the receiver (pulse-echo mode) and was focused on the interface between the two aluminium specimens. The transducer had a diameter of 10mm and was weakly focused having a focal length of 76.2mm in water. The signal reflected from the partially contacting interface was received back at the transducer, amplified, captured by a digital oscilloscope and passed to a computer for processing. An FFT was performed on each captured waveform to obtain its frequency spectrum. When the specimens were out of contact, virtually all the incident wave was reflected back to the transducer, and the reflection coefficient of this interface was therefore unity. The reflection coefficient for contacts under pressure was determined by dividing the measured wave amplitude by that obtained when the specimens were out of contact. This calculation was performed in the frequency domain by dividing the spectrum of the reflections from the partially contacting interface by a spectrum received from the interface when the top aluminium specimen was removed. Hence the reflection coefficient was measured over the usable bandwidth of the transducer which was 4-17MHz.

Load was applied across the aluminium-aluminium interface as shown in Figure 1 via a standard hydraulic materials testing machine. After a series of tests the results were analysed for drift of the signal by repeating the aluminium-air measurement and comparing this to the previously recorded aluminium-air measurement. The signal change was found to be always below 3% across the whole measurement frequency range

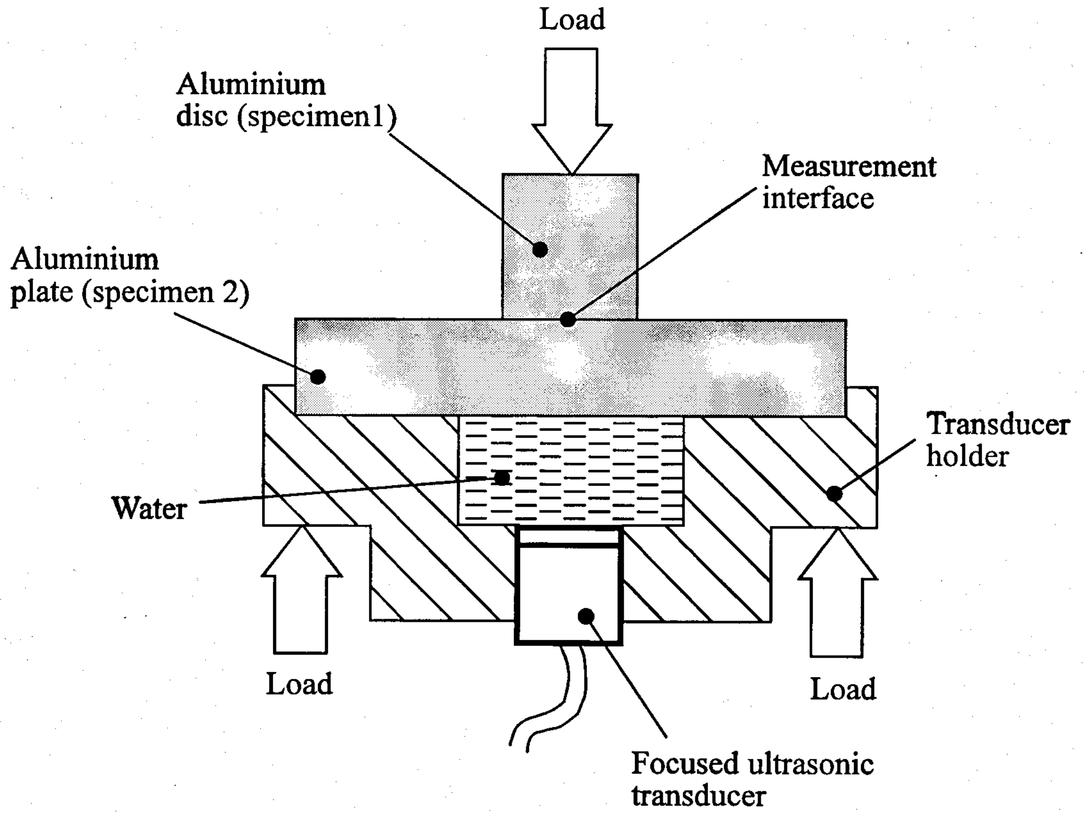


Figure 1 Schematic diagram of apparatus used to measure the reflection coefficient from an aluminium-aluminium interface.

Results

Figure 2 shows the measured variation of aluminium-aluminium reflection coefficient with frequency for a range of nominal pressures. The frequency dependence can be seen clearly, particularly in the pressure range 40-600MPa, where the reflection coefficient increases with frequency. At low loads and therefore low percentage contacts, the reflection coefficient is close to unity and almost frequency independent. As the load increases the reflection coefficient reduces until it reaches a minimum which is again almost frequency independent. It appears that the reflection coefficient is tending towards a small but finite value (approximately 0.02) rather than zero which would be expected if the aluminium specimens had identical acoustic impedances. This is probably due to variation in the material properties of the aluminium used for the two specimens which were taken from different stocks.

The measured frequency dependence can now be compared with that predicted by the spring model. Equation (1) can be rearranged to solve for stiffness and so a stiffness corresponding to each measured point on Figure 2 can be calculated from the acoustic impedance of aluminium, the measured reflection coefficient and the frequency. Figure 3 shows the data of Figure 2 replotted as the variation of stiffness with frequency from which it can be seen that the curve for each load on Figure 2 maps onto a stiffness which is almost constant with frequency. This measurement is, therefore, in good agreement with the simple spring model of the interface hence validating of the use of the simple spring model for this prediction in the 'low frequency' region. At higher average pressures the calculation of stiffness becomes unstable because, as the reflection coefficient approaches zero, (as in the two highest pressure cases shown), the stiffness tends to infinity. In this situation small errors in reflection coefficient lead to large errors in calculated stiffness as the gradient of the curve of stiffness versus reflection coefficient tends to infinity as the reflection coefficient tends to zero.

In a further test the specimens were successively loaded and unloaded, with reflection coefficient measurements being made at convenient load steps. Figure 4 shows the measured variation of the reflection coefficient at a frequency of 10MHz with nominal pressure for three loading cycles. Figure 5 shows the first cycle of this data replotted as interfacial stiffness variation with pressure. From Figure 5 the stiffness can be seen to jump at the first load increment. This is probably due to a 'bedding down' process where some load is required to align the surfaces.

In both Figures 4 and 5 it can be seen that the first loading cycle follows a very different path to that of the later cycles indicating that most of the plastic deformation of the asperities occurs in the first loading cycle. Note that the bulk stress (equivalent to nominal pressure) is always below the yield value for aluminium of 400MPa. On unloading, the asperities are already flattened to a shape conformal with the opposing surface and so a greater real area of contact, and therefore greater interfacial stiffness, occurs at a given load. At the start of the second and third cycles the load was not entirely removed from the system so that the relative position of each specimen was kept constant. In this way the same points on each surface made contact in each loading cycle. The unloading lines follow similar paths, as do the second and third loading lines although a small amount of plastic deformation is evident from the hysterisis exhibited by the cycles. The bulk of the plastic flow occurs during the first cycle, although full asperity shakedown does not appear to have been achieved even in the third cycle.

PREDICTION OF INTERFACIAL STIFFNESS

One of the earliest contact models was presented by Greenwood and Williamson [12]. They considered the rough surface as a Gaussian distribution of hemispherically capped asperities. The deformation of each asperity as it comes into contact with an opposing smooth surface is given by the Hertzian equations of elastic contact [13]. The input to the model is the 'composite' profile which is the sum of the two original surfaces. A Gaussian distribution funcion is then fitted to the roughness height distribution function of the composite profile. The analysis yields a relationship between the nominal pressure and the dispacement of the mean line of the rough surface to the smooth surface. The stiffness of

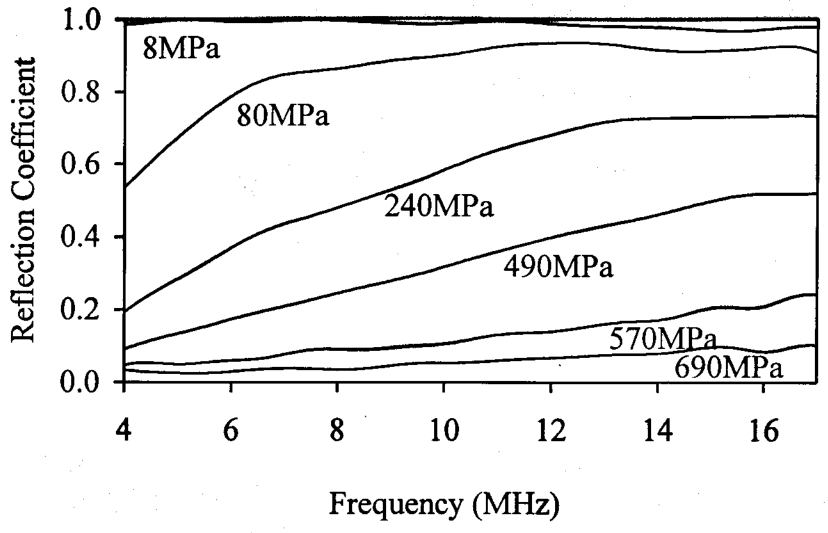


Figure 2 Measured aluminium-aluminium reflection coefficient variation with frequency for different interfacial pressures.

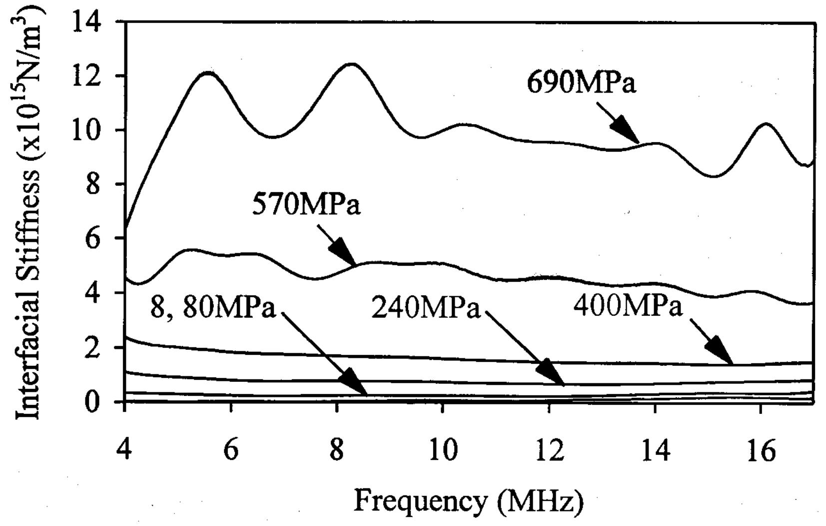


Figure 3 Variation of interfacial stiffness (calculated from experiment) with frequency for different interfacial pressures.

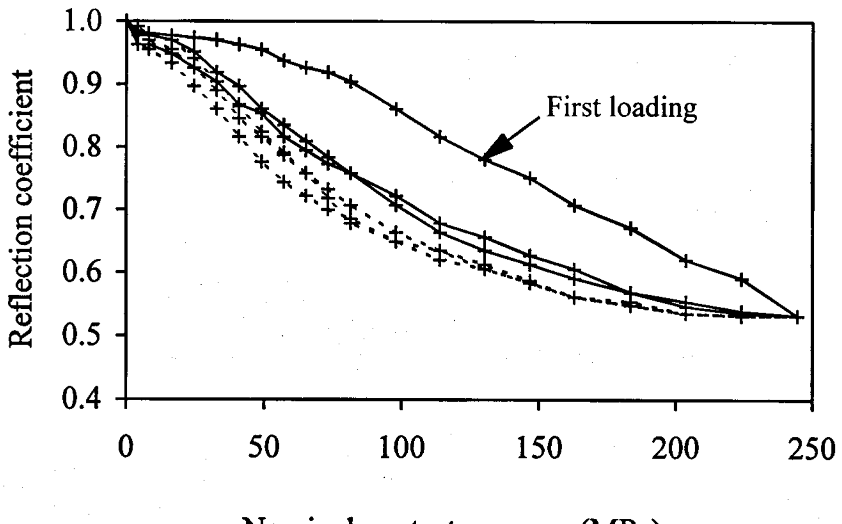


Figure 4 Measured aluminium-aluminium reflection coefficient variation with pressure for three loading cycles. Solid lines are loading and dashed lines are unloading.

the interface can then be obtained from the differential of nominal pressure with respect to the displacement of the meanline.

Nayak [14] developed a model of the plastic contact of a rough surface and a smooth, flat surface, treating the roughness as a Gaussian array of surface heights. In this model the material flows plastically when the rough surface touches the flat. This material is then redistributed evenly across the parts of the surface which are out of contact. As in the Greenwood and Williamson model a relationship between the nominal pressure and the displacement of the meanline of the sruface is obtained. This relationship is then differentiated with respect to the displacement of the meanline to give stiffness.

Numerical contact models

A more recent approach by Webster and Sayles [15] uses digitised roughness data from a surface profilometer. Two dimensional, elastic contact is then modelled between this surface and a smooth surface. The displacements at general nodal points, $u_i$ are expressed in terms of unknown point loads, $P_j$,

$$u_i = \sum C_{ij} P_j \qquad (2)$$

where $C_{ij}$ are known as influence coefficients which are determined from relations for the line loading of an elastic half space [13]. The matrix is inverted to deduce the loads and iteration is performed until the individual point loads sum to the applied load. Using this method the applied load can be related to the approach of the surface mean lines and the real area of contact. The stiffness is then determined from the rate of change of nominal pressure with the mean line approach. The model is elastic but since it does not treat the asperities as independently acting, it can be used over a wide range of contact loads.

Analysis of results

The surface profiles of the aluminium cylinder and plate used in the experiment whose results are shown in Figures 4 and 5 were measured using a conventional stylus profilometer. The stylus radius was 0.2μm, the sampling interval was 5μm and the sample length was 5000μm. For the elastic contact models the surface profile after the specimens were loaded to 250MPa was recorded. A summary of this data is shown in Table 1. Note that the final measured surface roughness was lower than that measured before the test, indicating plastic deformation of the asperities. For the plastic model the initial grit blasted surface profile was used. These surfaces were then summed to give a single surface of 'composite' roughness for input into the three contact models.

Figure 5 also shows the interfacial stiffness variation with pressure as predicted by the three contact models plotted on the same graph as that calculated from the experiments. The plastic prediction was made using roughness profiles taken before contact and should

| Description of surface | RMS roughness $\sigma$ (μm) | Average wavelength, $\lambda_{ave}$ (μm) | $\sigma/\lambda_{ave}$ |
|---|---|---|---|
| Cylinder - before loading | 1.41 | 18.2 | 0.078 |
| Cylinder - after loading | 1.08 | 17.3 | 0.063 |
| Plate - before loading | 1.23 | 16.6 | 0.074 |
| Plate - after loading | 1.11 | 16.5 | 0.067 |

Table 1 Roughness parameters of the two aluminium specimens used in the experiment of Figures 4 and 5 before loading and after loading to 250mpa.

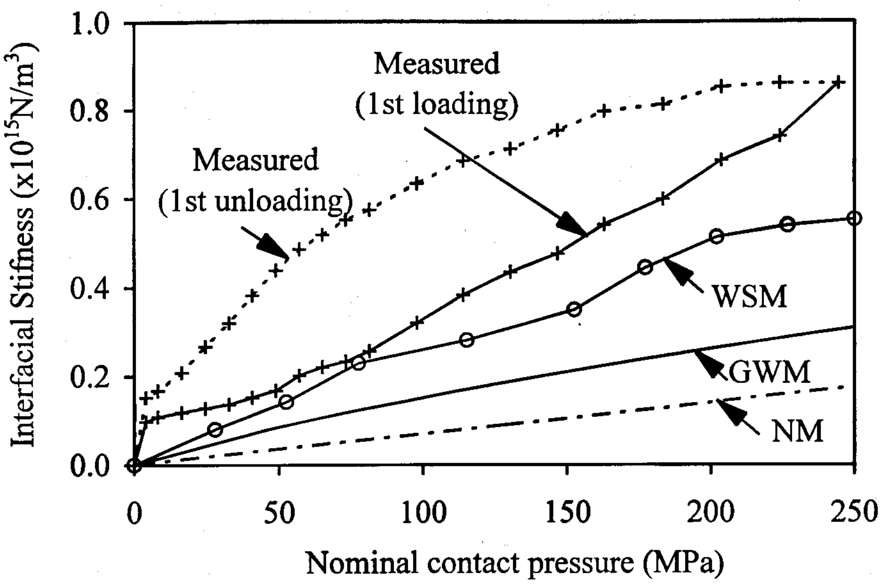


Figure 5 Comparison between interfacial stiffness predictions and that calculated from experiment. WSM is the Webster and Sayles model prediction, GWM is the Greenwood and Williamson model prediction and NM is the Nayak model prediction.

be compared with the loading line where most of the plastic contact occurs. The elastic statistical model and the numerical contact model (which is also elastic) predictions were made using roughness profiles taken after the unloading cycle had been completed and these predictions should be compared with the unloading line which is mostly elastic.

From Figure 5 it can be seen that the agreement between the predictions and the experiments is generally within an order of magnitude, the numerical contact model providing the closest agreement with experiment. Note that the points given by the numerical contact model do not fall on a smooth curve because of the uneven distribution of asperity sizes in the real profile, whereas the statistical models give smooth curves as they assume smooth asperity size distribution patterns. One source of error in the numerical contact model prediction is that the grit blasted surface has a three dimensional topography whereas the numerical contact model used assumes a two dimensional contact. The size and direction of this error is not known. Of the two statistical models the plastic model gives the higher reflection coefficient and hence lower stiffness, at a given pressure. It can be seen that the contact models always predict lower stiffnesses (corresponding to a higher reflection coefficient) than were measured experimentally at the same nominal pressure. For the case of elastic unloading this difference could be because the models do not take into account the fact that the surfaces have previously been plastically deformed against one another and so the profiles now 'fit' together. This fitting together will tend to increase the stiffness of the interface above that predicted by considering the contact between two arbitrarily positioned surfaces which would therefore tend to improve the agreement between experiment and theory. The reason for the poor prediction by the plastic model is not fully understood but could be due to the way in which the plasticity was modelled. The model of Nayak [14] assumes completely plastic behaviour whereas in reality materials will exhibit a combination of both elastic and plastic behaviour, dependent on the local stress conditions.

## CONCLUSIONS

The relationship between ultrasonic reflection from the interface between two aluminium specimens and the nature of the surface contact has been studied. Reflection coefficients from aluminium-aluminium interfaces under pressure have been measured as a function of frequency and loading conditions, clear frequency dependence of reflection coefficient being measured. This frequency dependence of reflection coefficient was found to be in good agreement with that predicted by a simple spring model of the interface.

The reflection coefficient was also measured from the aluminium-aluminium contact over a number of loading and unloading cycles. There was clear evidence of plastic deformation during the first loading of the contact even at nominal pressures as low as 10% of the yield stress. Subsequent cycles still showed some evidence of plasticity and further work to investigate this 'shakedown' process is planned.

Both elastic and plastic statistical contact models as well as a numerical contact model were used to predict the variation of interfacial stiffness with pressure. These models agreed qualitatively with the experimentally determined stiffness variations and the magnitude of the predicted stiffness was within an order of magnitude in all cases. The numerical contact model gave the closest prediction to the experimental values. The elastic contact predictions could be improved if they could take into account the fact that the two surfaces had previously plastically deformed around one another and so the surfaces 'fitted' together. The errors in the plastic model could be explained to some extent by the simplifying assumptions made in the modelling of plasticity in the asperities.

## REFERENCES


1. K.L. Woo and T.R. Thomas, Wear, Vol. 58, p. 331 (1980).
2. P.B. Nagy, J. NDE, Vol. 11, p. 127 (1992).
3. J.H. Rose, in *Review of Progress in QNDE*, Vol. 8B, eds. D.O. Thompson and D.E. Chimenti (Plenum, New York, 1989), p. 1925.
4. J-M. Baik and R.B. Thompson, J. NDE, Vol. 4, p. 177 (1984).
5. T.P. Pialucha, "The reflection coefficient from interface layers in NDT of adhesive joints", Ph.D. Thesis, University of London, 1992.
6. H.G. Tattersall, J. Applied Physics D, Vol. 6, p. 819 (1973).
7. A.B. Wooldridge, "The effects of compressive stress on the ultrasonic response of steel-steel interfaces and of fatigue cracks", CEGB North Western Region, Report No. NW/SSD/RR/42/79, 1979.
8. J. Krolikowski and J. Szczepek, Wear, Vol. 148, p. 181 (1991).
9. T. Arakawa, Materials Evaluation, Vol. 41, p. 714 (1983).
10. K. Kendall and D. Tabor, Proc. of the Royal Society, Vol. 323A, p. 321 (1971).
11. B.W. Drinkwater, T.P. Pialucha and P. Cawley, in *Review of Progress in QNDE*, Vol. 13, *op. cit.* (1994) p. 1399.
12. J.A. Greenwood and J.B.P. Williamson, Proceedings of the Royal Society of London, Vol. 295 part A, p. 300 (1966).
13. K.L. Johnson, *Contact Mechanics* (Cambridge University Press, Cambridge, 1985).
14. P.R. Nayak, Wear, Vol. 26, pp. 305 (1973).
15. M.N. Webster and R.S. Sayles, Transactions of the ASME, Journal of Tribology, Vol. 108, No.3, p. 314 (1986).

MODELLING THE REFLECTION OF ULTRASOUND FROM SOLID-SOLID INTERFACES USING SPRING MODELS

If the wavelength of the ultrasonic wave is comparable to the sizes of the air gaps in the plane of the interface then complex scattering phenomena occur [3] in which resonances are set up between neighbouring gaps. In this wavelength regime the precise shape of each air gap can significantly affect the scattered field and hence the proportions of energy reflected and transmitted. This is, therefore, not a useful regime in which to study the contact. If the wavelength is increased further until it is large compared to the sizes of the air gaps then the proportions of the ultrasonic wave transmitted and reflected are no longer dependent on the exact shape and size of each air gap but on the stiffness, and to a small extent on the effective mass and damping of the interface. If the sizes of the gaps are in the range 5-50μm then a wavelength of above 500μm is required to operate in this long wavelength region. This corresponds to a frequency of below 13MHz in aluminium. The effect of the mass term in a mass-spring model of a partially contacting interface was shown by Baik and Thompson [4] to be negligible and it is known that damping of an interface layer only weakly affects the reflection coefficient [5]. The mass and damping of the interface also become less significant as frequency is decreased and so in this low frequency region it is only the stiffness of the interface which governs the reflection coefficient.

The stiffness of the interface is not uniquely dependent on the real area of contact but on both the size and number of contacts. For example the same real area of contact can be obtained with many small contacts or a few large contacts but these interfacial geometries will have different stiffnesses. For this reason contact parameters other than the stiffness of the interface cannot be uniquely determined by measurement of the normal stiffness of the interface alone.

If the partially contacting interface is modelled as a spring then, following the analysis of Tattersall [6], it can be shown that if the two materials on either side of the interface have identical acoustics impedances, $z$, then the amplitude of the reflection coefficient, $R$, is given by,

$$|R_{12}| = \frac{1}{\sqrt{1+\left(\frac{2K}{\omega z}\right)^2}} \qquad (1)$$

Where, $K$, is the stiffness of the interface, $\omega$ is the angular frequency and subscripts 1 and 2 refer to the top and bottom media respectively. From equation (1) it can be seen that the reflection coefficient is frequency dependent. At zero frequency the reflection coefficient is equal to zero which corresponds to complete transmission of the wave across the interface. As the frequency of the wave increases (the ratio of gap size to wavelength becomes larger) the amount of scattering increases and so the reflection coefficient increases. The model becomes invalid when the wavelength is comparable to the gap size.

MEASUREMENT OF ALUMINIUM-ALUMINIUM REFLECTION COEFFICIENTS

Background

Measurement of the frequency dependence of the reflection coefficient from partially contacting interfaces has proved difficult in the past and studies have shown conflicting results [7]. Most have been performed with single frequency transducers [8-10] and so have few data points to analyse. An additional reason for these difficulties is probably a result of the difficulty of aligning the contacting surfaces correctly. Drinkwater and Cawley [11] showed that slight misalignments and/or specimen thickness variations can also greatly affect the measured frequency dependence. In this study wide band wide ultrasonic transducers have been used which allow a more thorough investigation of the frequency dependence of reflection.