Experimental Investigation of Thermal Contact Conductance: Variations of Surface Microhardness and Roughness[1]

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ABSTRACT

Surface roughness parameters were measured using nine different sampling intervals. The results showed that the roughness of profile were nearly a constant at all sampling intervals, slope, peak curvature and density of profile decreased with increasing sampling interval, the distribution of peak height was different from the profile height distribution and was not Gaussian. It was found that the surface microhardness value varied with the indentation size and the surface preparation procedure under small load. A model was developed which used a discretizing method to obtain the contact radius and area in each section of the surface summit height distribution curve. This model eliminated some assumptions made by previous models and can be used to predict the thermal contact conductance without assuming the deformation mode and surface summit height distribution. The predicted thermal contact conductance values were in good agreement with experimental results.

KEY WORDS: contact conductance; microhardness; sampling interval; surface roughness.

1. INTRODUCTION

When a heat flux passes through a joint, because of the imperfection of the surfaces, thermal contact resistance exists. The resistance is defined as the ratio of the temperature drop at the interface to the average heat flux across the interface. Thermal contact conductance is the reciprocal of the contact resistance. Heat transfer through contact joint occurs in three forms: conduction through contact spots, conduction through the gas filled voids and radiation between contact surfaces. This work is restricted to two nominally flat surfaces in contact in vacuum and when radiation is negligible.

A workable contact conductance model need solution for three problems: the characteristics of profile peaks, surface summits and its distribution, the contact mode of two rough surfaces and heat conduction through the contacting spots. The aims of this work are to study surface parameters and its distribution experimentally, to determine the microhardness value under different surface condition, and to develop a contact conductance model that may eliminate some of the assumptions made by previous models.

Greenwood and Williamson [1] (GW) assumed that rough surfaces have normally distributed summit height, constant summit curvature and density of summits equals to the square of peaks density, and majority of asperities deform elastically. An average contact radius derived from Hertz's elastic equation was used to representing the full range of actual contact sizes. A plasticity index was introduced as a measure of the plasticity of the interface.

Cooper, Mikic and Yovanovich [2] (CMY) assumed that surface profile height is normally distributed while slope is randomly distributed and asperities undergo plastic deformation. An average contact radius was again used to represent the full range of actual contact sizes. Constant hardness was used in the model to derive the contact area and contact conductance.

Later Yovanovich and his co-workers [3,4] modified this model to account the variations of surface microhardness with indentation size by using the microhardness value corresponding to the average contact size through an iterative procedure.

Mikic [5] modified CMY's model considering three special cases of asperities deformation: elastic contact, plastic contact of asperities with plastic flow, and plastic contact of asperities with elastic displacement of substrate. A plasticity index was used to determine the mode of deformation for the surfaces in contact. Variation of microhardness was not considered.

Sridhar and Yovanovich [6] (SY) believed that the majority of asperities deform elastically or elastoplastically. An elastoplastic model was developed, which was claimed to suit any load range without the need to assuming deformation mode. The assumption in this model, that contact radius is not load dependent, was discussed by Madhusudana and Li [7].

Parmenter and Marschall [8] found that thermal contact conductance values for stainless steel-aluminum pair lay somewhere between the prediction of CMY's plastic model and GW's elastic model. Sridhar & Yovanovich [9] explained that this was probably due to the appropriate hardness not being used.

The disagreements in the literature lead one to question the assumption of those models. Does height of summits distribute normally? Do summits deform elastically with few spots undergo plastic deformation (GW & Mikic), or entirely plastically (CMY)?

Section 2 of this paper is devoted to the surface profile measurement that used a direct analysis method to obtain surface profile parameters and its distribution, section 3 presents the experiment results and discussion of a series microhardness tests and section 4 reports results of contact conductance test and comparison with models

2. VARIATION OF THE SURFACE ROUGHNESS

One objective of this work was to experimentally study surface roughness parameters and their distribution under different sampling interval and co-relate those parameters.

2.1 SPECIMEN PREPARATION

Test specimens ($\phi 25 \times 45$mm) were made of SS304 stainless steel rod. Two ends were ground flat to the roughness around 0.75μm (RMS). Four thermocouple holes ($\phi 1.6$mm$\times$19mm) were drilled along the length of specimen at 9mm intervals. Four different type beads were used to produce various rough surfaces as shown in Table 1. Specimen 63 was mechanically lapped to 0.08μm (RMS) before bead blasting. Specimens were then cleaned with Shellite solvent made by Shell in a Sanophon ultrasonic cleaning bath for 15 minutes and stored away.

2.2 ROUGHNESS TEST EQUIPMENTS AND PROCEDURE

Surface roughness test used a Talysurf 4 surface roughness tester and a 386 PC installed with an RTI™-815 A/D card. Talysurf 4 has an output port that allows tapping of the true representative of the surface being scanned by the stylus as electrical signals. In the test, the electrical signals were fed into the converter, the converted data were stored in a data file in the computer for analysis. The data were first plotted on the screen to check the waviness. Roughness parameters were calculated according to BS 6741 [10] & Whitehouse [11]. Talysurf 4 has a selection of three cut off lengths and three traversing speeds, which provides nine sampling intervals from 1.125μm to 6.35μm.

Six specimens were randomly selected from a pool of 150 specimens and each of them was subjected to a different method of bead blast. Each specimen was scanned using all nine sampling intervals. Eight traces were made on each specimen at various positions for each sampling interval, resulting in 72 traces per specimen. Thus a total of 432 traces were made.

2.3 RESULTS AND DISCUSSION

The roughness test results for specimen 17 are listed in Table 1. It was found that the RMS roughness is nearly a constant for all nine sampling intervals used. However, RMS slope, RMS curvature, mean peak curvature and number of high spots and peaks varied with sampling interval. In general small sampling interval resulted large RMS slope, RMS curvature and mean peak curvature, more peaks were counted at small sampling interval. This result agreed with the predictions of Nayak [12] and Greenwood [13]. It is recommended that sampling interval be reported together with the surface roughness parameters for comparison.

The distribution of profile height, slope and curvature were, in general, Gaussian, but there were some scatter. The distribution of peak height was confirmed to be not Gaussian, as shown in Fig. 1. It is also clearly shown in Fig. 2 that peak curvature was not increasing with peak height as predicted by Nayak [12] and Greenwood [13]. The actual distribution of peak height and peak curvature is used in section 4 to predict the contact conductance.

The test results yielded the following equations for surface roughness and slopes.

$$R_q=1.248R_a+0.035 \quad (1)$$

$$\Delta_q=1.311\Delta_a-0.003 \quad (2)$$

$$\Delta_q=0.1399\ln(R_q)+0.1803 \quad (3)$$

Where R and Δ are surface roughness and slope, a and q denote the RMS value and mean absolute value. The above three equations suit the RMS roughness range of 0.887~13.375μm, and RMS slope range of 0.1~0.658. Equation (3) had maximum error of 21%.

The uncertainty of the roughness test was due to the calibration (5%), test equipment (2%) and digitization (2%), totally uncertainty was estimated to be 5.74%,

3. VARIATION OF SURFACE MICROHARDNESS

3.1 TEST EQUIPMENT AND PROCEDURE

A series of experiments were conducted to study the microhardness value under different surface condition. An MHP-100 microhardness tester made by Carl Zeiss was used. It is equipped with a Vickers diamond pyramid indenter and may apply maximum load of 115 gram. The optical objective and eyepiece employed produced a total magnification of 960. Lapped (0.08μm RMS) and ground specimen (0.8μm RMS) were used in the test. Six indentations were made under each test load and microhardness was taken as the load over the projected area of indentation. Each Load was applied in 10 seconds and maintained for 30 seconds.

3.2 RESULTS AND DISCUSSION

The microhardness values of lapped and ground stainless steel specimens are shown in Fig. 3. The results indicated that at very low load, the value of microhardness varied not only with the indentation size but also with the surface preparation procedure. The results agreed with the experimental work of Sridhar & Yovanovich [14] and Madhusudana et. al.[15]

The microhardness tests had maximum uncertainty of 60.77% at smallest load (3.79g). Majority of the test results had uncertainty below 13.78% for load higher than 17.5g.

4. DEVELOPMENT OF CONTACT CONDUCTANCE MODEL

In section 2 and 3 we have confirmed that the profile peak height distribution (or indeed summit height) was not Gaussian, surface microhardness was not constant as assumed in some models. A model is needed to account the variation of surface summit height distribution and variation of microhardness with contact size.

4.1 SINGLE ASPERITY IN CONTACT WITH A FLAT SURFACE

We consider a single asperity in contact with a smooth flat surface, the asperity is assumed to have a height Z above mean plane, slope of Δ and the tip radius R, the contact between the asperity and the flat surface may be elastic, elastoplastic or plastic. It may be shown

that there exists a maximum elastic deflection δ_1 and a minimum plastic deflection δ_2, when deflection $\delta < \delta_1$, deformation is elastic and Hertz's equations [16] hold; when $\delta > \delta_2$, deformation is plastic and contact pressure is the hardness of material; when $\delta_1 < \delta < \delta_2$, deformation is elastoplastic, assuming linear increasing of contact area a^2 and mean pressure p_m, we have, for elastoplastic deformation of asperity

$$a^2 = \left[\frac{d(2d_2 - d_1) - d_1 d_2}{d_2 - d_1}\right] R \qquad (4)$$

$$p_m = \left(\frac{d - d_1}{d_2 - d_1}\right)(H - 1.1Y_0) + 1.1Y_0 \qquad (5)$$

where H and Y_0 are the hardness and yield stress of material, a is the contact radius and p_m is contact mean pressure.

4.2 DISCRETIZATION OF DISTRIBUTION CURVE

When a rough surface is in contact with a smooth flat surface, the asperities may deform in any of the above three modes. The key factor is the deflection. For a given load, some high asperities deform plastically, some medium height asperities deform elastoplastically and some low asperities may deform elastically. The combination of deformation sustains the total load.

In order to study asperities individually for its deformation mode, we discretize the summit height distribution curve into a number of sections. The mean value of summit height, slope, tip radius and number of summits for each section is used in the analysis. The deformation of asperities in each section is bonded by the three modes described above. Total area of contact may be obtained through force balance according to the number of summits deforming plastically, elastoplastically and elastically.

It should be noticed that by discretizing the summit distribution curve, we need not assume the distribution of peak height, summit height or curvature; we may then use different microhardness value, according to the size of contact, for each section that deforms plastically, and plastic flow of deformed material may be considered as well.

4.3 TWO ROUGH SURFACES IN CONTACT

It has been proved by O'Callaghan & Cameron [17] that the two rough surfaces in contact is negligibly different from the contact of a smooth and an equivalent surface. Using the discretizing method described above, the equivalent surface in contact with a smooth flat surface under any load may be solved using iterating procedure, the actual contact size and area may be obtained, contact conductance may then be calculated [5]. The plastic flow of deformed material is considered as the uniform rise of contact surface, as suggested by Pullen & Williamson [18].

5. THERMAL CONTACT CONDUCTANCE EXPERIMENT

5.1 EXPERIMENT APPARATUS

Contact conductance experiments were conducted in an axial heat flow cut bar apparatus similar to the one described by Madhusudana [19]. A PC installed with a 16-bits Sensory-419 data acquisition board was used to analyze the type T thermocouples' reading.

5.2 TEST PROCEDURE AND DATA ANALYSIS

The test specimens were cleaned with acetone prior to assembly, and then a light load of 100kPa was applied to the test column to secure the alignment. the system was left to degas over 12 hours before the heater was switched on. Vacuum was kept at 0.02 mbar throughout the test. The system was considered to be in steady state when each temperature reading did not vary by 0.1°C over a period of 15 minutes, and the difference between the heat flux in the two specimens was less than 3%. The temperature drop at the interface was calculated using the method of

least square and extrapolated to two contact ends. The heat flux through the junction was taken as the average value in the top and bottom specimens.

5.4 RESULTS AND DISCUSSION

Experimental results and predictions by the three models are shown in Fig. 4. CMY's plastic model [5] (constant microhardness value of 2.79GPa) over predicted the value of contact conductance by as much as 400%, Mikic's elastic model [5] under estimated the value of contact conductance. The present model agreed with the experiment results. The slight difference in low load range may due to the plastic flow of material not being uniformly distributed on the contact surface as assumed in [18]. The result of present model indicated that under very small load (0.01MPa), the asperities deformed elastoplastically, as the load increased, the majority of asperities deformed plastically, however microhardness value varied with contact size in each section. Maximum experiment uncertainty was estimated to be 10.72%.

6. CONCLUSION

Surface roughness parameters were studied experimentally, it was found that surface peak height (or summit height) was not normally distributed; peak curvature distribution was random. It was concluded from a series of tests that surface microhardness value varied not only with indentation size but also with surface condition. A model was developed to predict thermal contact conductance. In this model there is no need to assume any specific distribution of profile height or mode of deformation. The prediction of current model agreed with the experimental results. The present model may be further extended to predict the contact conductance of wavy or non-flat surfaces and repeated loading.

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Table I. Beads and pressure used and roughness test results

Specimen	SP 63	SP 65	SP 54	SP 59	SP 17	SP 133
Bead	Glass	Steel	Aluminum Oxide	Steel	Garnet	Garnet
Pressure(KPa)	250	1000	150	1800	550	250
SAMPLING INTERVAL vs ROUGHNESS PARAMETERS FOR SPECIMEN 17						
SI (μm)	σ_q (μm)	Δ_q	R_q [1](μm)	C_m [2]	HSC[3]	PNC[4]
6.350	5.145	0.350	12.902	0.093	11.335	21.260
4.644	5.209	0.381	9.884	0.124	12.022	25.052
4.250	4.977	0.396	8.889	0.135	13.627	26.863
4.233	5.023	0.384	9.291	0.130	12.279	26.845
3.175	4.992	0.410	7.029	0.168	13.058	32.054
2.533	5.055	0.429	6.102	0.190	13.528	34.910
2.167	5.015	0.45	5.375	0.208	13.654	37.644
1.478	5.002	0.459	3.772	0.296	14.591	45.888
1.125	4.846	0.470	3.028	0.379	15.741	55.926

[1]R_q=RMS radius of asperity, [2]C_m=Mean peak curvature (1/μm), [3]HSC=High spots count (1/mm), [4]PNC=Peak number count (1/mm)

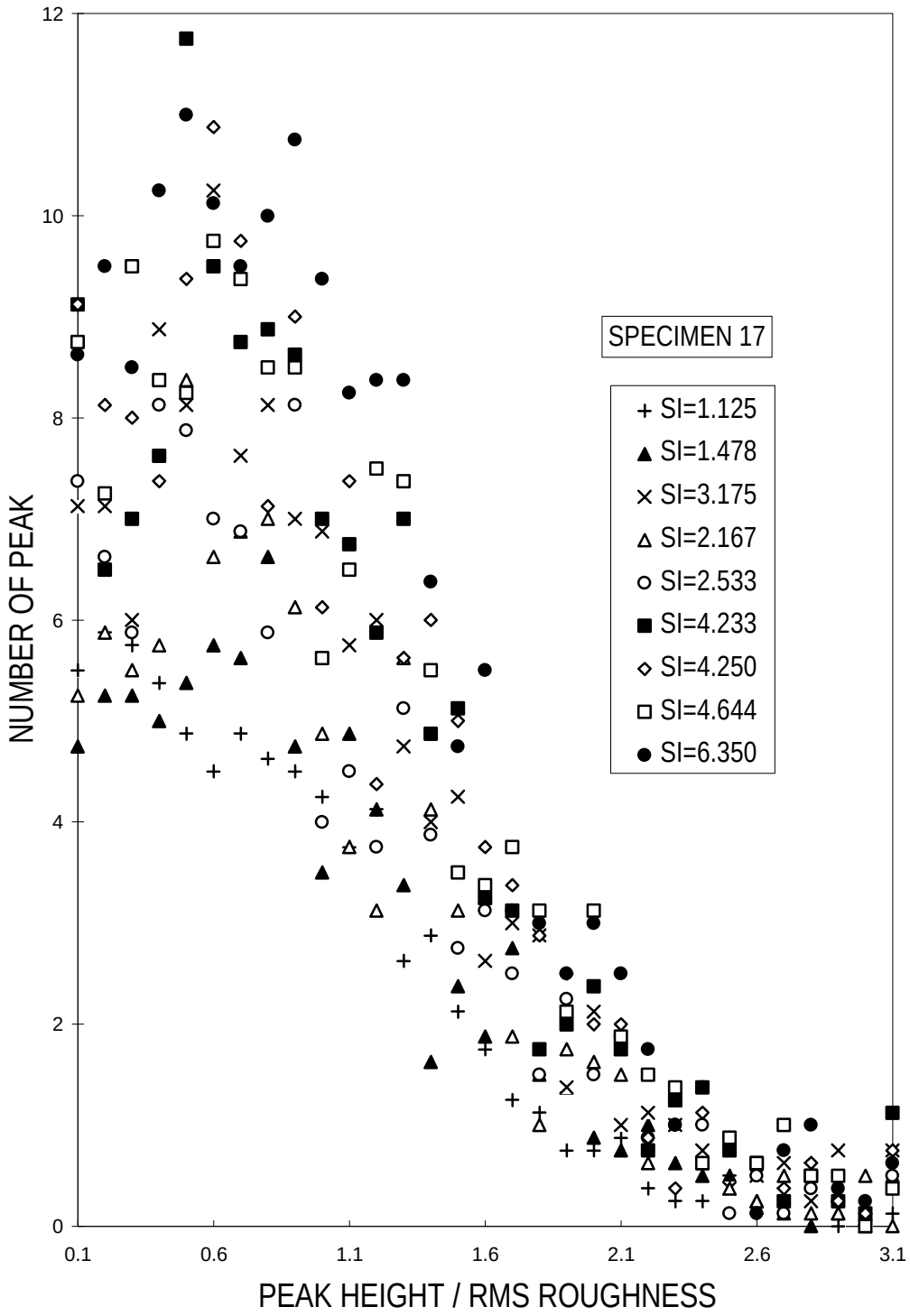
FIGURE CAPTIONS

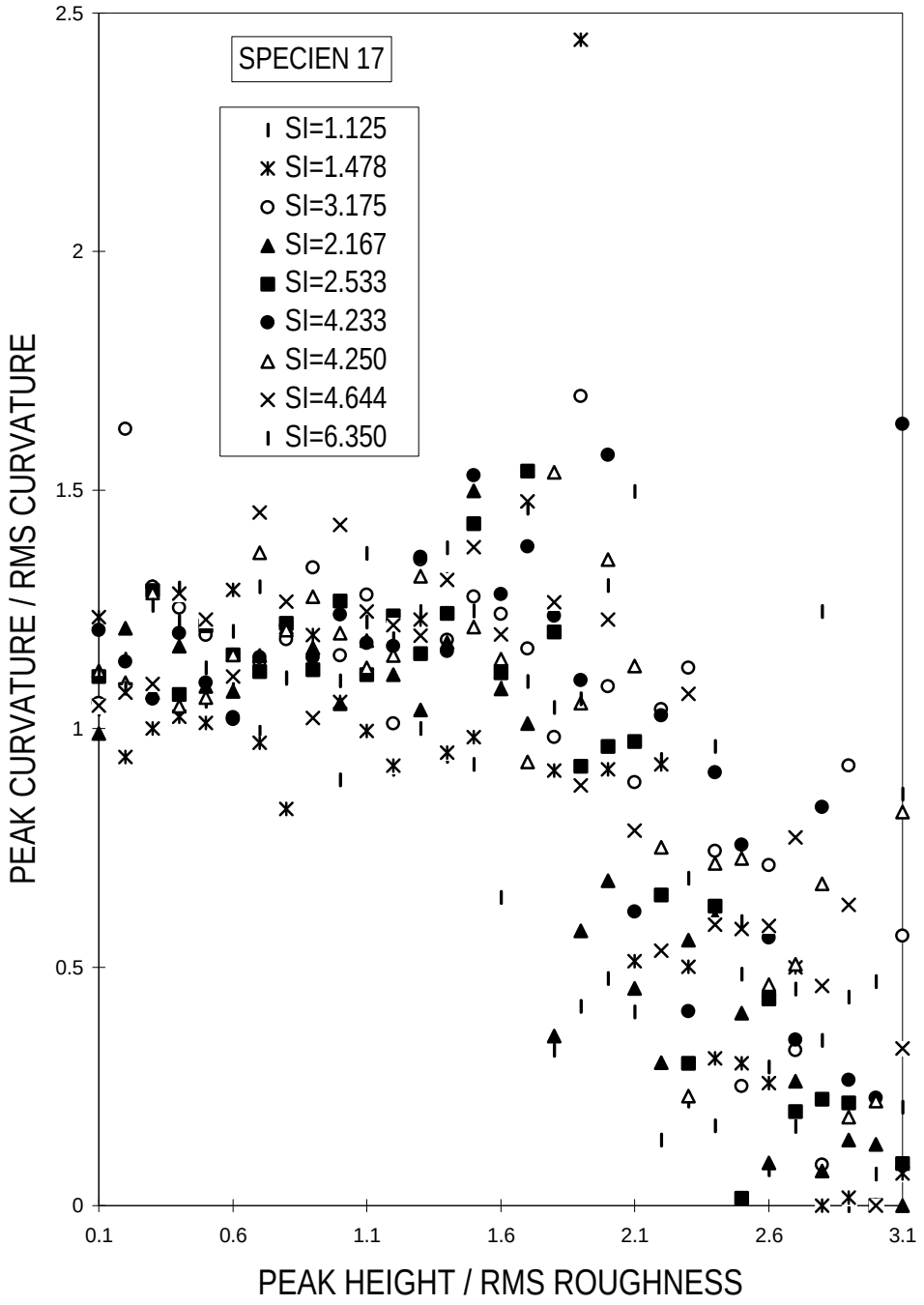
Figure 1 Distribution of the profile peak height

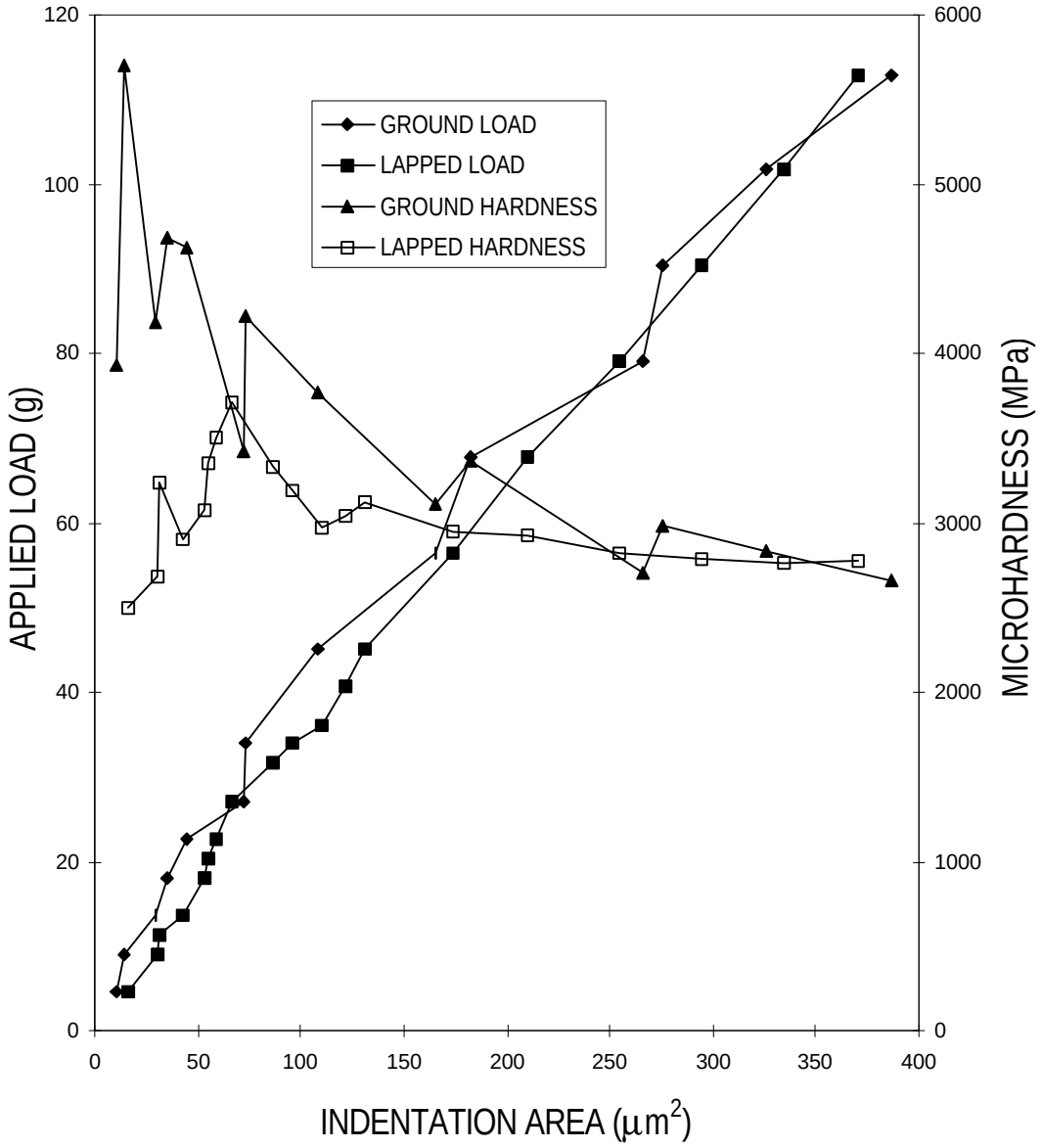
Figure 2 Peak curvature vs peak height

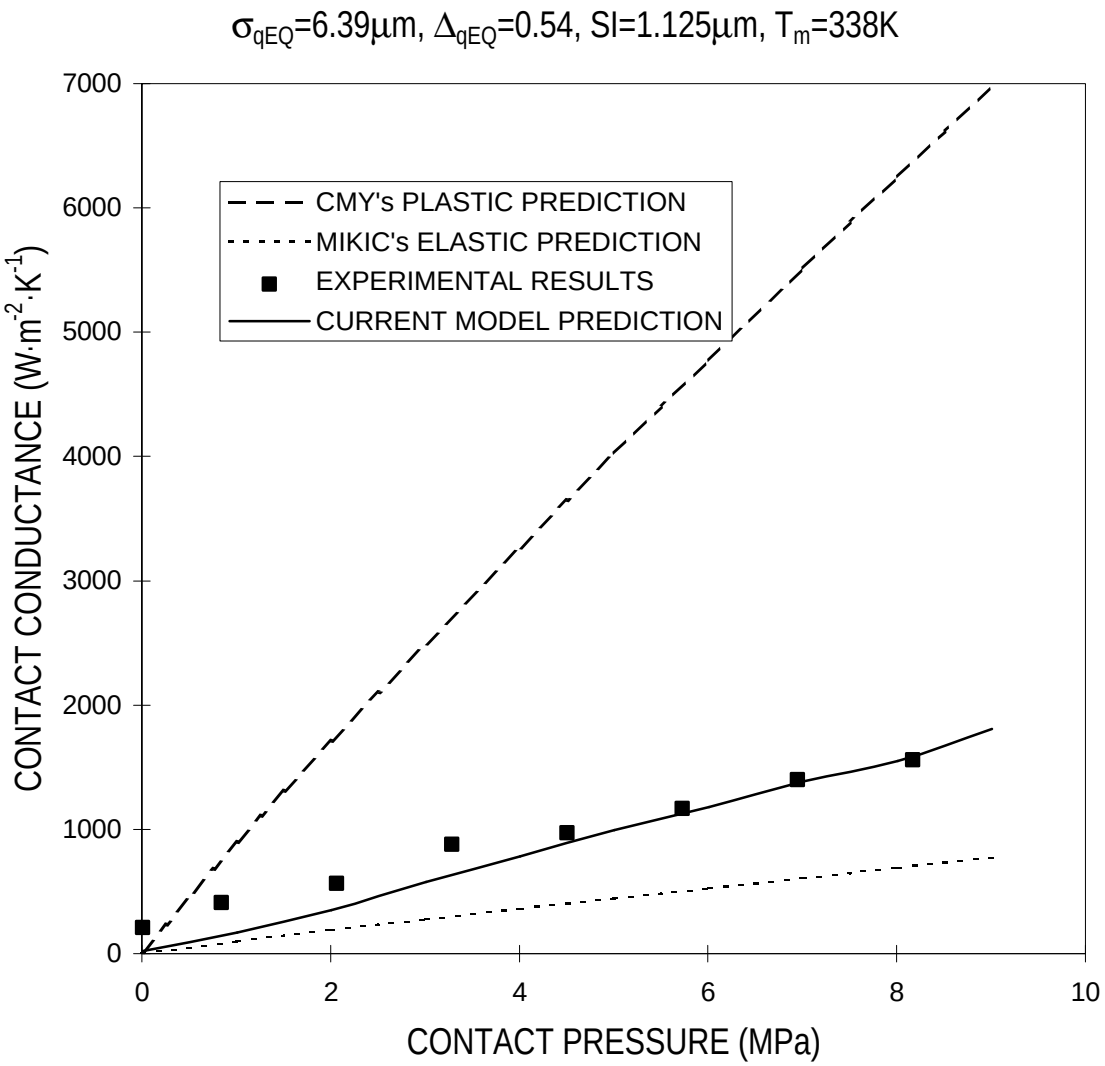
Figure 3 Microhardness, indentation area and load for ground and lapped specimens

Figure 4 Contact conductance experimental results vs predictions of models


SPECIMEN 17
SI=1.125
SI=1.478
SI=3.175
SI=2.167
SI=2.533
SI=4.233
SI=4.250
SI=4.644
SI=6.350
NUMBER OF PEAK
PEAK HEIGHT / RMS ROUGHNESS
0
2
4
6
8
10
12
0.1
0.6
1.1
1.6
2.1
2.6
3.1


SPECIEN 17
SI=1.125
SI=1.478
SI=3.175
SI=2.167
SI=2.533
SI=4.233
SI=4.250
SI=4.644
SI=6.350
PEAK CURVATURE / RMS CURVATURE
PEAK HEIGHT / RMS ROUGHNESS
2.5
2
1.5
1
0.5
0
0.1
0.6
1.1
1.6
2.1
2.6
3.1


GROUND LOAD
LAPPED LOAD
GROUND HARDNESS
LAPPED HARDNESS
APPLIED LOAD (g)
MICROHARDNESS (MPa)
INDENTATION AREA (μm2)
0
20
40
60
80
100
120
0
1000
2000
3000
4000
5000
6000
0
50
100
150
200
250
300
350
400


σqEQ=6.39μm, ΔqEQ=0.54, SI=1.125μm, Tm=338K
CMY's PLASTIC PREDICTION
MIKIC's ELASTIC PREDICTION
EXPERIMENTAL RESULTS
CURRENT MODEL PREDICTION
CONTACT CONDUCTANCE (W·m-2·K-1)
CONTACT PRESSURE (MPa)
0
1000
2000
3000
4000
5000
6000
7000
0
2
4
6
8
10