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COMPARISONS BETWEEN PLASTIC CONTACT HARDNESS MODELS AND EXPERIMENTS

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ABSTRACT

The objective of this paper is to test empirical correlations available in the literature to predict the surface micro-hardness of metals. The surface micro-hardness is an important imput parameter for thermal contact conductance models. The usual way of obtaining information about surface micro-hardness is by Vickers micro-hardness tests at various loads, which demands considerable time. The empirical correlations that are tested here need a single bulk hardness measurement at room temperature to estimate the micro-hardness variation near the surface at any temperature level. The application of the correlation is very easy and straightforward. Thermal contact conductance experimental data available in the literature for SS 304, Ni 200 and Zr-alloys are tested here. The results show that the empirical correlations worked very well for SS 304 and Ni 200. For Zr-4, the results were not satisfactory, indicating that this alloy respond to work-hardening in a different way from the other metals tested.

NOMENCLATURE

c_1	Vickers correlation coefficient; MPa
c_2	Vickers correlation coefficient
C_c	dimensionless contact conductance (Eq. 1)
d	Vickers average diagonal; μm
H	Hardness; MPa
$H^?$	Dimensionless hardness
h_c	contact conductance; $W/m^2 \cdot K$
k	solid thermal conductivity; $W/m \cdot K$
k_s	harmonic mean thermal conductivity, $= 2k_1k_2/(k_1+k_2)$; $W/m \cdot K$
m	effective mean absolute asperity slope, $= \sqrt{m_1^2+m_2^2}$
P	apparent contact pressure; MPa
RMS	root-mean-square value
T	temperature; K

Subscripts

0	reference
$1,2$	surfaces 1 and 2 or solids 1 and 2
a	apparent
c	contact
r	real
rm	room
v	Vickers

Greek Symbols

σ	RMS surface roughness; μm $= \sqrt{\sigma_1^2+\sigma_2^2}$; μm

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INTRODUCTION

Since actual surfaces present deviations from their idealized geometrical form, known as roughness and waviness, when two solids are put into contact, they will touch only at their highest asperities. The heat transfer across the interface between real solids is not as effective as if the solids were perfectly smooth and flat. Since the real contact area is much smaller than the apparent contact area ($< 2\%$), a resistance to heat flow, known as thermal contact resistance, appears at the interface between the contacting solids. Heat transfer across the interface between two solids has been the subject of study of various researchers over many years. Contact heat transfer has many applications in engineering, such as ball bearings, microelectronic chips and nuclear energy.

When two solids are pressed together, the contacting asperities will deform and form small spots of solid-solid contact. In the remaining portion of the apparent contact area the bodies are separated by very thin gaps. Heat transfer between two contacting solids can take place by three different modes: conduction through the contact spots, radiation through the gap in the remaining part of the apparent area and conduction through the gas that fills the gap. These heat transfer modes are treated separately and the sum of the conductances associated with each of these heat transfer modes is called the joint conductance. In this work, only the heat transfer associated with the solid to solid contact is considered. There are several models available in the open literature to predict the gap and the radiation conductance at the interface between contacting bodies.

Since the solid-to-solid contact heat transfer is more effective than the gap and the radiation conductances, the heat flow comming from the hotter body have to constrict towards the contact spots and then spread when it reaches the colder body. The constriction and subsequent spreading of heat flow originates the called contact resistance at the interface. The inverse of the contact resistance per unit aparent area is generally known as contact conductance.

There are several thermal contact conductance models available in the literature. Almost all the existing thermal contact conductance models are composed of three sub-models: thermal, geometrical and mechanical deformation models. The thermal model predicts the contact conductance for a given set of contact parameters: shape, size and number of contact spots. These contact parameters are obtained from a particular mechanical deformation model of the asperities, which can be elastic, plastic or elastoplastic. The deformation model requires a geometric model of the surface in order to be able to predict the contact parameters.

This work is focused on the issue of the deformation of the contacting asperities, i.e., the mechanical deformation model. Only surfaces undergoing plastic deformation are considered here. The crucial parameter that controls the plastic deformation of the contacting asperities is the surface micro-hardness. The usual way of obtaining this information is from Vickers micro-hardness tests at several indentation loads, which is a time consuming task. To avoid that, Sridhar and Yovanovich[1] proposed empirical correlations to estimate the surface micro-hardness based on the bulk hardness, which can be assessed through a single Brinell hardness test. It is also known that the hardness of metals is a function of temperature. Since hardness measurements are commonly made at temperatures different from the temperature encountered in thermal contact problems, Nho[2] proposed correaltions to correct the micro-hardness of metals for the actual interface temperature. The objectives of this work are to test the accuracy of the correlations porposed by Sridhar and Yovanovich[1] and by Nho[2] to estimate surface micro-hardness. These correlations are used here to reduce thermal contact conductance experimental data available in the literature.

THEORY REVIEW

Cooper, Mikic and Yovanovich[3] developed a theoretical thermal contact conductance model for contacting surfaces whose asperities experience plastic deformation. Various researchers in the thermal contact conductance field have employed this model during the last decades and it has been shown to be generally very accurate. Yovanovich[4] correlated the model in a very simple form, as follows:

$$C_\mathtt{c} = \frac{h_\mathtt{c}\sigma}{k_\mathtt{s} m} = 1.25\left(\frac{P}{H_\mathtt{c}}\right)^{0.95} \qquad (1)$$

where $h_\mathtt{c}$ is the thermal contact conductance, $k_\mathtt{s}$ is the harmonic mean of the thermal conductivities of the contacting bodies, and σ and m are the RMS roughness and the mean absolute slope of the combined profile of the two contacting surfaces, respectively. The apparent contact pressure is P and $H_\mathtt{c}$ is the plastic contact hardness. This model is valid for isotropic surfaces, i.e., surfaces that do not present any directional roughness texture.

The plastic contact hardness $H_\mathtt{c}$, appearing in the expression above, is defined as the mechanical pressure that the contacting asperities can support. As the contacting surfaces are pressed against each other, the asperities of the harder surface indent the softer surface, which experiences plastic deformation. If the two materials have similar hardnesses, mutual deformation takes place. As a measure of $H_\mathtt{c}$, Cooper, Mikic and Yovanovich[3] proposed the use of the bulk hardness of the softer of the two contacting materials. According to the authors, the bulk hardness should be obtained by indentation hardness tests, such as the Brinell test. However, Hegazy[5] showed that the bulk hardness is not a good measure of the supporting contact pressure. According to the author, the use of bulk hardness makes the model of Cooper Mikic and Yovanovich[3] to overpredict experimental data by as much as 300%, in some cases. This is because only the material very close to the surface suffers deformation under load, and the surface is generally much harder than the bulk of the material due to work hardening during the surface preparation. The bulk hardness tests employ relatively large indentation loads and therefore the indenter penetrates very deep into the surface. As a measure of H_c, Hegazy[5] proposed the use of the surface micro-hardness instead of the bulk hardness. He proposed a model to predict the plastic contact hardness near the surface, which gave excellent agreement between thermal contact conductance theory and experiments. He measured the Vickers micro-hardness for various indentation loads. The Vickers micro-hardness test employs indentation loads as low as $0.1N$, and the penetration is generally a few micrometers deep. Therefore, the hardness of the material very close to the surface is assessed. The obtained Vickers micro-hardness values (H_v) were then correlated to the respective diagonal length of the square indentations left by the indenter (d_v), which is proportional to the indentation depth, in the following form:

$$H_v = c_1 \left(\frac{d_v}{d_0} \right)^{c_2} \tag{2}$$

where d_0 is some arbitrary reference value, which is chosen, for convenience, to be $d_0 = 1\mu m$. The c_1 and c_2 coefficients appearing in the expression above are called the micro-hardness correlation coefficients, and they give a representation of the metal hardness variation with depth.

Song and Yovanovich[6] proposed a model to predict the dimensionless contact pressure P/H_c, for a contacting pair with known σ, m, c_1 and c_2. The authors correlated their model in the following form:

$$\frac{P}{H_c} = \left[\frac{P}{c_1 (1.62\,\sigma/m)^{c_2}} \right]^{\frac{1}{1+0.071 c_2}} \tag{3}$$

The value obtained for P/H_c from the expression above is directly used in Eq. (1) to predict the thermal contact conductance h_c.

So far, the only way of assessing the surface micro-hardness, i.e. assessing c_1 and c_2, is from Vickers micro-hardness tests at various loads, which demands considerable time. In order to overcome this problem, Sridhar and Yovanovich[1], proposed empirical correlations to predict c_1 and c_2 as a function of the Brinell hardness of the metals, which can be obtained from a single indentation. The authors analyzed the surface micro-hardnesses of several metals and their relation to the bulk hardness. Using micro-hardness tests from Hegazy[5] and Nho[2] for SS 304, Ni 200 and Zr-alloys, as well as their own untreated and heat-treated tool steel and Ti-alloy specimens, Sridhar and Yovanovich[1] proposed the following empirical correlations to estimate c_1 and c_2 based on the material bulk hardness:

$$\frac{c_1}{3178} = \left[4.0 - 5.77 H_B^* + 4.0 \left(H_B^*\right)^2 - 0.61 \left(H_B^*\right)^3 \right] \tag{4}$$

and

$$c_2 = -0.370 + 0.442 \left(\frac{H_B}{c_1} \right) \tag{5}$$

where H_B is the Brinell hardness and $H_B^* = H_B/3178$. These correlations are valid for metals with Brinell hardnesses between 1300 and 7600 MPa.

It is well known that the hardness of metals is a function of temperature: the higher the temperature, the softer the metal. Hardness measurements are generally conducted at room temperature, while the interface temperatures of actual thermal contact problems could reach much higher temperatures. Nho[2] conducted experiments to analyze the effect of temperature on the micro-hardness correlation coefficients c_1 and c_2 of Al 6061-T5, SS 304 and Ni 200. The author found that c_2 is not sensitive to temperature variations between approximately 20 and 200^oC. On the other hand, c_1 decreased nearly exponentially with temperature. The author proposed the following correlations to estimate the c_1 coefficients for SS 304, Ni 200 and Al 6061-T5 at high temperatures:

<u>For SS 304:</u>

$$\frac{c_1}{c_1(T_{rm})} = exp[-1.675x10^{-3}(T - T_{rm})] \tag{6}$$

<u>For Ni 200:</u>

$$\frac{c_1}{c_1(T_{rm})} = exp[-1.372x10^{-3}(T - T_{rm})] \tag{7}$$

<u>For Al 6061-T5:</u>

$$\frac{c_1}{c_1(T_{rm})} = exp[-1.19x10^{-3}(T - T_{rm})] \tag{8}$$

which are valid for $20 < T < 200^oC$. In these equations, $c_1(T_{rm})$ is the value of c_1 obtained at room temperature T_{rm}.

The objective of this work is to compare the models reviewed here with thermal contact conductance experimental data from Hegazy[5], and Antonetti[7] for conforming isotropic rough surfaces. The tests were performed under vacuum environment, with samples possessing various roughness levels, and for different metals. The data sets consist of the contact between bead-blasted/lapped surfaces. The study is focused on the analysis of the accuracy of the Sridhar and Yovanovich[1] correlations for c_1 and c_2 (Eqs. 4 and 5). The accuracy of the correlations proposed by Nho[2] to correct c_1 for the actual inteface temperature is also analyzed in more detail in this paper.

COMPARISON BETWEEN THEORY AND EXPERIMENTS

Hegazy[5] measured the thermal contact conductance of the interface between lapped/bead-blasted surfaces of similar metals possessing various roughness levels. The author tested SS 304, Ni 200 and Zr-alloys. The first two are commom materials employed by the industry and the Zr-alloys are generally used by the nuclear energy industry. The interface temperature during the tests were around 180^oC.

Figure 1 shows the comparison between theory and SS 304 experimental data. Four pairs, presenting four different values of the ratio σ/m are shown in this graph and are compared with the theoretical model (Eqs. 1 and 3). In this graph, c_1 and c_2 were obtained by the author from Vickers micro-hardness measurements at room temperature. The RMS difference for all 4 pairs is only 16%. The RMS difference of each pair can also be seen. The agreement is very good, in general, especially at higher contact pressures. The theory underpredicts experiments at light contact loads, which according to Milanez, Yovanovich and Culham[8], is due to the truncation of the highest contacting asperities and is not related to the incorrect prediction of the supporting contact pressure H_c.

Since the interface temperature during the tests (approximatelly 180^oC) were higher than the temperature during the Vickers micro-hardness tests, the data shown in Fig. 1 was reduced again using the c_1 coeficient corrected according to Eq. (6). The results are shown in Fig. 2. In this graph, the theory slightly overpredicts the experiments at high loads. As c_1 is corrected for temperature, the data points are displaced to the right in Fig. 2 because the plastic contact pressure ($H_c \sim c_1$) is smaller than in Fig. 1. However, the RMS difference is approximately the same (16%) in both cases.

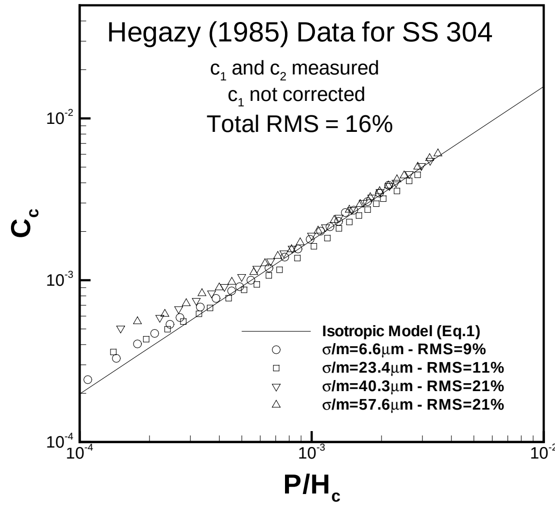

Figure 1 - SS 304 data from Hegazy[5] (c_1 and c_2 measured, c_1 not corrected)

In order to verify the accuracy of the correlations from Sridhar and Yovanovich[1] for c_1 and c_2 (Eqs. 4 and 5), the same SS 304 data sets from Hegazy[5] were reduced again. For SS 304, the bulk hardness was measured by Hegazy[5] and presented a value of $H_B = 1474MPa$. For this value of bulk hardness, the Sridhar and Yovanovich[1] correlations give $c_1(T_{rm}) = 6753MPa$ and $c_2 = -0.273$, against $c_1(T_{rm}) = 6271MPa$ and $c_2 = -0.229$, which were measured by Hegazy[5]. Figure 3 shows the comparison between theory and the SS 304 experimental data from Hegazy[5] with c_1 and c_2 estimated using the correlations from Sridhar and Yovanovich[1]. Comparing Figs. 2 and 3, one see that the results obtained using the estimated values of c_1 and c_2 are simmilar to the results using the measured values. Therefore the Sridhar and Yovanovich[1] correlations were accurate in this case.

A behavior similar to the SS 304 data presented above was noticed with the Ni 200 data from Hegazy[5] as well. Using c_1 obtained from measurements at room temperature leads the theory to predict experiments very well, with a RMS difference of 12%. Using the c_1 value corrected of for the actual interface temperature, the theory slightly overpredicts the experiments at high loads, exactly in the same way as shown previously for SS 304. The RMS differences are 18% using the measured values of c_1 and c_1 and 15% using the predicted values using the Sridhar and Yovanovich[1] Correlations. Therefore, for the Ni 200 data set from Hegazy[5], the Sridhar and Yovanovich[1] correlations showed to be accurate, simmilarly to the SS 304 data set.

The comparisons between Zr-2.5wt%Nb and Zr-4 data and theoretical predictions for both the measured and the estimated values of c_1 and c_2 are presented in Figs. 4 and 5, respectively. The RMS difference of all data sets for the measured c_1 and c_2 values is 20%. Using the values estimated by the Sridhar and Yovanovich[1] correlations, the RMS difference is 50%.

This reasonably large value of RMS implies that the correlations for c_1 and c_1 were not suitable for these data sets. The c_1 and c_2 values that Hegazy[5] obtained from his specimens are quite different from the values Sridhar and Yovanovich[1] used to obtain his correlations. Table 1 presents the c_1 and c_2 values measured by Hegazy[5], the values used by Sridhar and Yovanovich[1] to obtain Eqs. (4) and (5), and the values that come from Eqs. (4) and (5). As it can

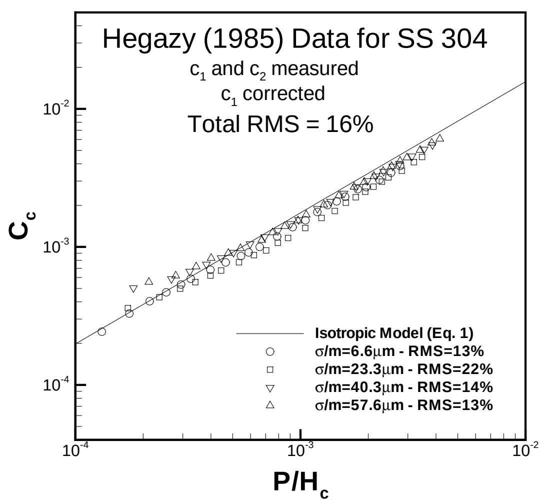

Figure 2 - SS 304 data from Hegazy[5] (c_1 and c_2 measured, c_1 corrected)

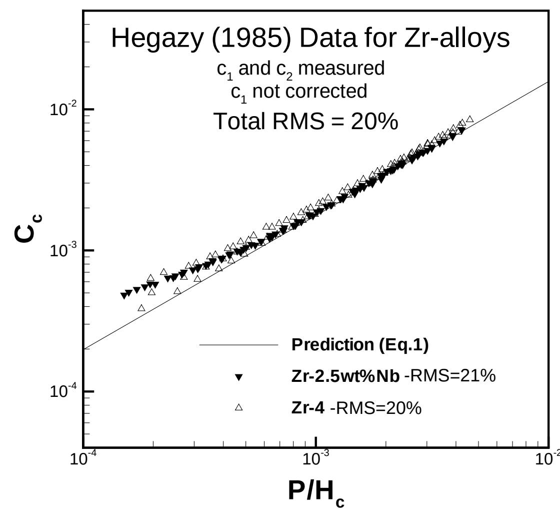

Figure 4 - Zr-alloys data from Hegazy[4] (c_1 and c_2 measured, c_1 not corrected)

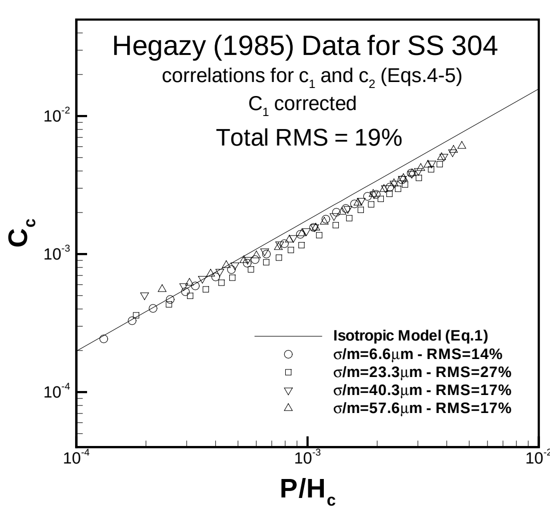

Figure 3 - SS 304 data from Hegazy[5] (c_1 and c_2 from Eqs. 4 and 5, c_1 corrected)

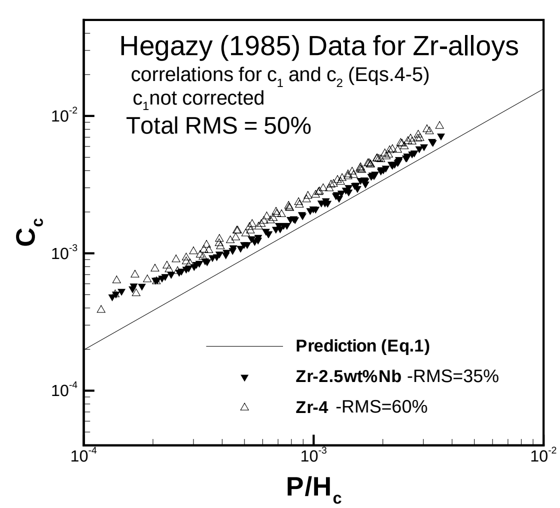

Figure 5 - Zr-alloys data from Hegazy[5] (c_1 and c_2 from Eqs. 4 and 5, c_1 not corrected)

be seen in this table, for Zr-2.5wt%Nb, SS 304, and Ni 200, the values computed using the Sridhar and Yovanovich[1] correlations (last column) are in good agreement with the values measured by Hegazy[5] (second column). Also for these metals, the values employed by Sridhar and Yovanovich[1] (third column) to obtain Eqs (4) and (5) are the same values measured by Hegazy[5]. However, for Zr-4, Sridhar and Yovanovich[1] used very different values to obtain their correlations (third column) from the values measured by Hegazy[5] (first column). As a result, the values coming from the Sridhar and Yovanovich[1] correlations (last column) are quite different from the measured values (first column). This explains why the comparison between theory and experiment shown in Fig. 4 looses accuracy when compared with Fig. 5.

From these observations, it can be concluded that the Zr-4 alloy present a behavior distinct from SS 304, Ni 200 and Zr-2.5wt%Nb regarding to surface micro-hardness. The last three metals present consistent micro-hardness measurements in different samples, while it is clear from the second and third columns of Table 1 that the samples measured by Hegazy[5] and the measurements used by Sridhar and Yovanovich[1] to find the correlations given by Eq. (4) and (5) are quite different. The reason for this distinct behavior is probably related to the way different metals respond to the work-hardening during the surface preparation. However, it is still very difficult to predict how the work-hardneing takes place during the surface preparatio. The literature lacks works in this field.

Antonetti[8] also measured the contact conductance between Ni 200 specimens presenting four distinct values of σ/m. The data was reduced and plotted along with the isotropic contact conductance model (Eq. 1) and the results are shown in Figs. 6 to 8. Figure 6 was obtained using the measured values of c_1 and c_2, with c_1 not corrected for temperature. Figure 7 was also obtained using the measured values of c_1 and c_2, but with c_1 corrected for the actual interface temperature. Figure 8 was obtained with c_1 and c_2 predicted using Eqs. (4) and (5), and c_1 corrected for temperature (Eq. 7). In Fig. 6 the agreement is excelent for the entire range of contact pressures, with a RMS difference of only 6%. When c_1 is corrected for temperature (Fig. 7), the theory tends to slightly over-predict the experimental data, with a RMS difference of 12%. The Sridhar and Yovanovich[1] correlations for c_1 and c_2 makes the theory predict the data points very well (Fig. 8), with a RMS difference of 8%. Therefore, the Ni 200 data from Antonetti[8] presented a behaviour very simmilar to the Ni 200 and SS 304 data from Hegazy[5].

Table 1 - Bulk Hardness (H_B [MPa]), c_1 [MPa] and c_2

Material	Measured by Hegazy[5]	Used to obtain Eqs. (4) and (5) (Sridhar and Yovanovich[1])	Computed using Eqs. (4) and (5)
Zr-2.5wt%Nb	$c_1 = 5884$	$c_1 = 5884$	$c_1 = 6190$
$H_B = 1727$	$c_2 = -0.267$	$c_2 = -0.267$	$c_2 = -0.237$
Zr-4	$c_1 = 3320$	$c_1 = 5677$	$c_1 = 6372$
$H_B = 1913$	$c_2 = -0.145$	$c_2 = -0.278$	$c_2 = -0.249$
Ni 200	$c_1 = 6304$	$c_1 = 6304$	$c_1 = 6309$
$H_B = 1668$	$c_2 = -0.264$	$c_2 = -0.264$	$c_2 = -0.245$
SS 304	$c_1 = 6271$	$c_1 = 6271$	$c_1 = 6753$
$H_B = 1472$	$c_2 = -0.229$	$c_2 = -0.229$	$c_2 = -0.273$

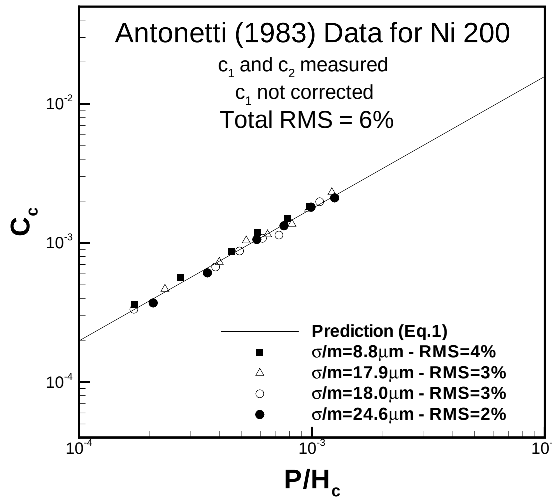

Figure 6 - Ni 200 data from Hegazy[4] (c_1 and c_2 measured, c_1 not corrected)

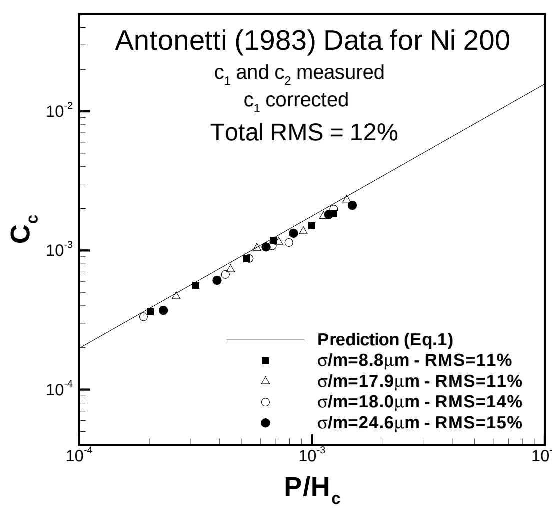

Figure 7 - Ni 200 data from Hegazy[4] (c_1 and c_2 measured, c_1 corrected)

SUMMARY AND CONCLUSIONS

The objective of this work was to compare thermal contact conductance experimental data between conforming rough surfaces under vacuum against models available in the open literature. The available data include SS 304, Ni 200, Zr-4 and Zr-2.5wt%Nb pairs from Hegazy[5] and Antonetti[7]. The contact conductance models analyzed here are based on the model of Cooper et al.[3], for asperities experiencing plastic deformation. The surface microhardness coefficients c_1 and c_2 used here, which are very important input parameters to the thermal contact conductance model, were both the measured values and the values estimated using the empirical correlations proposed by Sridhar and Yovanovich[1].

The correlations proposed by Nho[2] to correct the c_1 coefficient for the actual temperature of the interface were also tested here. The correlations proposed by Nho[2] to correct c_1 for the actual interface temperature in general make the theory to slightly overpredict the experimental data. All the experimental data used here seem to be better predicted when the c_1 values at room temperature are used instead of the corrected ones. However, it is well known that metals decrease hardness with increasing temperature, and since $H_c \sim c_1$, c_1 should decrease with temperature. The cause for the theory to predict the experiments better using c_1 at room temperature could be the inaccurate measurement of the surface roughness parameter σ/m. The present authors believe that the measured roughness parameter σ/m could have been under-estimated by Hegazy[5] and Antonetti[7]. It is well known that both σ and m are sensitive to the "cut-off" length of the roughness measurement system (stylus profilometer). There are no standards dictating which "cut-off" lenght should be employed for thermal contact conductance purposes. An inapropriate "cut-off" lenght could easily make σ/m be under-estimated, making the thermal contact conductance theory to predict data accuratelly, despite using an inapropriate value of c_1.

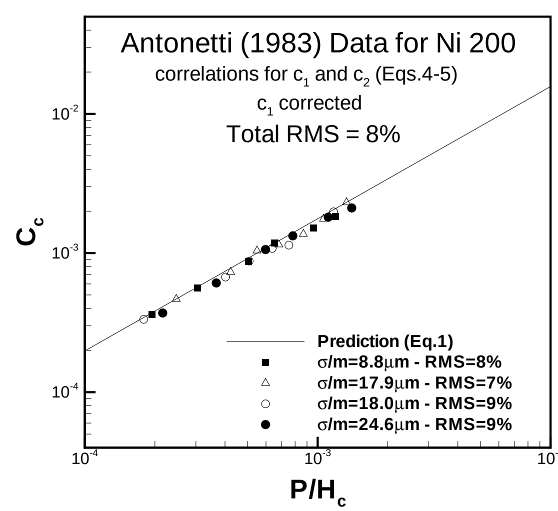

Figure 8 - Ni 200 data from Hegazy[4] (c_1 and c_2 from Eqs. 4 and 5, c_1 corrected)

For Ni 200 and SS 304, the c_1 and c_2 values computed using the Sridhar and Yovanovich[1] correlations gave very good results. The RMS differences for each data set vary only a few percent if one uses the estimated c_1 and c_2 instead of the measured values. For the Zr-alloys, the results were not so good, especially for Zr-4. It is believed that this alloy responds to work-hardening during surface preparation in a different way to the other metals tested. Further studies are needed in order to test the validity of the empirical correlations for c_1 and c_2 over a larger spectrum of metals.

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