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# Finding the topography of a surface using a new method and its application on Thermal Spray Coatings

**Ali Marzban[1]**

**[1]Northeastern University**
**360 Huntington Ave, Boston, MA**
**marzban.a@husky.neu.edu**

## Abstract

The author reports the change in measured dielectric constant of thermal barrier coatings after using different kind of polishing procedure on it. TS YSZ coatings on Al substrates samples were used and their dielectric constant was measured. The surface of the samples was polished and the dielectric constant of them was measured. The measured dielectric constant of the samples increased when the surface was smoother. The capacitance of the structure including air gap and coating was modeled by series method and converted to dielectric constant. The author suggests an inverse procedure to measure the surface roughness and topology of any material by finding its dielectric constant. By this way, the real area of contact and real contact pressure can be found based on measuring the air gap from dielectric constant.

## 1. Introduction

Thermal spray (TS) coatings and materials including thermal barrier, tribological and anti-corrosive coatings have established application across huge number of engineering fields [1]. TS is attractive for these systems due to its low cost, ability to coat large areas and flexibility in material feedstock. These attributes, along with improvements in process diagnostics have spurred the exploration of TS for more functional applications including fuel cells [2], conformal electronic sensors [3] and biomedical implants [4].

Air or gas gap between two metal walls is typical in many industries. Because of various reasons such as aging, size change, temperature and radiation influence, vibrations, creep, etc. In order to prevent this, the gap width, e.g. between two concentric metal tubes should be continuously monitored. Typically the gap width is measured by using eddy-current technique [7, 8]. This flow creates a reaction field which affects the pick-up voltages in the receive coil. The change in the overall reaction field due to the air gap creates the typical response signal. However, the accuracy of such measurements is rather low. Theoretically, to improve the accuracy, the high-frequency eddy current probe can be used. However, due to electromagnetic field attenuation, such a probe provides only low amplitude response. Moreover, the results of eddy-current measurements are affected by changes in material electric conductivity. The other alternative technique, which can be used for accurate gap measurement, is the ultrasonic method. Ultrasound is not affected by variations in electrical conductivity or permeability, and it can provide the desired accurate measurements and 100% mapping. Another method for measuring the air gaps is photothermal radiometry [9]. All of the above methods are expensive and the resolution of them is really dependent on the equipment resolution and mapping procedure. The effect of air gap on measured dielectric constant of materials was investigated before [9, 10] but this effect wasn't used as a method to measure the air gap or to inspect the topography of a material.

Schematic Thermal Spray process is shown in Fig. 1. In this study TS YSZ coatings (0.20 – 0.40 mm thick) on Al substrates samples were used and their dielectric constant was measured. The surface of the samples was polished by using different sand papers, and the dielectric constant of them was measured again. By using the smoother sand papers, the dielectric constant of the samples increased.

The electrode can attach to the coating with a very small air gap between them on a smooth surface and the measured dielectric constant will be increased. In some cases a conductive material like copper foil or a graphite layer will be used to prevent the air gap on the sample. But these methods will change the surface topology.

In this study, the capacitance of the structure including air gap and coating was modeled by series capacitance method and then it was converted to dielectric constant. So the measured dielectric constant could be predicted by having the actual dielectric constant of the material (i.e. coating) and the thickness of air gap, $h_{air}$.

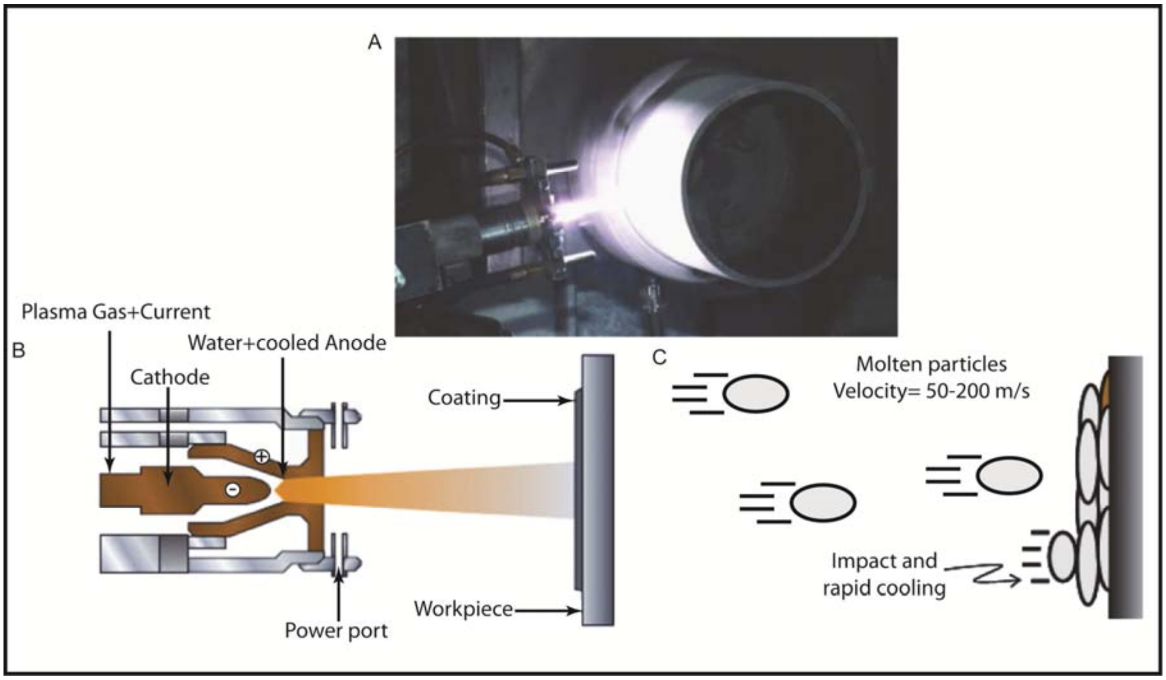


**Fig. 1 – A)** Thermal Spray Procedure **B)** Schematic Thermal Spray process **C)** High velocity molten particles which make splats on a substrate

The author suggests an inverse procedure to measure the surface roughness and topology of any material by finding its dielectric constant as a Nondestructive Test (NDT). In this method, the dielectric constant of an unknown surface will be measured and then it will be modeled using the actual material dielectric constant and a series of capacitance (air and coating). The experimental and analytical results can be matched by changing the air-gap thickness. So we can roughly measure the air gap amount. The accuracy of the method depends on the size of the electrode. If we can have a very small electrode, we can predict topology of the surface with a very high resolution (Figure 2). Later on, by relating the air-gap thickness, $h_{air}$, to the topology of the surface, we can find the real area of contact and real contact pressure.

## 2. Method

We had different samples of Thermal Spray coatings which are shown in Table 1. We used sample number four and polished it with sand papers of 400 and 600. Average particle diameters of these sand papers are 23 and 16 µm respectively. The capacitance of the coatings was measured by an impedance analyzer operating at 1KHz (HP 4294A precision impedence analyzer and HP 16451B Dielectric test fixture attachment).

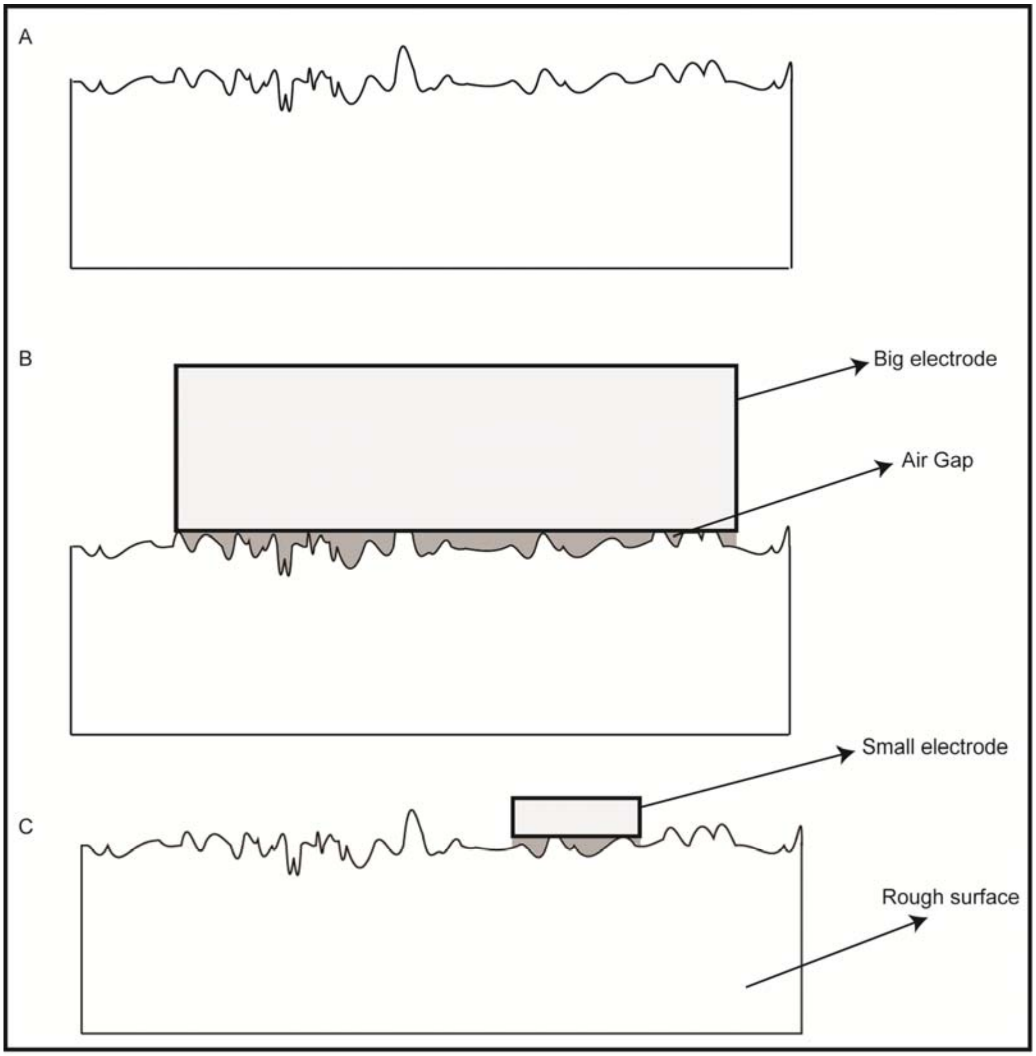


**Fig. 2 – A)** A rough surface. **B)** measuring the air gap by a Big electrode and **C)** a small electrode.

| | **Sample#1** | **Sample#2** | **Sample#3** | **Sample#4** |
|---|---|---|---|---|
| **Coating Thickness (mm)** | 0.2 | 0.22 | 0.26 | 0.40 |
| **Current (A)** | 700 | 700 | 700 | 700 |
| **Argon (slm)** | 40 | 55 | 55 | 30 |
| **Helium (slm)** | 10 | 10↔15 | 10 | 5 |
| **Hydrogen (slm)** | 0 | 0 | 0 | 0 |
| **Carrier (slm)** | 4.0 | 4.0 | 4.0 | 4.0 |
| **Federate (RPM)** | 3.0 | 3.0 | 3.0 | 3.0 |

**Table 1** – Different parameters of coating samples.

Capacitance is the ability of a body to hold an electrical charge. Capacitance is also a measure of the amount of electric charge stored for a given electric potential. The measured capacitance was converted to dielectric constants by the following formula:

$$\varepsilon_r = \frac{t_a\, C_p}{A\, \varepsilon_o}$$

where $\varepsilon_r$ is dielectric constant, $t_a$ is average thickness of coating, $C_P$ is capacitance, $A$ is area of electrodes, and $\varepsilon_o$=8.85e-12 F/m. The dielectric constant (or relative permittivity) of a material is the ratio of the amount of stored electrical energy when a potential is applied, relative to the permittivity of a vacuum (which is equal to one by definition). The measured capacitance and dielectric constant of unpolished and polished coatings are shown in Table 2. The schematic electrodes are shown in Figure 3.

| | **Average Particle diameter (μm)** | **$C_p$ (pF)** | **Dielectric Constant** | **Predicted Air gap amount by FEM (μm)** |
|---|---|---|---|---|
| **Unpolished** | - | 4.02851 | 9.2732 | 28.001 |
| **400** | 23 | 4.4101 | 10.1516 | 23.589 |
| **600** | 16 | 5.2718 | 12.1352 | 16.261 |

**Table 2** – Capacitance and Dielectric Constant of unpolished and polished samples.

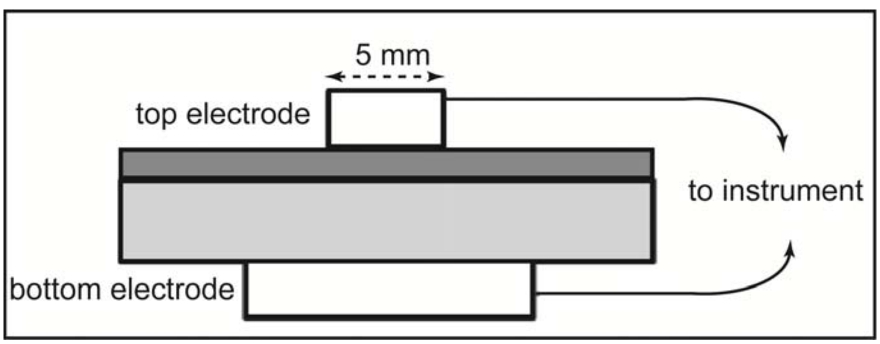


**Fig. 3 –** Electrodes for measuring the capacitance

## 3. Analytical analysis

Air and coating are in series configuration (Fig. 4), so the total capacitance of the structure can be measured by

$$\frac{1}{C} = \frac{1}{C_c} + \frac{1}{C_{air}}$$

where $C$ is the total capacitance of the structure, and $C_c$ and $C_{air}$ are the capacitance of the air, and coating respectively. So by using the relation between dielectric constant and capacitance, the non-dimensional formula for dielectric constant of the structure will be

$$\frac{\varepsilon}{\varepsilon_c} = \frac{1 + \frac{h_{air}}{t_a}}{1 + \left(\frac{h_{air}}{t_a}\right)\frac{\varepsilon_c}{\varepsilon_{air}}}$$

where $\varepsilon$ is total calculated dielectric constant, $\varepsilon_c$ is the material dielectric constant (i.e. Coating), and $\varepsilon_{air}$ is the air dielectric constant ($\varepsilon_{air}$=1).

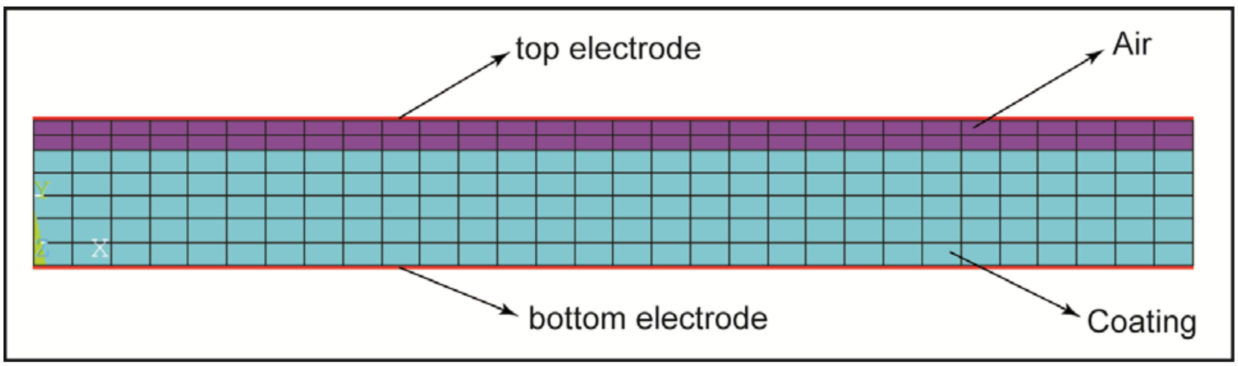

**Fig. 4 –** Series model of Air and Coating

The dielectric constant of the Zirconia and air are around 22 and 1 respectively. By increasing the air gap amount, the dielectric constant of the structure will be decreased which is shown in Figure 5. So by comparing the measured dielectric constant and Figure 5, we can roughly predict the air gap amount. For example in our case, for polished samples with 400 and 600 sand papers, the predicted amount of air gap is about 16.261 and 23.589 µm which are comparable with 23 and 16 µm as it shown in Table 2 too. So the air gap for the unpolished sample with dielectric constant of 9.269 is about 28.001µm.

## 4. Finding real contact area and real pressure

If a smooth surface (i.e. electrode) and a rough surface (nominally flat), come into contact until their reference planes (taken to pass through the mean of the peak height distribution) are separated by a distance d, then there will be contact at those asperities whose height, z, is greater than d (Fig. 6). The classical statistical model for a combination of elastic and elastic-plastic contacts between a rough surface and a smooth surface was considered based on Greenwood and Williamson [12] (G&W). They assumed that (1) the rough surface is covered with a large number of asperities, which, at least near their summit, are spherical; (2) asperity summits have a constant radius of $R_p$; (3) their heights vary randomly; and (4) most engineering surfaces have a Gaussian distribution of peak heights. Many surfaces follow a Gaussian distribution.

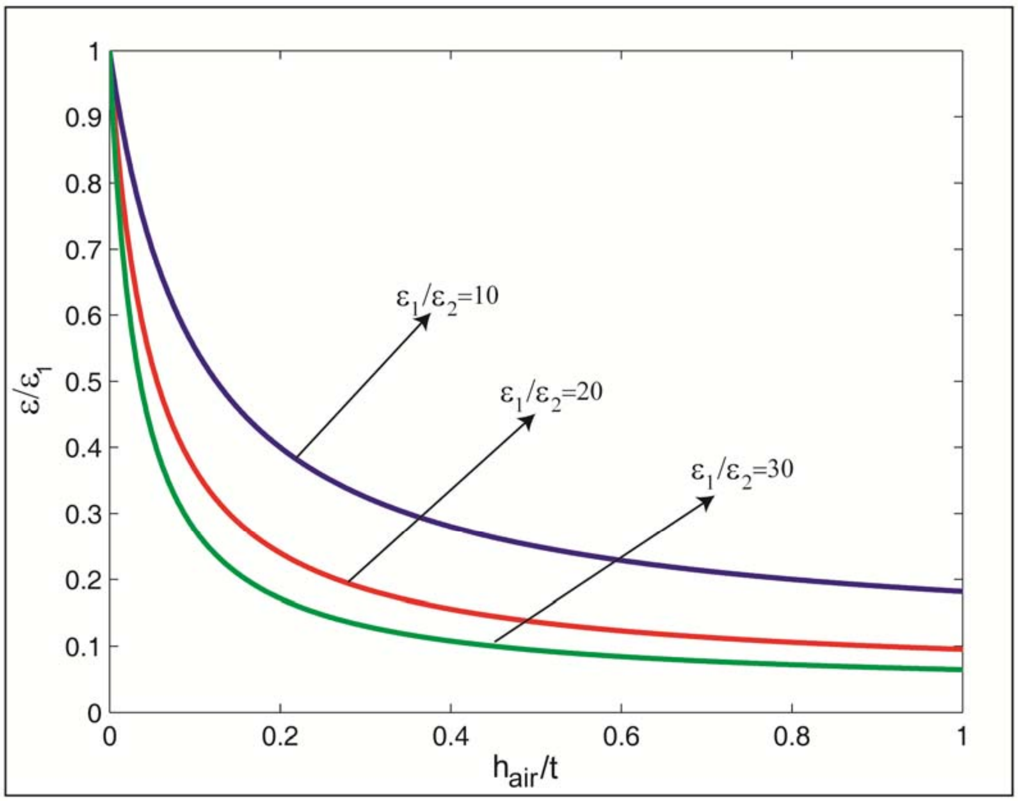


**Fig. 5 –** Dielectric constant vs. Air gap amount From Analytical solution

If we consider that the rough surface peak heights having a probability density function of *p(z)*; the apparent pressure, $p_a$, mean real pressure, $p_r$, (elastic) real area of contact, $A_{re}$, number of contact spots, *n*, and mean asperity real area of contact can be calculated as a function of separation, *d* for elastic contacts in static conditions with no tangential stresses using G&W's assumptions.

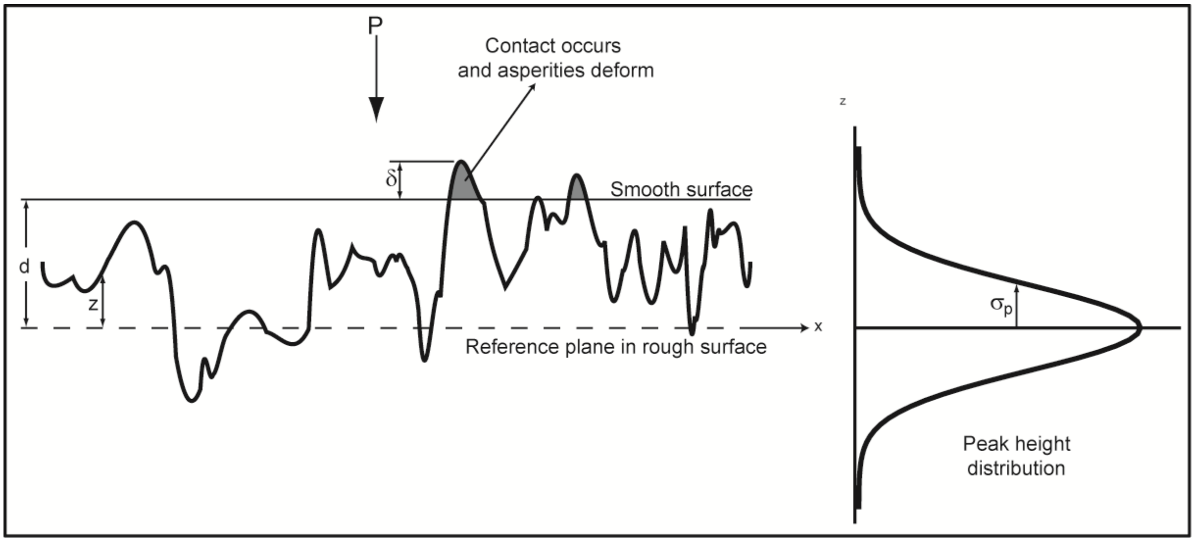


**Fig. 6 – Contact of electrode and rough surface and peak height distribution**

If the two surfaces come together until their reference planes are separated by a distance *d*, then there will be contact at any asperity whose height was originally greater than *d*. Thus, the probability of making contact at *z* is

$$P(z_p > d) = \int_d^{\infty} p(z_p) dz_p$$

and if there are N asperities in all, the expected number of contacts will be

$$n = N \int_d^{\infty} p(z_p) dz_p$$

Also, since $\delta = z - d$, the total (elastic) real area of contact is

$$A_{re} = \pi N R_p \int_d^{\infty} (z_p - d)\, p(z_p)\, dz_p$$

Similarly, based on Hertz contact theory of two spheres, we can find the expected total load as

$$W = p_r A_{re} = p_a A_a = (\frac{4}{3}) N E^* R_p^{1/2} \int_d^\infty (z_p - d)^{3/2}\, p(z_p)\, dz_p$$

where $p_r$ and $p_a$ are real pressure and apparent pressure, respectively, $A_a$ is the apparent area, and $E^*$ is the composite modulus as

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$$

It is convenient to work with dimensionless variables as follow

$$\frac{p_a}{(\eta R_p \sigma_p) E^* (\sigma_p / R_p)^{1/2}} = \left(\frac{4}{3}\right) F_{3/2}(D)$$

$$\frac{p_r}{E^* (\sigma_p / R_p)^{1/2}} = \left(\frac{4}{3\pi}\right) F_{3/2}(D) / F_1(D)$$

$$A_{re} E^* (\sigma_p / R_p)^{1/2} / p_a A_a = \left(\frac{3\pi}{4}\right) F_1(D) / F_{3/2}(D)$$

$$n R_p \sigma_p E^* E^* (\sigma_p / R_p)^{1/2} / p_a A_a = F_0(D) / \left(\frac{4}{3}\right) F_{3/2}(D)$$

$$(A_{re}/n) R_p \sigma_p = \pi\, F_1(D) / F_0(D)$$

where D, the dimensionless separation, is $d/\sigma_p$; $\eta$ is the density asperity summit per unit area ($N/A_a$) on a surface with smaller density; and $F_m(D)$ is a parabolic cylinder function given by

$$F_m(D) = \int_D^\infty (s - D)^m p^*(s) ds$$

where $p^*(s)$ is the standardized peak-height probability density function in which the height distribution has been scaled to make its standard deviation unity. In our case which peak-height distribution following a Gaussian height distribution

$$F_m(D) = \left[\frac{1}{(2\pi)^{1/2}}\right] \int_D^\infty (s - D)^m \exp\left(\frac{-s^2}{2}\right) ds$$

For a Gaussian distribution, $D$, $p_r$, $A_{re}$, $n$, and $A_{re}/n$ vs $p_a$ can be obtained. Next the data are fitted to a power form using the least-squares fit and are presented as following formulas based on Bhushan [13].

$$D = 1.40[\log(0.57/P_a)]^{0.65}$$

$$\frac{P_r}{E^*\left(\sigma_p/R_p\right)^{1/2}} = 0.42\ P_a^{0.04}$$

$$\frac{A_{re}}{A_a\left(\eta R_p \sigma_p\right)} = 2.40 P_a^{0.96}$$

$$\frac{n}{\eta A_a} = 1.21 P_a^{0.88}$$

$$\frac{A_{re}/n}{R_p \sigma_p} = 2.00 P_a^{0.08}$$

where $P_a = p_a/\left[\left(\eta R_p \sigma_p\right) E^*\left(\sigma_p/R_p\right)^{1/2}\right]$.

Now, a relationship between the average air-gap amount and the interplanar separation, *d*, will be proposed. So by finding the air-gap amount from experimental data and analytical results for dielectric constant of the material, the interplanar separation, *d*, real pressure, $p_r$, real area of contact, $A_{re}$, number of contact spots, n, and mean asperity real area of contact, $A_{re}/n$, can be found.

The air-gap area, $A_{air}$, can be found by the following formula,

$$A_{air} = Lh - \int_0^L z(x)\, dx + \sum_{i=1}^{n} A_i$$

where *z(x)*, is the surface profile, *n* is the number of asperities in contact with smooth surface and $A_i$ is pressed area of the *i*-th asperity (Fig. 7A).

So the average air gap amount, $h_{air}$, is

$$h_{air} = \frac{A_{air}}{L} = h - \frac{1}{L}\int_0^L z\, dx + \frac{1}{L}\sum_{i=1}^{n} A_i$$

$$h_{air} = h - m + \frac{1}{L}\sum_{i=1}^{n} A_i$$

where *m*, is mean value of the profile.

As it is shown in Fig. 7B, the pressed area of the *i*-th asperity is

$$A_i = R^2 \arcsin\left(\frac{a_i}{2R}\right) - \frac{a_i}{2}\left(R - \delta_i\right)$$

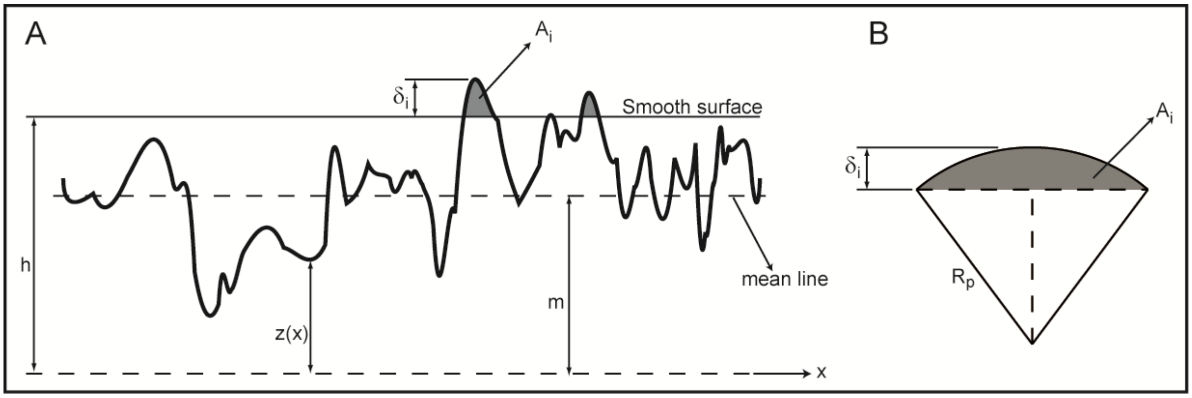


**Fig. 7 – A) Contact of electrode and rough surface and mean reference line of it B) Pressed area of *i*th asperity**

Now, if we consider that $h=d$; i.e. the x-axis is located at reference plane of the mean of the peak height distribution; $\delta_i$ and $a_i$ will be

$$\delta_i = z_p - d$$

$$a_i = \sqrt{R\delta_i} = \left[R\left(z_p - d\right)\right]^{1/2}$$

So,

$$A_i = R^2 \arcsin\left(\left(\frac{z_p - d}{4R}\right)^{1/2}\right) - \left(R\left(z_p - d\right)\right)^{1/2}\left(R + d - z_p\right)$$

and then the average air-gap amount is

$$h_{air} = d - m + \frac{N}{L}\int_d^\infty A_i\, p\left(z_p\right) dz_p$$

so by considering a Gaussian distribution of peak heights

$$h_{air} = d - m + \left[\frac{1}{\sigma_p (2\pi)^{1/2}}\right]\frac{N}{L}\int_d^\infty \left(R^2 \arcsin\left(\left(\frac{z_p - d}{4R}\right)^{1/2}\right) - \left(R\left(z_p - d\right)\right)^{1/2}\left(R + d - z_p\right)\right)\exp\left(\frac{-z_p^2}{2\sigma_p^2}\right) dz_p$$

If we non-dimensionalize the above equation, it will be

$$\frac{h_{air}}{\sigma_p} = D - \frac{m}{\sigma_p} + \left[\frac{\sigma_p\, R^{*3}}{(2\pi)^{1/2}}\right]\frac{N}{L}\int_{D'}^\infty \left(\arcsin\left(\left(\frac{t - D'}{4}\right)^{1/2}\right) - \left((t - D')\right)^{1/2}(1 + D' - t)\right)\exp\left(\frac{-R^{*2}t^2}{2}\right) dt$$

where $R^*=R/\sigma_p$, $D'=d/R$, and $t=z_p/R$.

Now if we consider that the mean line of the structure is the same as the mean line of the peak distribution (d=m) and considering $R^*=1$, we can find $H_{air} = \frac{h_{air}\,(2\pi)^{1/2}\mathrm{L}}{\mathrm{N}\,\sigma_p{}^2}$ vs. $D$ which is shown in Fig. 8. By having $D$, we can find the other topological property of the structure such as $p_a$, $p_r$, $A_{re}$, $n$, and $A_{re}/n$.

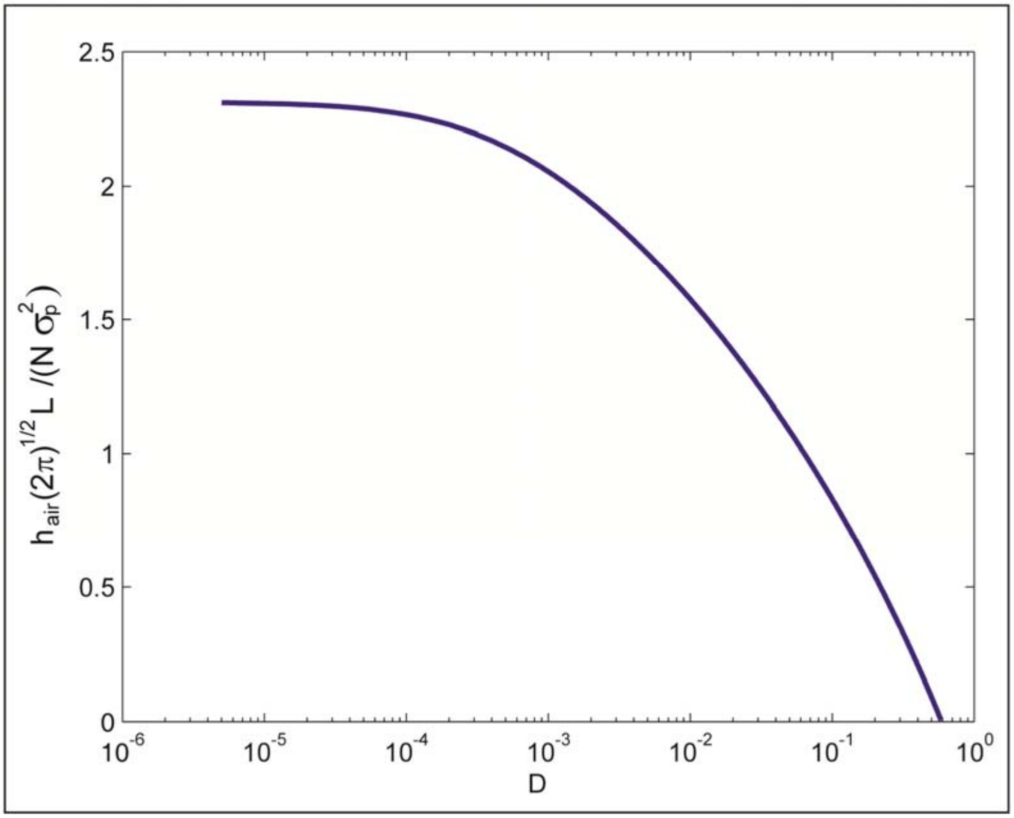


**Fig. 8 – non-dimensional $h_{air}$ vs. non-dimensional $d$ for $R^*=1$**

## 5. Conclusion

If we have smaller electrodes, the resolution of the method will increase significantly. The dimension of our electrode is about 5mm. Even with this big electrode, we measured the air gaps in order of 10 µm. By measuring dielectric constant of a material, we can measure the air-gap and then find the other topological property of the structure.

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