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FOCUSING ON PARTICLES, CONTACT ANGLE AND SURFACE THERMODYNAMICS

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EDITORIAL COMMENTS

By way of leading up to the **TENTH INTERNATIONAL SYMPOSIUM ON PARTICLES ON SURFACES: DETECTION, ADHESION AND REMOVAL**, to be held in Toronto Canada, June 19-21, 2006 we thought it would be apropos to comment on a number of aspects of particle geometry as it relates to particle adhesion to surfaces as this is clearly a topic of interest to those who would like to remove particles from a surface and, in a reciprocal manner, to those who would like particles to adhere also. This leads directly to the concept of fractals which was spearheaded by Benoit Mandelbrot in the mid 1970's.¹ Aside from nanotechnology, it is quite likely that no other subject has received quite as much attention from the academic community and is currently a frontier research topic in many institutions. Our treatment will be quite down to earth and deal directly with the problem of particle shape and only exhume more abstruse issues such as Hausdorff dimension,..etc as absolutely required.

In addition, since the **FIFTH INTERNATIONAL SYMPOSIUM ON CONTACT ANGLE, WETTABILITY AND ADHESION** directly follows the particle symposium, and in fact overlaps with it at midweek, we also touch upon a topic relating to the surface free energy of solids. This is an enigmatic conundrum related to the Gibbs Thomson equation from crystallization theory. The Gibbs Thomson formula is used by the crystallization community to estimate the surface free energy of a forming crystal. A number of theoretical and experimental arguments have been put forward to support this approach. The problem is that the numbers that come out are orders of magnitude different from what more conventional methods like contact angle measurements predict! Now if we were only talking about a factor of two or something then one could easily explain away the discrepancy as being due to any of a number of gremlins that plague surface measurements, but two orders of magnitude is too far over the top to explain away.

We will get on to the Gibbs Thomson paradox after dealing with the particle shape problem. Right now Dr. Mittal and I would like to extend our cordial invitation to all the readers of the newsletter to join us in Toronto this June where these problems and many other related ones can be discussed in a scholarly manner and in a most

¹ "Fractals Form, Chance and Dimension", Benoit Mandelbrot (W. H. Freeman and Company, 1977).

congenial environment. Full details of the symposia including the Final programs are at the end of this newsletter.

PARTICLE SURFACE GEOMETRY AS IT RELATES TO PARTICLE ADHESION

It is eminently clear that the adhesion of a particle to a given surface will depend in a critical way on both the surface roughness of the particle and that of the surface. An elementary discussion of this problem is given in the text by Kendall.² The basic point is that any given particle, under dry conditions, adheres to a surface through some area of intimate contact. The elementary treatments of the problem start by considering spherical particles on perfectly flat surfaces which give rise to nice closed formulae for the force of adhesion. For example, in the case of two spherical particles in close contact the attractive force can be closely estimated by Bradley's rule:

$$F = \frac{-\pi WD}{2} \quad (1)$$

Where:

W = Work of adhesion between particles
D = Particle diameter

Formulae like Eq.(1) tend to remind me of the old joke that was kicking around way back when I was still an undergraduate about the theoretical physicist's tendency to greatly oversimplify complex problems. A farmer comes to a well known and highly regarded physicist/philosopher and tells him that his cow is ill and not giving milk and can he recommend a solution to the problem. The physicist tells him to come back the next day while he cogitates upon the problem. The farmer returns and the physicist begins his lecture "Consider a spherical cow...". When dealing with the types of particle contamination one has to deal with in real life situations Eq.(1) is roughly equivalent to the spherical cow approximation

² "Molecular Adhesion and its Applications" Kevin Kendall (Kluwer Academic/Plenum Publishers, New York, 2001). For those interested we have reviewed this volume in Vol2No1 Spring-Summer 2005 of the newsletter which is available in the newsletter archive online at (www.mstconf.com/Newsletters.htm).

though it does have the saving grace of being accurate for true spherical particles in a certain size range. What we want to explore here is the next approximation to Eq.(1) which will more accurately model the rough and highly variegated particles that we commonly find contaminating the surfaces we want to clean. In order to do this we need to move up the ladder of geometric complexity from simple Euclidian entities like spheres to what have become know as fractal shapes that more closely resemble the surfaces we find nearly everywhere in nature. Before continuing, however, it will be helpful to give a brief and hopefully understandable overview of the mathematical concept of a fractal surface.

Fractals for Dummies

If you grew up in the late 1950's and early 1960's as I did you learned in school about all the nice geometric entities first treated by Euclid several millennia ago. Lines were straight and flat and solid objects had nice smooth surfaces. As you progressed to study the calculus you learned that the term "smooth" implied that the derivatives of the function describing the surface in question were all continuous and existed to all orders. True at that time the mathematicians already knew of outlaw functions that were continuous everywhere but had no derivatives of any order and were therefore incredibly rough, but those desperados were safely locked away and treated as rare aberrations which only the sadists would associate with. The functions one was typically exposed to belonged to a class labeled as C^∞ which essentially meant having continuous derivatives of all orders. All of the polynomials and the trigonometric functions were typical examples. For our purposes the most relevant property of a C^∞ function is that no matter how tortuous it might appear, if you magnify any particular segment to a high enough resolution, it will ultimately look like a straight line as shown in figure (1).

Examining figure 1 we see that as we blow up a particular region going from (a) to (d) we see that the curve progressively loses more and more of its detail till finally at (d) it looks like a straight line which will not change on further magnification. this property underlies the well known Taylor expansion formula which allows one to expand a smooth function $f(x)$ about any particular point x_0 in a power series as follows:

$$f(x) = f(x_0) + \frac{df}{dx}\bigg|_{x_0}(x-x_0) + \frac{1}{2} \frac{d^2f}{dx^2}\bigg|_{x_0}(x-x_0)^2 + \dots \quad (2)$$

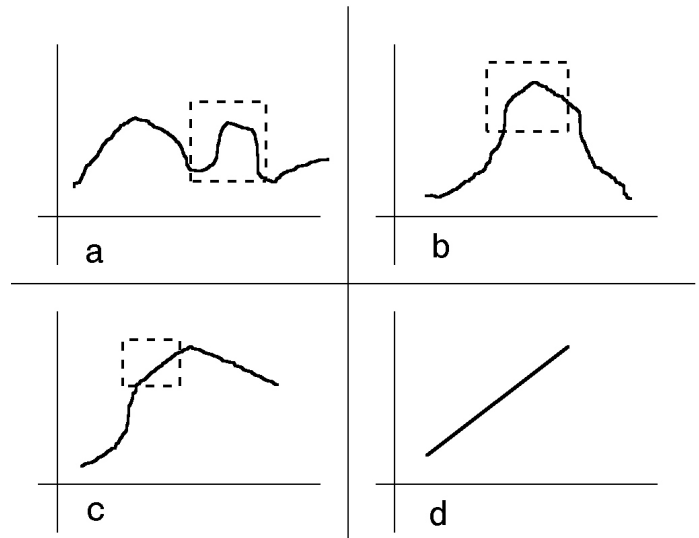


Figure 1 C^∞ function magnified several times till in a small enough region it appears to be a straight line. This property holds for every subregion of the function and is the basis for the well known Taylor expansion formula.

The Taylor formula clearly assumes that the first order approximation at x_0 is a straight line followed by quadratic and higher order terms. Thus all is well with the C^∞ functions in that we can approximate them at any point to any desired degree of accuracy using polynomial expansions such as the Taylor formula.

The C^∞ functions have served as reliable workhorses of science and technology ever since the days of Newton and Leibnitz who first brought them to the world stage as the foundational concept of the calculus. However, another class of functions were steadily gathering more and more attention. In particular, the pioneering work of Jean Perrin on Brownian motion and that of Lewis Fry Richardson on the measurement of coastlines began to poke holes in the theory of smooth functions by providing examples of physical processes from nature that defied all attempts at resolution via the machinery of the calculus. With Brownian motion, for instance, you had a dynamical behavior so irregular that the common assumption of continuous first and second derivatives no longer held up. The Brownian particles clearly were not behaving like cannon balls which follow a smooth near parabolic trajectory. Rather they jumped around so erratically that it was questionable whether any kind of smooth function could be found which would reliably represent the velocity of the particle much less its acceleration. If this was not bad enough, Richardson's work on measuring coastlines was bringing to light the fact that the

result you get depends on the length of your measuring stick. The shorter the measuring stick the longer the coastline becomes due to the fact that as one starts to measure distances at finer and finer scales one winds up taking a much larger number of smaller measurements due to the high degree of irregularity of any given coastline. We can get a clearer idea of what is happening by looking at one of the classic fractal entities known as the Koch curve. The recipe for generating a Koch curve is quite simple even though it leads to a rather astonishing entity as illustrated in figure (2). In building the Koch curve one starts in frame (a) of figure (2) with a simple straight line of unit length. What could be simpler than that? The basic algorithm is illustrated in frame (b) whereby one divides the initial line into three equal segments and erects upon the middle segment an equilateral triangle of side $1/3$. In frame (c) one simply repeats the process for each straight line segment in frame (b). Frame (d) repeats the process again now acting on the line segments in frame (c). The mathematical Koch curve is arrived at after one has performed this process an infinite number of times, a task which we will not attempt here. However, figure (3) shows what the curve starts to look like after many iterations. The curve in figure (3) looks harmless enough from a distance but nonetheless has some amazing properties. First it is clearly continuous everywhere, but equally clear is the fact that it has no derivatives anywhere. It is one of the rogue functions mentioned earlier. In particular, Taylor's formula given in Eq.(2) is wholly useless in dealing with such a curve. In fact, if we go through the magnification exercise outlined in figure (1) for any segment of the Koch curve we discover the amazing property that no matter what level of magnification we use the resulting curve looks exactly like what we started with! That is each magnified frame, after a suitable rotation, would look exactly the same as every other one. This property is called **self similarity**. One does not find it in any of the C^∞ curves.

Another property one might like to enquire into is the length of the curve. Just how long is this thing? For our mild mannered curve in figure (1) we can easily imagine a simple procedure whereby if we take a piece of flexible string and lay it out along the curve from end to end and then lift it off, straighten it out and lay it along a rule we would be able to read off its length. It is not at all clear that this stratagem would work for the curve in figure (3). It works nicely for figure (1) due to the inherent smoothness of the curve but we clearly will have trouble with figure (3) due to the inherent roughness at every scale. In fact the length of any segment of the Koch curve is

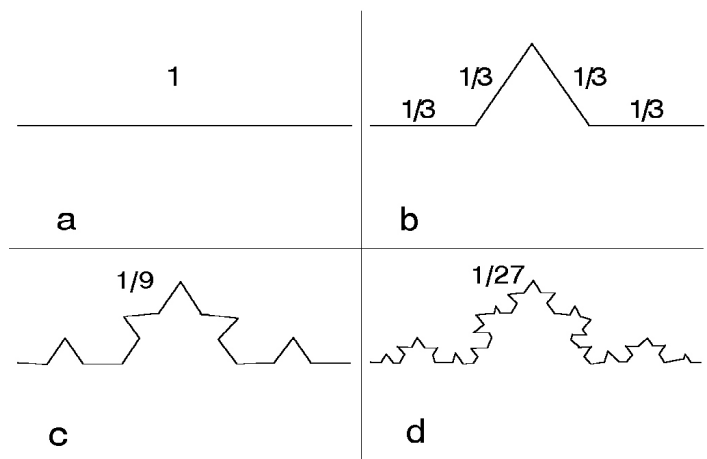


Figure 2: Progressive stages of building a Koch curve.

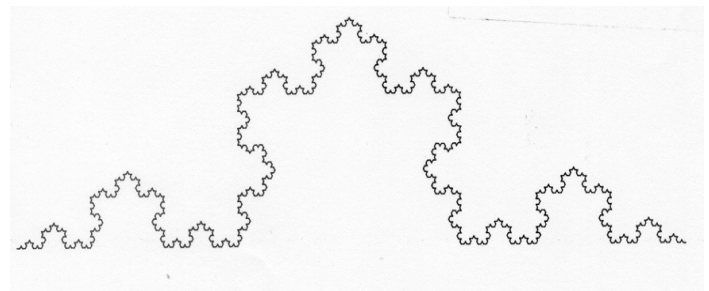


Figure 3: Approximate limiting shape of Koch curve in the limit of an infinite number of iterations.

effectively infinite. This beast simply does not have a well defined one dimensional length. It is as if it existed in some higher dimension which is in fact the case. But what dimension are we talking about? It is clearly not 2 dimensional and not one dimensional. It is like something out of the twilight zone. We seem to perceive it yet we really don't. It in fact exists in a fractional dimensional space which leads us to our next topic.

Fractal Dimension

In the case of our old friends the Euclidian shapes such as lines, planes and spheres, we had a clear idea that each of the entities existed in one of what are called the topological dimensions 1, 2 and 3. We clearly cannot shoehorn the curve in figure(3) into any of those boxes so we have to think up something new. We can sneak up on this problem by studying figure (2) in more detail. Say someone asked us to measure the lengths of the curves in this figure. The line in figure (2a) is the trivial case where the length $L=1$. Figure (2b) requires a little more work. Here we simply take a rule of length $1/3$ and we see that we have to lay it out 4 times to cover the curve giving a total

length of 4/3. Following the same procedure it is easy to see that for figure (2c) we need a rule of length (1/9) and have to lay it out 16 times. The general procedure quickly becomes clear and we can summarize the results in a simple table.

Table 1: Successive Approximations to Length of Koch Curve from Figure (2)

FRAME NUMBER	RULE LENGTH	NUMBER OF SIDES	TOTAL LENGTH L
0	1	1	1
1	1/3	4	4/3
2	1/9	16	16/9
3	1/27	64	64/27
N	$(1/3)^N$	4^N	$4^N(1/3)^N = 4^N/3^N = (4/3)^N$

Table 1 summarizes the results given in figure (2) and in the last row indicates the general formula for the side length, the number of sides and the total length one would have at the Nth frame if one cared to carry on the process to that extreme. Note that the total length $L(N) = (4/3)^N$ and grows without bound as N increases. This is very inconvenient since one would like to work with finite entities. However, somewhere along the line someone had the idea that if we take the logarithm of the numerator and denominator of the length formula we get a finite number that can serve as a measure of the "dimension" of the object in question. Thus we have:

$$D = \frac{\ln(4)^N}{\ln(3)^N} = \frac{\ln 4}{\ln 3} \approx 1.2618 \quad (3)$$

Eq.(3) has the nice property that it is independent of N the frame number and is defined solely by two numbers which are intrinsic to the geometric shape being generated. We may define these numbers as being the fragmentation ratio r_f which is 1/3 for this case and the fragmentation number N_f which is 4 for the Koch curve. Thus as we build the curve going from frame to frame in figure (1) we segment each straight section in the current frame into 4 pieces each 1/3 the size of the original segment. Thus we might conjecture a more general form of Eq.(3) as:

$$D = \frac{\ln(N_f)}{\ln\left(\frac{1}{r_f}\right)} \quad (4)$$

We can in fact easily demonstrate that Eq.(4)

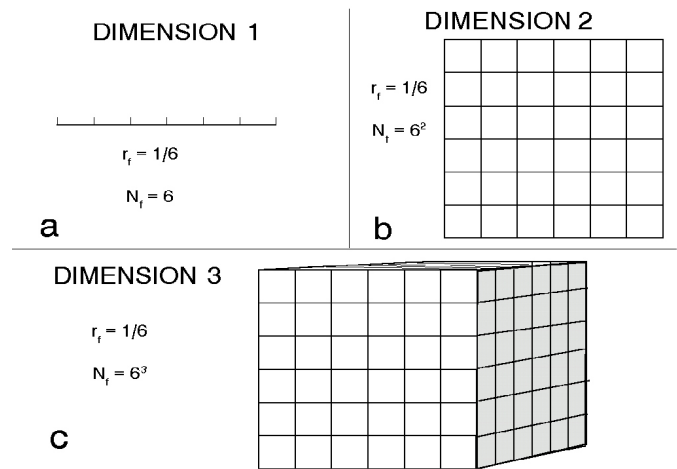


Figure 4 Elementary example of 3 Euclidian objects illustrating the fragmentation ratio r_f and the fragmentation number N_f for the case where $r_f = 1/6$. The fragmentation number N_f is the number of line segments, squares or cubes of side r_f required to cover the respective objects completely.

reduces to the topological definition of dimension for standard Euclidian objects. Figure (4) gives a simple example of 3 Euclidian objects where r_f and N_f are defined for the case where r_f is set to 1/6 for illustrative purposes. In figure (4a) for example, we measure the line of unit length by taking a rule of length $r_f = 1/6$ and finding that it takes 6 such segments to cover the line. Figure (4b) generalizes the process to the unit square. Again keeping the rule size at 1/6 we find that we need $N_f = 6^2 = 36$ squares of side 1/6 to completely cover the square. Figure (4c) illustrates the obvious generalization to the unit cube. Table 2 summarizes the results.

Table 2: Summary of Topological and Hausdorf Dimension of the Euclidian Objects in Figure (4) for an Arbitrarily Small Rule Length $r_f = 1/N_f$.

Object	Topological Dimension	r_f	N_f	Hausdorf Dimension $D = \ln(N_f)/\ln(1/r_f)$
UNIT LINE	1	1/6	6	1
UNIT SQUARE	2	1/6	6^2	2
UNIT CUBE	3	1/6	6^3	3

Comparing columns 3 and 5 clearly illustrates that Eq.(4) for the fractal dimension reduces to the Euclidian or topological dimension for these simple objects. Equation (4) is often referred to as the Hausdorf dimension which provides a useful generalization of the term "dimension" which can

be applied to both strange objects such as the Koch curve and to the simple Euclidian objects we are all familiar with. It should be noted that Eq.(4) is by no means the most general definition of dimension that one could come up with and neither is it unique in that a number of other schemes can be derived that achieve similar results. The main virtue of Eq.(4) is that it is one of the simplest formulas available for getting at the highly abstract notion of the dimension of fractal entities.

Up to this point we have been dealing with what are called geometric fractals in that they are defined by relatively simple geometric rules and they exhibit an exact property of self similarity. In fact the Koch curve in figure (3) is a rather tame object by fractal standards which is its main virtue for illustrative purposes. One can further generalize the fractal concept by going to yet more complex entities know as statistical fractals. Anyone familiar with statistical process control charts for the manufacture of an item such as ball bearings knows that when measured to high precision the ball diameters show random fluctuations about some mean value. Thus although the mean diameter of the bearings may be closely controlled the precise diameters of some random selection of bearings will jump around in a random fashion. Typically, however, for a well controlled manufacturing process the distribution of diameters about the mean will be defined by some well characterized probability distribution function such as the Gaussian distribution which is determined by the mean diameter value and its standard deviation parameter. All is considered well if the standard deviation parameter lies within some suitably determined bounds. Thus the key property of the statistical process control chart is the fact that it can be precisely defined in a statistical sense by a well known probability distribution. Consider now a curve somewhat analogous to the Koch curve in figure (3) except that instead of the regular triangular shapes which define the Koch curve, every segment now looks like a piece of a statistical process control chart at every level of magnification. For the Koch curve the precise geometry of the curve is reproduced for every segment at every level of magnification. For the statistical fractal, however, what is invariant is the statistical behavior of the curve. Thus no two segments of the curve will look exactly the same but the random behavior of the fluctuations of the curve will follow the same probability distribution for every segment at every level of magnification. At this stage one starts to get dizzy trying to imagine such an object, however, the Brownian motion of a particle floating in the air is closely approximated by just such an

arabesque entity. Indeed the shape of particles contaminating surfaces are also candidates for the menagerie of statistical fractals.

Power Law Behavior

Before closing this elementary tutorial, it is important to mention one more property that characterizes fractal behavior and that is the power law behavior of the number of segments N_s required to cover a given section of a fractal curve in terms of the rule length r_f . Richardson's measurements on the length of coastlines and other studies suggest that the data is best fit by a formula of the form³:

$$N_s = Cr^{-D}$$

WHERE

$$N_s = \text{Number of segments} = N_f^N \tag{5}$$

$$N_f = \text{fragmentation number}$$

$$r = \text{rule length} = r_f^N \quad (r_f = \text{fragmentation ratio})$$

$$N = \text{Frame number from fig.(1)}$$

We can get at the exponent D by taking the logarithm of both sides and solving as follows:

$$\begin{aligned} D &= -\frac{\ln N_s - \ln C}{\ln r} \\ &= -\frac{N \ln N_f - \ln C}{N \ln r_f} \tag{6} \\ &= -\frac{\ln N_f}{\ln r_f} = \frac{\ln N_f}{\ln \left(\frac{1}{r_f} \right)} \text{ as } N \text{ tends to } \infty \end{aligned}$$

Thus the exponent in the power law relation given by Eq.(5) turns out to be none other than the fractal dimension defined in Eq.(4).

To summarize, what we learn up to this point is that the simple Euclidian objects we all learned about in our younger days barely begin to cover the universe of geometrical objects which can in fact exist both as mathematical entities and to a good approximation as real items of everyday experience. What is most relevant, however, from the point of view of studying particle behavior is

³ See for instance Mandelbrot Chapter 2 from footnote 1.

that fractal surfaces offer a more relevant tool for estimating the surface properties of particulate matter and this affects not only particle appearance but also particle interactions and in particular particle adhesion to surfaces. Unfortunately what we have covered can only serve as a brief introduction to fractals and their behavior. The reader interested in delving further into this topic is encouraged to look into Prof. Mandelbrot's second volume⁴ on this topic which covers everything from the shapes of clouds to the behavior of financial markets. Those with a more mathematical bent will enjoy the excellent volume by Michael Barnsley.⁵ Be forewarned though that this is not your elementary coffee table browse at leisure volume. Barnsley will bring you face to face with the calculus of metric spaces and Hausdorff measures and you should feel comfortable with interpreting the panoply of mathematical symbols such as $\{\epsilon \subset \supset \otimes \wedge \forall \exists\}$. Having given fair warning, however, I can nonetheless recommend this volume as one of the more readable and in fact captivating treatments of this topic. Finally for those interested in physical applications will find many examples covered in the edited volume by Pietronero and Tosatti.⁶

Fractal Surfaces and Particle Adhesion

The essence of this little essay is to assert that the surface properties of the common types of particle contamination one is likely to confront in day to day applications are closer to some sort of fractal than they are to smooth spheres. In the microelectronics industry, for example, one of the most common substrate materials for packaging high end microchips, such as microprocessors, is sintered alumina. Before sintering, the alumina is a fine powder of Al_2O_3 particles mixed to some extent with glass particles commonly referred to as frit. Without getting into the details of the precise formulation it is easy to see that the alumina particles form a dandy source of hard irregular particles that can easily get spread around unless special precautions are taken. The typical alumina

⁴ "The Fractal Geometry of Nature", Benoit B. Mandelbrot (Freeman and Company, New York, 1977)

⁵ "Fractals Everywhere", Michael Barnsley (Academic Press, Inc., Boston, 1988)

⁶ "Fractals in Physics" Ed. L. Pietronero and E. Tosatti (North Holland Physics Publishing, Amsterdam, 1985)

particle is formed by a grinding process that yields a fairly compact shape with a highly irregular surface. Thus this type of particle is likely to be better characterized by a fractal shape than any of the Euclidian solids. The first question that comes to mind is how does this affect the adhesion of such a particle to a given surface? A clue comes already from the work of Gane et. al.⁷ who studied the force required to separate cylinders of hard materials such as sapphire and titanium carbide and found that the results were some 2 to 3 orders of magnitude smaller than expected. This result they attributed to the uncontrollable surface roughness of their samples. We can begin to get a handle on this problem by considering the simple model depicted in figure (5).

In this figure we see a schematic profile of a hypothetical particle with a rough surface. We gain an estimate of the surface roughness by containing the apparent rough surface region within two concentric geometric spheres. The inner sphere of radius R_1 is the largest sphere that fits entirely within the solid core of the particle. The outer sphere of radius R_2 is the smallest sphere that contains the entire particle. We see that the shell region between the surfaces of the spheres contains the irregular topography of the particle and it is this region which will define the surface behavior of the particle with regard to interactions with other surfaces or other particles.

One important question we might ask is what is the density of the material in this surface shell region? This will simply be the mass within the region divided by its volume. Calculating the volume is the easy part so we do that first. From elementary solid geometry we know that the volume of any sphere is given by $(4/3)\pi R^3$ so the volume within the shell region is simply given by:

$$\Delta V = \frac{4}{3}\pi(R_2^3 - R_1^3) \quad (7)$$

We now assume that the thickness δ of the shell region is small compared to the particle radius, i.e.

$$\delta = R_2 - R_1 \ll R_1 \quad (8)$$

From Eq.(8) we can express R_2 as $R_1 + \delta$ and substitute this into Eq(7). By expanding the term $(R_1 + \delta)^3$ as a cubic polynomial and saving only terms linear in the small quantity δ we greatly

⁷ N. Gane, P. F. Pfaelzer and D. Tabor, Proc. R. Soc. London, Ser. A 340, 495 (1974).

simplify Eq.(7) to:

$$\Delta V = 4\pi R_1^2 \delta = 3 \left(\frac{4}{3} \pi R_1^3 \right) \frac{\delta}{R_1} = 3V_1 \frac{\delta}{R_1} \quad (9)$$

Now if we know that the density of the particle material is ρ and if we assume the particle to be perfectly smooth, i.e. a perfect Euclidian sphere, then we would calculate the mass Δm within the shell region as:

$$\Delta m = \rho \Delta V = 3\rho V_1 \frac{\delta}{R_1} \quad (10)$$

We know, however, that Eq.(10) cannot be correct for our "real" particle since we are aware that its surface is very rough and thus highly porous. Furthermore, from our discussion of fractal behavior above we strongly suspect that Δm will follow some kind of power law behavior. Thus we conjecture that the correct formula for the mass in the surface shell region will look more like the following:

$$\Delta m = 3\rho V_1 \left(\frac{\delta}{R_1} \right)^\alpha \quad (11)$$

The power law exponent α will be some number greater than 1 which, since $(\delta/R_1) \ll 1$, will make the mass predicted by Eq.(11) significantly less than that given by Eq.(10) which is what we expect. We can now combine Eqs.(9) and (11) to give an expression for the density of the surface shell layer:

$$\rho_s = \frac{\Delta m}{\Delta V} = \rho \left(\frac{\delta}{R_1} \right)^{\alpha-1} \quad (12)$$

ρ = Particle density
 ρ_s = Density of shell layer

Eq.(12) can be further solved for the surface layer thickness δ :

$$\delta = R_1 \left(\frac{\rho_s}{\rho} \right)^{\frac{1}{\alpha-1}} \quad (13)$$

The quantity δ is clearly important from the point of view of particle adhesion since it in effect limits how close the particle can come to a smooth surface. In fact for a spherical particle of nominal radius R the force of attraction to a given surface

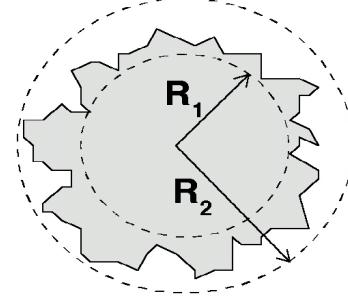


Figure 5 Schematic of a particle with a rough surface. The sphere of radius R_1 is the largest smooth sphere which fits entirely within the particle. The concentric sphere of radius R_2 is the smallest which contains the entire particle.

can be represented as a Hamaker style relation of the form:

$$F_s(z) = \frac{HR}{6z^2} \quad (\text{Smooth sphere})$$

$$F_s = \text{Attractive force (N)} \quad (14)$$

R = Particle radius (m)

H = Hamaker constant (J)

z = Separation distance (m)

In the case of smooth surfaces the minimum separation distance is some length z_0 which is relatively constant for most smooth surfaces and has been estimated as being roughly 1.6×10^{-10} m. For our hypothetical "real world" particle with a rough surface we need to replace z in Eq.(14) with δ as given by Eq.(13) to yield:

$$F_r(z) = \frac{H}{6R \left(\frac{\rho_s}{\rho} \right)^{\frac{2}{\alpha-1}}} \quad (\text{Rough sphere})$$

$$F_r = \text{Attractive force (N)} \quad (15)$$

R = Particle radius (m)

H = Hamaker constant (J)

ρ = Particle density (kg/m^3)

ρ_s = Surface density (kg/m^3)

We can get some idea of the effect of the surface roughness on the attractive force by taking the ratio of Eq.(15) to (14) as follows:

$$\frac{F_r(z)}{F_s(z)} = \left(\frac{z_0}{R} \right)^2 \left(\frac{\rho_s}{\rho} \right)^{\frac{2}{1-\alpha}} \quad (16)$$

All quantities in Eq.(16) are as defined in Eqs.(14) and (15) and z_0 is the minimum separation distance for smooth surfaces as discussed above. As with all power law relations, Eq.(16) is more easily dealt with if we take the logarithm of both sides. In this case we use logs to the base 10:

$$\log \frac{F_r(z)}{F_s(z)} = 2 \log \left(\frac{z_0}{R} \right) + \frac{2}{1-\alpha} \log \left(\frac{\rho_s}{\rho} \right) \quad (17)$$

To get some idea of how big an effect the surface roughness can have we can insert some representative numbers into Eq.(17) and see what comes out. For instance, assume we have a 0.1 micron particle and we want to see what happens to the attractive force when the particle surface is rough as modeled by our simple fractal equations. Taking z_0 as roughly 10^{-10} meters then the term z_0/R comes to 10^{-3} which implies $\log(z_0/R)=-3$. Assume also that the density of the surface layer is 1/10 the bulk particle density and further take α as 1.5. Inserting these numbers into the right hand side of Eq(17) gives $\log (F_r/F_s) = -2$. Thus the attractive force on the rough particle is two orders of magnitude smaller than that on the smooth one which is consistent with the findings of Gane et. al. mentioned above in reference 7.

Eq.(17) is indeed a dandy little formula for estimating the effect of surface roughness on particle adhesion and also for learning something about the fractal geometry of particle surfaces. For example, if one had data from an atomic force microscope experiment on the attractive force vs particle size for geometrically similar particles of two different densities, then Eq(17) suggests that plotting the log of the ratio of the measured force to that expected for smooth spheres versus the log of z_0/R should yield a straight line of slope 2 and intercept $[2/(1-\alpha)]\log(\rho_s/\rho)$. With data on particles of two different densities one should be able to back out estimates of the parameters α and ρ_s from the measured intercept data. However, as with just about everything else in the field of fine particle analysis, Eq.(17) comes with a host of disclaimers that must be taken into account. Rimai and Quesnel⁸ have discussed a number of potential problems in some detail so we need only mention a few here. In particular one expects to run into problems with particles of softer materials such as pure metals and polymers where elasticity effects must be taken into account. We can expect

soft particles to squash the surface layer and thus radically change the surface geometry. Such elasticity effects are at the basis of the well known Johnson, Kendall and Roberts (JKR) formalism of particle adhesion. Thus we expect Eq.(17) to work best on the refractory materials such as alumina discussed above. Problems don't end with the question of particle elasticity, however. It is clear that contamination by all forms of liquids will greatly affect the results since they can wet the particle substrate interface and act as a sort of low viscosity glue which will have a major effect on the net attractive force. Also lurking in the corner are electrostatic effects which can arise due to trapped surface charges again modifying the attractive force. Having said all this however, Eq.(17) does have the redeeming feature of giving us a better picture of particle surface geometry. At least we will no longer be considering "spherical cows".

THE GIBBS-THOMSON EQUATION MEETS CONTACT ANGLE DATA

Introduction

The history of science and technology suggests that many of the most important advances are brought about by the resolution of some paradox or another which conventional wisdom cannot deal with. The classic case which comes to mind is the question of the stability of atomic matter. The prediction of classical mechanics and classical electrodynamics was absolutely clear and unequivocal. An electron could not orbit around a proton in any meaningful classical sense because it would be constantly changing its direction and thus accelerating which existing theory predicted would cause the electron to radiate away its energy and thus ultimately crash into the proton. Thus classical theory predicted that the hydrogen atom could not exist. It took the advent of quantum theory to resolve the dilemma. The science of surface thermodynamics has a similar if not quite so weighty conundrum of its own in the form of the so called Gibbs-Thomson equation.

The problem arises from what seems at first to be a fairly harmless question concerning the measurement of the solid liquid interfacial tension which is commonly labeled as γ_{sl} . It appears in the classic Young-Dupree equation along with its brethren the solid-vapor interfacial tension γ_{sv} and the liquid-vapor tension γ_{lv} as follows:

⁸ "Fundamentals of Particle Adhesion", Donald S. Rimai and David J. Quesnel (Global Press, 2001)

$$\gamma_{lv} \cos \theta = \gamma_{sv} - \gamma_{sl} \quad (18)$$

The angle θ is the well known contact angle that a drop of the liquid makes with the solid. Of all the quantities in Eq.(18) the contact angle and the surface tension γ_{lv} are the least controversial. The contact angle can be measured with precise instruments and the liquid-vapor surface tension can be evaluated independently by capillarity measurements. In fact rather extensive tables of γ_{lv} have been published for a wide range of liquids so it is no more controversial than the liquid density. The solid-vapor and solid-liquid surface tensions are another matter altogether. With these quantities controversy abounds and one is apt to find rather divergent numbers given for any particular material depending on the investigator and the measurement method used as we will see in what follows. The problem of extracting values of γ_{sl} and γ_{sv} from contact angle data have been covered in detail in the edited volume by Neumann and Spelt⁹ who use the "equation of state" approach and by van Oss who uses the Lifshitz van der Waals/Acid-Base (LW/AB)¹⁰ method. Further discussion of this problem has been given in a previous issue of the Newsletter.¹¹ The problem is greatly complicated by the diverse nature of solid surfaces leading to divergent results between the different measurement methods. In consequence of this, alternate measurement measurements are sought out in order to try and bring about a consensus. An interesting idea but in this case using yet another measurement method only seems to expand the diversity of the results.

Enter the Gibbs-Thomson Relation

Drops sitting on solid surfaces are not the only situation in which one encounters solid-liquid interfaces. A crystal forming from the melt

⁹ "Applied Surface Thermodynamics", Ed. A. W. Neumann and Jan K. Spelt (Marcel Dekker, New York, 1996)

¹⁰ "Interfacial Forces in aqueous Media", Carel J. van Oss (Marcel Dekker, Inc., New York, 1994)

¹¹ MATERIALS SCIENCE AND TECHNOLOGY NEWSLETTER, Vol2No3-2005, Fall-Winter, 2005, available at the MST CONFERENCES website: (www.mstconf.com/Vol2No3-2005.pdf).

presents another physical system with a solid-liquid interface and the growing solid surface also possesses a surface tension describable by γ_{sl} . In this case the solid surface is assumed to be in quasi equilibrium with its own liquid phase and the obvious assumption is that γ_{sl} is the same quantity one would measure by placing a drop of the liquid on top of a block of the solid phase and performing the appropriate contact angle analysis? An eminently reasonable conjecture but when the actual measurements are performed the results do not pan out as expected.

Before opening pandora's box on the solid-liquid interfacial tension problem, a few words are in order concerning the Gibbs-Thomson relation. This equation in its various forms is one of the pillars of crystallization theory and a truly impressive literature has grown around it. An informative overview has been given by Makkonen^{12 13} who also analyzes the discrepancy which arises when trying to compare solid-liquid interfacial tension results based on this equation with those derived from contact angle measurements. The Gibbs-Thomson equation combines the Gibbs-Duhem relation with the Laplace equation. The Gibbs-Duhem part takes account of the heat of fusion of crystallization and the Laplace equation factors in the effect of surface strain energy caused by the curvature of the growing crystal front. Without going into further details the final result can be stated in following compact equation:

$$L \frac{\Delta T}{T_m} = -\gamma_{sl} \left(\frac{1}{r_1} + \frac{1}{r_2} \right) = -\gamma_{sl} K \quad (19)$$

Where:

L = Latent heat of fusion governing crystallization

$\Delta T = T - T_m$ = difference between liquid temperature and melting point temperature of solid phase T_m .

γ_{sl} = Solid liquid interfacial tension

K = $(1/r_1) + (1/r_2)$ = Mean local curvature defined in terms of the local principal radii of curvature $1/r_1$ and $1/r_2$.

The left hand side of Eq.(19) comes from the Gibbs-Duhem relation and essentially expresses

¹² "On the Methods to Determine Surface Energies", Lasse Makkonen, *Langmuir*, **16**, 7669 (2000).

¹³ "Gibbs-Thomson Equation and the Solid-Liquid Interface", Lasse Makkonen, *Langmuir*, **18**, 1445 (2002).

the amount of energy per unit volume given up by the liquid upon crystallization. The right hand side of Eq.(19) is the energy per unit volume taken up by the expanding crystal surface in the form of surface tension or, what comes to the same thing, surface energy. Eq.(19) apparently provides us with an additional means of determining the elusive solid-liquid surface tension γ_{sl} .

Gibbs-Thomson Confronts Contact Angle

Moy and Neumann¹⁴ have rounded up solid-liquid surface tension data on a number of materials in an attempt to compare the predictions of Eq.(19) with those of contact angle measurements and the results are not very promising. Solid-Liquid surface tensions are tabulated for 5 different materials. For each material as many as 5 different surface tension measurements are given of which three are derived from crystallization data using a Gibbs-Thompson type analysis and two are arrived at on the basis of contact angle measurements. The results presented by Moy and Neumann may be summarized as follows:

- ▶ Two sets of solid-liquid surface tension data are tabulated based on contact angle measurements. One set is derived from an equation of state analysis and the other from the Fowkes' equation which is essentially the precursor of the more modern (LW/AB) theory mentioned above.
- ▶ Three sets of solid-liquid surface tension data are tabulated based on Crystal nucleation data, crystal grain boundary analysis and the Skapski advancing crystal front method. All these approaches use the Gibbs-Thomson equation to estimate the solid-liquid surface tension.
- ▶ The comparison between the two different contact angle analyses is a mixed bag with good agreement being obtained for the two

normal alkanes listed (n-Dodecane and n-Hexadecane) and poor agreement for the more complex molecules Naphthalene and Biphenyl.

- ▶ Similarly, the agreement among the three sets of crystallization data based on the Gibbs-Thomson equation, while not too impressive, are at least within the same ballpark.
- ▶ The comparison between the contact angle analyses and the Gibbs-Thompson analyses, however, is truly abysmal. The discrepancy between these data sets ranges from one to two orders of magnitude across the board.

On the basis of these results the authors conclude that something must be inherently wrong with the Gibbs-Thomson approach. In contradistinction, Makkonen,^{12,13} on the basis of fairly cogent thermodynamic arguments, has argued quite the opposite, that the problem in fact lies with the contact angle work. A moment's thought, however, suggests that neither conclusion is correct and that each method has a certain level of validity within some restricted domain. It seems fairly apparent that the problem lies with the extreme complexity of solid surfaces and that the different measurement methods are not looking at the same thing though each method is quite likely giving a fair account of what it sees. In particular, each of the measurement methods comes with its own set of problems that tend to color the final result. For instance, Moy and Neumann point out that the Gibbs-Thomson analysis based on crystal nucleation data is suspect due to the extremely small size of the crystallites involved (typically crystals on the nanometer scale involving a few hundred molecules). In addition, nucleation studies can involve large degrees of super cooling, i.e. ΔT in Eq.(19) is large which implies that equilibrium arguments may not apply in this regime. Equally cogent counter arguments can be leveled against the contact angle approach. In particular there was an order of magnitude discrepancy between the two contact angle analyses for naphthalene and biphenyl mentioned above, so all is not peace and harmony within the contact angle world. The case of the ice/water interface summarizes the problem neatly.

¹⁴ "Theoretical Approaches for Estimating Solid-Liquid Interfacial Tensions", E. Moy and A. W. Neumann, in *Applied Surface Thermodynamics*, A. W. Neumann and Jan K. Spelt Eds. (Marcel Dekker, Inc., New York, 1996).

Table 3: Estimates of the Water/Ice Interfacial Energy γ_{sl} (mJ/m²) Derived from Different Experimental Analyses

Crystal nucleation*	Skapsi advancing front*	Grain boundary*	Equation of State*	(LW/AB) component wise analysis [#]	(LW/AB) classic Young Dupree analysis [#]
26.1	44	29	0.38	0.04	1.5
*Data from reference 14; # Data from reference 15					

Table 3 presents 6 different estimates for γ_{sl} for the water/ice interface. The data in the first 4 columns comes from the paper of Moy and Neumann.¹⁴ The data in the last two columns comes from the work on the water/ice system by van Oss et. al.¹⁵ One always hates to use water as an example since it is one of the most anomalous liquids known and will nearly always give unusual results. The data in table 3 certainly follow through on this expectation. What is clear from this table is that though the results vary considerably within each method there is a distinct phase separation between the first three columns and the last three. The Gibbs-Thomson data average close to 33 mJ/m² whereas the contact angle data average about 0.6 mJ/m². This is the basic mystery we are faced with and I think that we will find that, due to the complexity of the solid surfaces involved, the two separate methods simply are not looking at the same thing. One could go on to near encyclopedic lengths giving physical arguments as to why this discrepancy exists but time and space prohibit it. Rather, since the underlying theme of these essays is the joint issues which are of concern to both those interested in particle contamination and contact angle behavior we will advance an argument based on surface geometry which clearly enters this problem in a most fundamental way.

Fractal Surfaces and the Gibbs-Thomson Equation

Looking again at figure (5) we can clearly consider it to be some sort of elementary model of a growing crystal nucleus as opposed to being a contaminant particle. The common denominator is

¹⁵ "Surface Tension Parameters of Ice Obtained from Contact Angle Data and from Positive and Negative Particle Adhesion to Advancing Freezing Fronts", C. J. van Oss, R. F. Giese, R. Wentzek, J. Norris and E. M. Chuvilin, in *Contact Angle, Wettability and Adhesion: Festschrift in honor of Professor Robert J Good*, K. L. Mittal Ed. (VSP, Utrecht, the Netherlands, 1993)

of course the surface geometry. Arthur Adamson in fact has already proposed a modified equation for the contact angle on a fractal surface in his classic text on the physical chemistry of surfaces.¹⁶ We can propose a similar modification of the Gibbs-Thomson equation based on the same arguments that lead to Eq.(11) above. We first rewrite Eq.(19) in the following equivalent form:

$$L \frac{\Delta T}{T_m} = -\gamma_{sl} K = -\gamma_{sl} \frac{dA}{dV} \quad (20)$$

In this equation we simply replace the local surface curvature K with its definition in terms of the rate of change in surface area with volume. This is just straightforward geometry. By combining Eqs.(10) and (11) above we can estimate the change in volume for a fractal surface as:

$$\Delta V = 3V \left(\frac{\delta}{R} \right)^\alpha = 4\pi R^3 \left(\frac{\delta}{R} \right)^\alpha \quad (21)$$

Arguments very similar to those used in deriving Eqs.(10) and (11) can be employed to derive the change in surface area ΔA which accompanies the change in volume ΔV as follows:

$$\Delta A = 2A \left(\frac{\delta}{R} \right)^\beta = 8\pi R^2 \left(\frac{\delta}{R} \right)^\beta \quad (22)$$

All quantities in Eq.(22) are the same as in Eq.(21) except that we now have a new scaling exponent β taking the place of the old exponent α . We can take the ratio of Eqs.(22) to (21) to estimate the derivative dA/dV appearing in Eq.(20):

¹⁶ *Physical Chemistry of Surfaces; sixth edition*, Arthur W. Adamson and Alice P. Gast (John Wiley & Sons, New York, 1997). See in particular Chapter X, "The Solid-Liquid Interface - Contact Angle" p. 358.

$$\frac{dA}{dV} \approx \frac{\Delta A}{\Delta V} = \frac{1}{R} \left(\frac{\delta}{R} \right)^{\beta-\alpha} \quad (23)$$

Using the derivative dA/dV just derived in place of the local curvature K in Eq.(19) yields the following version of the Gibbs-Thomson equation modified for fractal surfaces:

$$\frac{\Delta T}{T_m} = -\frac{\gamma_{sl}}{L} \frac{1}{R} \left(\frac{\delta}{R} \right)^\epsilon \quad (24)$$

All parameters in Eq.(24) are as defined for Eq.(19) and the new scaling exponent ϵ is given by $\beta - \alpha$. We can easily solve Eq.(24) for the solid liquid surface tension γ_{sl} as follows:

$$\gamma_{sl} = -LR \left(\frac{R}{\delta} \right)^\epsilon \frac{\Delta T}{T_m} \quad (25)$$

Since the ratio R/δ in Eq.(25) is greater than 1 and the exponent ϵ is negative i.e. $\alpha > \beta$ the factor $(R/\delta)^\epsilon$ will be less than 1 and thus the predicted value of γ_{sl} will be significantly less than that yielded by the standard Gibbs-Thomson equation given by Eq.(19). Thus an analysis based on Eq.(25) could potentially bring the Gibbs-Thomson estimates of γ_{sl} into closer agreement with those from contact angle. However, we need to recognize that Eq.(25) is simply a hypothetical suggestion for reconciling the discrepancy between the Gibbs-Thomson results and the contact angle data for the solid-liquid surface tension measurements mentioned above. The usual caveats and disclaimers apply to this equation as many other possibilities exist which could give an alternative explanation. Nonetheless, Eq.(25) does have the advantage of being straightforward in concept as well as simple in form. The concept simply states that in order to get more accurate surface tension data for the solid liquid interfacial tension we need a more accurate model of the solid surface as this strongly affects the net interacting surface area. In particular, we argue that due to the complex nature of solid surfaces in general, the local microscopic geometry of a growing crystal surface can be significantly different from a surface prepared in a different manner such as cutting or polishing an existing block of the material in question. Interesting idea. Could be wrong, but hey in this game you can try just about anything.

Now on to something completely different.

When is the Final Program Truly Final

One of the more trying tasks associated with organizing an international symposium is pulling together a "final program" with specific time slots for each presenter. We fully realize that people are very busy these days with crowded schedules that leave them little leeway in making appointments so when they are participating in a symposium they need to know as early as possible when their talk is scheduled. In addition they want to know when talks they have a particular interest in are scheduled also so they can make their travel and hotel arrangements accordingly.

Making airline reservations is particularly vexing as these days it more closely resembles making a stock purchase than a travel arrangement. Prices tend to vary widely and depend in a most sensitive manner on the details of the itinerary. Horror stories abound concerning passengers who have identical accommodations for a given flight but whose ticket prices differ by a factor of 2 or more. It's ironic to note that in the pre deregulation days airline prices were not cheap but were nonetheless fairly stable and predictable. Airlines were forced to provide service to all localities including remote places with little traffic. Service was so so and the food, to put it kindly, was marginal. Worst of all the airlines continually complained that they were not making money. Along comes deregulation which was supposed to cure all these ills. The feeling was that the "invisible hand of the market" will set things straight. Prices will come down, the airlines will make money and everyone will basically get what they really want. The subsequent reality was that prices did indeed come down but along with this salutary development we saw the demise of more than half of the existing airlines, nearly every small community lost its air service, pricing has become a crap shoot, the quality of the food has gone from poor to nonexistent and the airlines are still not making any money. Oh well, the best laid plans of mice and men as they say.

Getting back to the final program. Though we struggle mightily to get it out as early as possible and as accurately as possible the answer to our opening question is that the final program is not truly final till the meeting is over. Any given presenter listed in the program may have to opt out for any one of a number of reasons. The most common causes arise from personal difficulties such as a death in the family, unexpected illness, ...etc. We have experienced nearly everything. At one of the previous symposia one of the prominent speakers, who in fact was among the first to

register and who we had no question would be at the meeting simply passed away due to heart attack! My favorite case, however, occurred at one of our earliest symposia where we had one presenter fully registered and sitting in the audience with his presentation in hand (this was way back when people still used overheads). You would think that if ever there was a sure bet this would be it. Wrong. Barely minutes before his scheduled time our putative presenter gets a call from his management instructing him to cancel due to some undisclosed patent issues that were apparently hanging. So, on pain of losing his job our erstwhile presenter had to decline. What do you do in a case like this? Go to the next speaker or extend the coffee break that's what.

I don't want to scare you but people need to know that final programs are not entirely deterministic entities. However, the upcoming programs for Toronto appear to be in good shape. A few changes have already been made since the program was E-mailed to everyone nearly a month ago but nonetheless things are holding up as well as can be expected. We do try to keep everyone posted on changes as soon as they occur by updating the final program on the conference web site (www.mstconf.com). This is clearly the only feasible way of making the latest information available to everyone as quickly as possible. And by the way if you go to the web site you may want to check out previous issues of the newsletter.

Finally, Dr. Mittal and I would like to again extend our cordial invitation to all our readers to join us in Toronto this Summer for what promises to be a most fruitful and enjoyable meeting.

FINAL PROGRAM: TENTH INTERNATIONAL SYMPOSIUM ON PARTICLES ON SURFACES: DETECTION, ADHESION AND REMOVAL

Toronto, Canada; June 19-21, 2006

This will be the tenth event in the series of symposia on particles on surfaces initiated as part of the Fine Particle Society meeting in 1986. Particles are yield detractors in the manufacture of sophisticated and sensitive electronic components and are very undesirable in many other technologies. Contamination of optical surfaces and shorting of microelectronic circuits by conducting particles, among other concerns, underscore the importance of particle detection, adhesion and removal. On the other hand, however, in certain instances particle adhesion to surfaces is necessary. The purpose of this symposium is to address the vast ramifications of particles on solid surfaces by bringing together

specialists in many allied fields to discuss their latest findings and to identify areas for further investigation. Various types of substrates and particles including metals, oxides, glass, and polymers are covered. Finally, it is apropos that this meeting is being held back to back with the FIFTH INTERNATIONAL SYMPOSIUM ON CONTACT ANGLE, WETTABILITY AND ADHESION. Both of these symposia share a common and critical interest in the surface free energy of solid materials. The particle removal investigator knows this quantity strongly affects particle adhesion and for the contact angle person it is one of the prime measurement objectives. Thus on Wednesday the 21st we plan to bring both groups together for a joint session with papers of interest to both camps. It is hoped that a cross-fertilization of ideas will lead to insights of mutual benefit to all. The following is the list of papers to be presented at this meeting. Please note that the address given may apply only to the presenting author

SESSION I: DETECTION AND MEASUREMENT METHODS; Monday, June 19, 2006

8:30-8:35: INTRODUCTORY REMARKS

8:35-9:05: R. Snel, **J. C. J. van der Donck**, J. H. van den Berg, H. Meiling and H. Meijer; TNO Science & Industry, P.O. box 155, 2600 JA Delft, THE NETHERLANDS; **Particle Detection on Flat Substrates**

9:05-9:35: Kenneth J. Ward, Milo Overbay and **John W. Hellgeth**, Hewlett-Packard Company, Corvallis, Oregon; **Chemical Identification of Submicron Size Organic Particles Using Conventional FTIR Microscopy: New Horizons for an Old Technique.**

9:35-10:05: P. West and **N. Starostina**; "PacificNanotechnology" Inc., 17984 Sky Park Circle, Suite J, Irvine, CA 92614; **AFM Capabilities in Characterization of Particles: from Angstroms to Microns**

10:05-10:25: COFFEE BREAK

10:25-10:55: **Stephen Silverman** and Toufic Najia; Bartlett Bay Consulting, 10 Stanhope Rd, So. Burlington, VT 05403; **The Flip-Side of the Wafer: Backside Particles**

10:55-11:25: A. S. Geller and **C. C. Walton**; Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94550; **Improved Reticle Carrier Design Through Numerical Simulation**

11:25-11:55: Peter X. Feng, P.Yang, Gerardo Morell, Ram Katiyar, and Brad Weiner; Physics Department, University of Puerto Rico, San Juan, PR 00931; **Control of the Preferred Orientation of Nanoscale Carbon Particle Distributions**

11:55-1:30: LUNCH

**SESSION II: CLEANING TECHNOLOGY;
Monday, June 19, 2006**

1:30-2:00: John Durkee; 437 Mack Hollimon, Kerrville, TX 78028; **500 New Cleaning Solvents Discovered!!**

2:00-2:30: Adam Judd, Timothy Fredette, Tania Alarcon, Sherry Kirkland, Gary Stickel, Daniel Heenan, **Adam Kulczyk**, and Robert Kaiser; Entropic Systems, Inc., P.O. Box 397, Winchester, MA 01890-0597; **Development of a Two Step Precision Cleaning Process for the Decontamination of Sensitive Equipment Items Contaminated with Chemical Warfare Agents**

2:30-3:00: A. Lippert, P. Engesser, M. Köffler, F. Kumnig, R. Obweger, A. Pfeuffer and H. Okorn-Schmidt; SEZ AG, Research Center, Draubodenweg 29, 9500 Villach, AUSTRIA; **Keys to Advanced Single Wafer Cleaning**

3:00-3:20: COFFEE BREAK

3:20-3:50: Craig M.V. Taylor, J. B. Rubin, A. Busnaina and L.D Sivils; Los Alamos National Laboratory, Mail Stop J-964, Los Alamos, NM 87545; **Precision Cleaning of Semi-conductor Surfaces Using C₂ Based Fluids**

3:50-4:20: Thomas Bahnners, Helga Thomas and Eckhard Schollmeyer; Deutsches Textilforschungszentrum Nord-West e. V., Adlerstr. 1, 47798 Krefeld, GERMANY; **Electrospun Nanofibers - a Way to Improved Wet Filtration Efficiency of Textile Filter Media**

SESSION III: PARTICLE INTERACTIONS AND ADHESION; Tuesday, June 20, 2006

8:30-9:00: Mahdi Farshchi-Tabrizi, Michael Kappl and Hans-Jürgen Butt; MPI for Polymer Research, Ackermannweg 10, 55128 Mainz, GERMANY; **Influence of Humidity on Adhesion: an AFM Study**

9:00-9:30: Niels P. Boks, Henny C. van der Mei, Willem Norde and Henk J. Busscher; Department of BioMedical Engineering, University Medical Center Groningen and University of Groningen, Antonius Deusinglaan 1, 9713 AV Groningen, THE NETHERLANDS; **Microbial Adhesion Forces Studied in a Parallel Plate Flow Chamber**

9:30-10:00: F. Barbagini, W. Fyen, J. V. Hoeymissen, P. Mertens and J. Fransaer; IMEC, Kapeldreef 75, 3001 Heverlee, BELGIUM; **Time-dependent Interaction Force Between a Silica Particle and a Flat Silica Surface in Dodecane**

10:00-10:20: COFFEE BREAK

10:20-10:50: W. Wójcik, B. Jaczuk and R. Ogonowski; Department of Interfacial Phenomena, Faculty of Chemistry, Maria Curie-Skłodowska University, 20-031 Lublin, POLAND; **Interaction of Silica Particles Through a Liquid**

10:50-11:20: Alex Kabansky; Cypress Semiconductor, San Jose, CA 95134; **Progress in Wafer Cleaning focusing on Particles, Residue and Defects for Sub-100nm Silicon-Based CMOS Devices**

11:20-11:50: Klaus Opwis, Frank Schroeter, Torsten Textor and Eckhard Schollmeyer; German Textile Research Center North - West; Adlerstr. 1; D-47798 Krefeld, GERMANY; **Titanium Dioxide Nanoparticles in Photocatalytic Textile Applications**

11:50-1:30: LUNCH

SESSION IV: PARTICLE ADHESION AND REMOVAL; Tuesday, June 20, 2006

1:30-2:00: K. J. Belde and S.J. Bull; School of Chemical Engineering and Advanced Materials, University of Newcastle, Newcastle upon Tyne, NE1 7RU, UK; **Intentional Polymer Particle Contamination and the Simulation of Adhesion Failure in Transit Scratches in Ultra-Thin Solar Control Coatings on Glass**

2:00-2:30: Astrid Roosjen; University of Wageningen, Laboratory of Physical Chemistry and Colloid Science, Dreijenplein 6, Wageningen 6703 HB, THE NETHERLANDS; **Adhesion, Prevention of Adhesion and Removal of Bacteria from Surfaces in Aqueous Environment**

2:30-3:00: Jin-Goo Park; Hanyang University, Div. of Materials and Chemical Engineering, Ansan 426-791, KOREA; **The Effect of Chemicals on Adhesion and Removal of Slurry Particles During Cu CMP**

3:00-3:30: **Yakov Epshteyn**, A. Scott Lawing and Jesse Federowicz; Rohm and Haas Electronic Materials CMP Inc., 3804 E. Watkins St., Phoenix, AZ 85032; **Ceria Slurry Particles Removal Optimization**

(Note: At this point the PARTICLE symposium joins CONTACT ANGLE for a joint session all day the 21st)

FINAL PROGRAM: FIFTH INTERNATIONAL SYMPOSIUM ON CONTACT ANGLE, WETTABILITY AND ADHESION

Toronto, Canada; June 21-23, 2006

In his opening remarks at the first symposium in this series Professor Robert Good pointed out that Galileo in the 17th century was quite likely the first investigator to observe contact angle behavior with his experiment of floating thin gold leaf on top of a water surface. Since that time contact angle measurements have found wide application as a method of determining the energetics of surfaces. This, in turn, has a profound effect on the wettability and adhesion of liquids and coatings to surfaces. This symposium is concerned with both the fundamental and applied aspects of contact angle measurements. Issues such as the applicability and validity of various measurement techniques and the proper theoretical framework for the analysis of contact angle data will be of prime concern. In addition, a host of applications of the contact angle technique will be explored including but not limited to: wettability of powders, fibers, wood products, inks, paper, polymers and monolayers. Further attention will be given to the use of contact angle data in evaluating surface modification procedures, determining relevance of wettability to adhesion, the role of wettability in bioadhesion, ophthalmology, prosthesis and in the control of dust in mining and milling applications. The primary focus of this symposium is to provide a forum for the discussion of cutting edge advancements in the field and to review and consolidate the accomplishments which have been achieved thus far.

Finally, it is apropos that this meeting is being held back to back with the **TENTH INTERNATIONAL SYMPOSIUM ON PARTICLES ON SURFACES: DETECTION, ADHESION AND REMOVAL**. Both of these symposia share a common and critical interest in the surface free energy of solid

materials. The particle removal investigator knows this quantity strongly affects particle adhesion and for the contact angle person it is one of the prime measurement objectives. Thus on Wednesday the 21st we plan to bring both groups together for a joint session with papers of interest to both camps. It is hoped that a cross-fertilization of ideas will lead to insights of mutual benefit to all. The following is the list of papers to be presented at this meeting. Please note that the address given may apply only to the presenting author.

SESSION I, JOINT SESSION WITH 10TH PARTICLE SYMPOSIUM: PARTICLE WETTING AND INTERACTIONS: JOINT SESSION WITH CONTACT ANGLE SYMPOSIUM; Wednesday, June 21, 2006

8:00-8:05: INTRODUCTORY REMARKS

8:05-8:35: Jerry Y. Y. Heng and **Daryl R. Williams**; Department of Chemical Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK; **The Influence of Surface Chemistry in the Wetting Behaviour of Crystalline Pharmaceutical Solids**

8:35-8:55: **A. Synytska**, L. Ionov, S. Minko, K.-J. Eichhorn, M. Stamm and K. Grundke; Leibniz Institute of Polymer Research Dresden e.V., Hohe Str. 6, 01069 Dresden, GERMANY; **Model Structured Surfaces from Core-shell Particles. Influence of Chemical and Topographical Heterogeneities on Surface Wettability**

8:55-9:15: Laurent Forny, **Khashayar Saleh**, Isabelle Pezron, Ljepša Komunjer and Pierre Guigon; Laboratoire Génie des Procédés Industriels, UMR CNRS 6067 Université de Technologie de Compiègne, 60205 Compiègne Cedex, FRANCE; **Influence of Wetting Parameters and Mixing Conditions on Characteristics of Water-rich Powders Obtained by Encapsulation**

9:15-9:45: **Glen McHale**, Michael I. Newton, Neil J. Shirtcliffe, F. Brian Pyatt and Stefan H. Doerr; School of Biomedical & Natural Sciences, Nottingham Trent University, Clifton Lane, Nottingham NG11 8NS, UK; **Self-organisation of Soil and Granular Surfaces**

9:45-10:15: L. Labajos-Broncano, M. J. Nuevo, M. L. González-Martín, J. A. Antequera-Barroso and J. M. Bruque; Department of Physics, University of Extremadura, Campus Universitario, Avda. de Elvas s/n, 06071 Badajoz, SPAIN; **An Experimental Study about the Effect of the Interfacial Adsorption on the Imbibition of Aqueous Surfactant Solutions in Hydrophilic Porous Media**

10:15-10:35: COFFEE BREAK

10:35-11:05: B.P. Binks, J.H. Clint, P.D.I. Fletcher, T.J.G. Lees and P. Taylor; Surfactant & Colloid Group, Department of Chemistry, The University of Hull, Hull HU6 7RX, UK; **Effect of Surface Wettability on the Growth of Gold Nanoparticle Films**

11:05-11:35: D. Clause, L. Sacca, F. Gomez and I. Pezron; Université de Technologie de Compiègne, Département de Génie Chimique, CNRS UMR 6067 GPI, BP 20529, 60205 Compiègne cedex, FRANCE; **Emulsions Stabilized by Nanoparticles**

11:35-11:55: Chuan Guo Ma, Min Zhi Rong and Ming Qiu Zhang; Materials Science Institute, Zhongshan University, Guangzhou 510275, P. R. CHINA; **Use of Wetting Coefficient plus Surface and Adhesive Work to Predict Dispersion State of Nano-CaCO₃ Fillers**

11:55-12:15: A. Méndez-Vilas, A.B. Jódar-Reyes, M.G. Donoso, J.M. Bruque and M.L. González-Martín; Department of Physics, University of Extremadura, Campus Universitario, Avda. de Elvas s/n, 06071 Badajoz, SPAIN; **Nanoscale Exploration of Wetting/Dewetting Phenomena at Silicon Wafer Surface**

12:15-12:35: Anselm Kuhn, and **John Durkee**; 437 Mack Hollimon, Kerrville, TX 78028; **Wettability Measurements for Surface Cleanliness Testing - an Old Technique Revisited & Updated**

12:35-1:35: LUNCH

SESSION II JOINT SESSION WITH 10TH PARTICLE SYMPOSIUM: COLLOIDS, POWDERS AND DROPLETS: FRACTAL AND WETTING ASPECTS; Wednesday, June 21, 2006

1:35-2:05: Carel Jan van Oss; Department of Microbiology and Immunology; Department of Chemical and Biological Engineering, and Department of Geology; University at Buffalo, State University of New York, South Campus, Buffalo, NY 14214-3000; **Properties of Water in Colloidal And Biological Systems**

2:05-2:35: Po-zen Wong; Department of Physics, University of Massachusetts, Amherst, MA 01002; **Multilayer Adsorption on Fractal Surfaces**

2:35-2:55: M. Ojha, S. Panchangam. P.C. Wayner, Jr. and **J. L. Plawsky**; Dept of Chemical and Biological Engineering, Rensselaer Polytechnic Institute 110 Eighth St., Troy, NY 12180; **Effects of Surface Structure on Contact Line Behavior**

2:55-3:25: Anton A. Darhuber, Nikolai V. Priezjev and Sandra M. Troian, Microfluidic Research & Engineering Laboratory, Princeton University, Princeton, NJ 08544-5263; **Slip Behavior at Liquid/Solid Interfaces: Hydrodynamic Predictions versus Molecular-Dynamics Simulations**

3:25-3:45: Aiping Fang, **Thierry Ondarçuhu**, Erik Dujardin, André Meister and Raphaël Pugin; Centre d'Elaboration des Matériaux et d'Etudes Structurales, CEMES-CNRS, 29 rue Jeanne Marvig, 31055 Toulouse cedex 4, FRANCE; **Nanoscale Dispensing of Droplets**

3:45-4:05: COFFEE BREAK

4:05-4:25: Thierry Ondarçuhu and Agnès Piednoir; Nanoscience group, CEMES-CNRS, 29 rue Jeanne Marvig, 31055 Toulouse, FRANCE; **Interaction of a Contact Line With Nanometric Steps**

4:25-4:45: Mariëlle Wouters; TNO Industrial Technology, Polymer Technology, De Rondom 1, 5612 AP Eindhoven, THE NETHERLANDS; **Aspects of Wettability and the Improvement of Adhesion of UV Curable Powdercoatings on Polypropylene Substrates**

4:45-5:15: Dandina N. Rao and Subhash C. Ayirala; The Craft & Hawkins Department of Petroleum Engineering, Louisiana State University, Baton Rouge, LA 70803-6417; **Mechanistic Modeling of Dynamic Vapor-Liquid Interfacial Tension in Complex Petroleum Fluids**

5:15-5:45: O. Karoussi, **A. A. Hamouda**; University of Stavanger, P. O. Box 8002 Ullandhaug, 4068 NORWAY; **The Effect of Binary Fatty Acids Systems on Partitioning, IFT and Wettability of Calcite Surfaces**

5:45-6:05: **Frank Schröter**, Thomas Sottmann, Dierk Knittel and Eckhard Schollmeyer; Deutsches Textilforschungszentrum Nord-West e. V., Adlerstr. 1, 47798 Krefeld, GERMANY; **Phase Behavior of Non-Ionic Microemulsions of Water/Silicone Oil/Surfactant**

SESSION III: NOVEL AND ADVANCED MEASUREMENT METHODS; Thursday, June 22, 2006

8:00-8:30: Hossein Tavana and **A. Wilhelm Neumann**; Department of Mechanical Eng., University of Toronto, Toronto, Ontario M5S 1A4, CANADA; **Contact Angles: Measurement and Interpretation**

8:30-9:00: **Dennis Palms**, Rick Fabretto, Rossen Sedev, Joel De Coninck and John Ralston; Ian Wark Research Institute, University of South Australia, Mawson Lakes, SA 5095 AUSTRALIA; **Measurement and Interpretation of Dynamic Contact Angles and Contact Angle Hysteresis**

9:00-9:30: M. Brugnara, **C. Della Volpe**, G. Ischia, D. Maniglio, M.A. Rodríguez-Valverde and S. Siboni; Dept. Of Materials Engineering, University of Trento, Via Mesiano 77, 38050 Trento, ITALY; **Recent Advances in the Determination of an Equilibrium Contact Angle on Rough/Heterogeneous Surfaces**

9:30-10:00: F. J. Montes Ruiz-Cabello, P. Gea-Jódar, M. A. Rodríguez-Valverde and **M. A. Cabrerizo-Vílchez**; Biocolloid and Fluid Physics Group, Applied Physics Department, Sciences Faculty, University of Granada. E-18071 Granada, SPAIN; **Contact Angle of Polygonal Sessile Drops**

10:00-10:20: COFFEE BREAK

10:20-10:40: M. Brugnara, M.A. Rodríguez-Valverde, S. Siboni and **C. Della Volpe**; Polymers and Composites Laboratory, Dept. of Materials Engineering and Industrial Technologies, University of Trento. E- 38050 Trento, ITALY; **Comparison of Algebraic Algorithms for Drop Profile Fitting: Circle and Ellipse**

10:40-11:00: **M. G. Cabezas**, M. Hoorfar , H. Tavana and A. W. Neumann; Escuela de Ingenierías Industriales, Universidad de Extremadura, ESPAÑA; **Axisymmetric Drop Shape Analysis (ADSA) for the Determination of Contact Angle**

11:11:30: **M. J. Nuevo**, L. Labajos-Broncano, M. L. González-Martín and J. M. Bruque; Department of Physics, University of Extremadura, Campus Universitario, Avda. de Elvas s/n, 06071, Badajoz, SPAIN; **An Experimental Study about the Effect of the Velocity on the Contact Angle in Experiments of Spontaneous Flow of Liquids in Porous Media**

11:30-11:50: A. Méndez-Vilas, M.G. Donoso, J.L. González-Carrasco, J.M. Bruque, and **M. L. González-Martín** ; Department of Physics, University of Extremadura, Campus Universitario, Avda. de Elvas s/n, 06071 Badajoz, SPAIN; **AFM Micro-Topography and Contact Angle Goniometry on Ti-Based Biomaterials**

11:50-12:10: **Bernt Boström**, FIBRO System AB, Stockholm, SWEDEN; **Evaluation of Very Low Contact Angles Using a Compact Video System**

12:10-1:30: LUNCH

SESSION IV: SUPERHYDROPHOBIC EFFECT; Thursday, June 22, 2006

1:30-2:00: **Emil Chibowski**, Konrad Terpilowski and Lucyna Holysz; Department of Physical Chemistry-Interfacial Phenomena, Faculty of Chemistry, Maria Curie-Skłodowska University, Lublin, POLAND; **Superhydrophobic Effect due to Deposition of Nano- and/or Microparticles on a Solid Surface**

2:00-2:30: **C. W. Extrand**; Entegris Inc., 3500 Lyman Blvd., Chaska, MN 55318; **Modeling Ultralyophobicity: a Liquid Drop Suspended on a Single Asperity**

2:30-3:00: A. Milne, W Li, K. Grundke and **A. Amirfazli**; Department of Mechanical Engineering, University of Alberta, Edmonton, AB, T6G 2G8 CANADA; **Wetting of Superhydrophobic Surfaces: Experimental and Theoretical Perspectives**

3:00-3:20: H. Tavana, A. Amirfazli, and A.W. Neumann; Laboratory of Applied Surface Thermodynamics, Department of Mechanical and Industrial Engineering, University of Toronto, Toronto Ontario, CANADA; **Fabrication of Superhydrophobic Surfaces of n-Hexatriacontane and Study of their Wetting Properties**

3:20-3:40: A. Safaei, D. K. Sarkar and M. Farzaneh; Université du Québec à Chicoutimi, CANADA G7H 2B1; **Superhydrophobic Properties of Silver Coated Copper**

3:40-4:00: COFFEE BREAK

4:00-4:20: N. Saleema, D. K. Sarkar, M. Farzaneh and E. Sacher; Canada Research Chair on Atmospheric Icing Engineering of Power Networks and Industrial Chair on Atmospheric Icing of Power Network Equipment, Université du Québec à Chicoutimi, CANADA G7H 2B1; **Effect of Temperature on Superhydrophobic Zinc Oxide Nanotowers**

4:20-4:40: D. K. Sarkar, and M. Farzaneh; Université du Québec à Chicoutimi, CANADA G7H 2B1; **Superhydrophobic Aluminum Surfaces**

4:40-5:00: P. J. Ramón-Torregrosa, M. A. Rodríguez-Valverde and **M. A. Cabrerizo-Vílchez**; Biocolloid and Fluid Physics Group, Applied Physics Department, Sciences Faculty, University of Granada. E-18071 Granada, SPAIN; **Effect of Acid-Etching on Titanium Wettability. A Crossover Between Wetting Regimes**

5:00-5:20: Jin-Goo Park; Hanyang University, Div. of Materials and Chemical Engineering, Ansan 426-791, KOREA; **Preparation and Characterization of Hydrophobic Anti-stiction Layer in Nano Imprinting**

5:20-5:40: Wen Zhong, Ning Pan and David Lukas; Department of Textile Sciences, University of Manitoba, Winnipeg, MB R3T 2N2 CANADA; **Wetting and Adhesion in Fibrous Materials: Stochastic Modeling and Simulation**

5:40-6:00: Mathilde Reyssat and David Quéré; ESPCI, Laboratoire de Physique et Mécanique des Milieux Hétérogènes, CNRS UMR 7636, Paris, FRANCE; **On « fakir » Drops**

SESSION V: SURFACE FREE ENERGY AND WETTABILITY STUDIES; Friday, June 23, 2006

8:00-8:30: Hans Riegler; MPIKG, Am Mühlenberg, D-14476 Potsdam, GERMANY; **Wetting Properties, Interfacial Mobility and Aggregation Behaviour of Long Chain Alkanes at Solid/Vapour Interfaces**

8:30-9:00: Martien A. Cohen Stuart; Lab. of Physical Chemistry and Colloid Science, Wageningen University, P. O. Box 8038, 6700 EK Wageningen, THE NETHERLANDS; **Wettability of 'Soft' Surfaces: the Contact Angle on Swollen Polymer Brushes and Gels**

9:00-9:30: Frieder Mugele; University of Twente, PO Box 217, 7500 AE Enschede, THE NETHERLANDS; **Generation of Charge-Controlled Microdroplets Using AC-Electrowetting**

9:30-10:00: Glen McHale, Michael I. Newton, Dale L. Herbertson, Neil J. Shirtcliffe and Stephen J. Elliott; School of Biomedical & Natural Sciences, Nottingham Trent University, Clifton Lane, Nottingham NG11 8NS, UK; **Electrowetting on Super-hydrophobic Surfaces**

10:00-10:20: COFFEE BREAK

10:20-10:50: Masataka Murahara; Entropia Laser Initiative Tokyo Institute of Technology, 2-12-1, O-okayama, Meguro, Tokyo, 152-8552, JAPAN; **Electrowetting-induced Photochemical Surface Modification of PTFE by Using ArF Laser**

10:50-11:10: Mika M. Kohonen; Department of Applied Mathematics, Research School of Physical Sciences and Engineering, Australian National University, Canberra ACT 0200, AUSTRALIA; **The Effects of Wall Sculpturing, Sap Solutes, and Drying on the Wettability of Tree Capillaries**

11:10-11:30: S. Temmel, T. Höfler and W. Kern; Polymer Competence Center Leoben GmbH, A-8700 Leoben, AUSTRIA; **Surface Properties of Polymers Functionalized by UV Irradiation**

11:30-12:00: Ilker S. Bayer, **Constantine M. Megaridis**, Daniel R. Gamota and Jie Zhang; Department of Mechanical and Industrial Engineering, University of Illinois at Chicago, Chicago, IL, 60607-7022; **Surface Free Energy Estimation and Wettability Characterization of UV Curable Coatings by Contact Angle Measurements**

12:00-12:20: Emil Chibowski, Konrad Terpilowski and Lucyna Holysz; Department of Physical Chemistry-Interfacial Phenomena, Faculty of Chemistry, Maria Curie-Sklodowska University, Lublin, POLAND; **Influence of Ambient Humidity on the Apparent Surface Free Energy of Smooth Solid Surface**

12:20-1:20: LUNCH

SESSION VI: BIOADHESION, CLEANABILITY AND SURFACE PROPERTIES; Friday, June 23, 2006

1:20-1:50: Alain Carré and Valérie Lacarrière; Corning European Technology Centre, 7bis Avenue de Valvins, 77210 Avon, FRANCE; **Cell Adhesion and Proliferation on Polystyrene Substrates of Different Surface Properties**

1:50-2:10: Klaus Opwis, Thomas Bahnners and Eckhard Schollmeyer; Deutsches Textilforschungszentrum Nord-West e. V., Adlerstr. 1, 47798 Krefeld, GERMANY; **Surface Modifications for the Control of Cell Growth on Textile Substrates**

2:10-2:30: M. L. González-Martín, A.M. Gallardo-Moreno, R. Calzado-Montero, J.M. Bruque and C. Pérez-Giraldo; Department of Physics, University of Extremadura, Campus Universitario, Avda. de Elvas s/n, 06071 Badajoz, SPAIN; **Physico-Chemistry of Initial Bacterial Adhesion. Insights into the Relations Between Experiments and Model Proposals**

2:30-3:00: Tanweer Ahsan; Henkel Corporation, 15350 Barranca Parkway, Irvine, CA 92688; **Adhesion Performance of Molding Compounds in Semiconductor Packaging**

3:00-3:20: Juha Lindfors, Janne Laine and Per Stenius, Laboratory of Forest Products Chemistry, Helsinki University of Technology - TKK, FINLAND; **Adhesion of Hydrophobing Agents to Wet and Dry Surfaces**

3:20-3:40: COFFEE BREAK

3:40-4:00: R. Sedev, N. Stevens and J. Ralston; Ian Wark Research Institute, Mawson Lakes, SA 5095, AUSTRALIA; **Receding Contact Angle in a Porous Medium**

4:00-4:30: Laurence Boulangé-Petermann, Christelle Gabet, Jean Charles Joud and Bernard Baroux ; Ugine-ALZ, Arcelor, FRANCE; **Effect of the Surface Properties on the Cleanability of Bare and Coated Stainless Steels**

4:30-4:50: Thomas Bahnners, Lutz Prager and Eckhard Schollmeyer; Deutsches Textilforschungszentrum Nord-West e. V., Adlerstr. 1, 47798 Krefeld, GERMANY; **Functional Top Coats on Coated Textiles for Improved or Self-attained Cleanability**

4:50-5:10: Sarthak K. Patel and R. N. Jagtap; Chemical & Materials Engineering Department, University of Alberta, Edmonton, Alberta, CANADA; **Stimulate of Contact Angle with Respect to Grafting of Butyl Acrylate Hybrid - PUD Adhesives for Plastic Laminates**

5:10-5:30: Tao Du, Yazhen Wang, Peng Xia and Yan Luo; Research Center of Material Science and Engineering, Guilin University of Electronic Technology, Guilin, CHINA; **Study of ABS Resin Bond with Acrylonitrile-Modified Epoxy Resin**

REGISTRATION INFORMATION

DATES:

JUNE 19-21, 2006: TENTH INTERNATIONAL SYMPOSIUM ON PARTICLES ON SURFACES: DETECTION ADHESION AND REMOVAL

JUNE 21-23, 2006: FIFTH INTERNATIONAL SYMPOSIUM ON CONTACT ANGLE, WETTABILITY AND ADHESION

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SHORT COURSE ON APPLIED ADHESION MEASUREMENT METHODS, JUNE 24, 2006:

Associated with these symposia MST gives a short course on adhesion measurement methods. Since nearly all of the MST symposia have some relation to adhesion phenomena, the ability to quantify the adhesion of one material layer to another is clearly one of the unifying themes. This course is designed to mesh with the topical symposia by presenting an overview of the most useful adhesion measurement techniques which are being used to evaluate the **PRACTICAL ADHESION** of coatings. Emphasis will be given to methods which can be carried out in a manufacturing environment as well as in the lab and which give results that are directly relevant to the durability and performance of the coatings. The effects of material elastic properties and residual stress are considered as well as other external influences which affect coating adhesion.

Audience: Scientists and professional staff in R&D, manufacturing, processing, quality control/reliability involved with adhesion aspects of coatings or laminate structures.

Level: Beginner to Intermediate

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Duration: 1 day

Registration fee: \$595: Includes course notes, handouts and a copy of the newly published handbook and reference volume: **ADHESION MEASUREMENT METHODS: THEORY AND PRACTICE** (CRC Press, 2006).

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- ▶ Understand advantages and disadvantages of a range of adhesion measurement techniques.
- ▶ Gain insight into mechanics of adhesion testing and the role of intrinsic stress and material properties
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- ▶ Gain perspective from detailed discussion of actual case studies of product manufacturing and development problems.

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