

MANIPULATION OF VAN DER WAALS' FORCES BY GEOMETRICAL PARAMETERS IN MICRO-MATERIAL HANDLING

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ABSTRACT

This paper explores the manipulation of Van der Waals' forces by geometrical parameters in a micro-material handling system. It was observed that the flat-flat interactive surfaces exerted the highest intensity of Van der Waals' forces followed by cone-flat, cylinder-flat, sphere-flat and sphere-sphere interactive surfaces, respectively. A conical micro-gripper proved to be versatile in manipulating the Van der Waals' forces efficiently in a 'picking up' and 'releasing' mechanism of micro-work parts. It was deduced that the pick-up position should be rough and spherical, and the placement position should be smooth and flat for an effective 'pick-and-place' cycle to be realised.

Keywords: micro-material handling, Van der Waals' forces, interactive surfaces, geometrical parameters, surface roughness.

1. INTRODUCTION

Micro-material handling has become a focus area in current micro-manufacturing research. Several forces influence the picking up and releasing of micro-work parts. These include Van der Waals' forces, electrostatic forces, capillary forces and gravity. Research has proven that Van der Waals' forces dominate at micro-level (Li et al., 2006, Eichenlaub et al., 2006) in non-humid environments. The Van der Waals' forces are affected by several parameters in micro-material handling. These parameters include the shape geometry of the micro-work parts, micro-grippers, pick-up position and placement position, material type, and micro-environmental parameters (which include temperature, pressure and humidity). This paper focuses on the geometrical parameters of the materials interacting during micro-material handling, in relation to the Van der Waals' forces experienced. The other parameters are assumed to be constant. The flat-flat, sphere-sphere, sphere-flat, cone-flat, and cylinder-flat interactive surfaces are analysed. The modelling and analysis is completed with respect to radius of curvature (in the 1 μm to 10 μm range); separation distance (from 1 μm to 10 μm range); included-half-cone angles (within 0° to 90° range) and surface roughness (from 0.1 μm to 1.0 μm range). A synthesis is performed of how these parameters could be optimised in achieving an effective and efficient micro-material handling system.

Generally, the Van der Waals' force, F , between two interacting surfaces, is given by equation (1), (Parsegian 2006):

$$F = - \frac{A_H Y^n}{ND^n} \quad (1)$$

where:

A_H - is a material property called Hamaker coefficient. This is a coefficient which indicates the intensity of the Van der Waals' forces exerted by a specific material with respect to its chemical nature,

D - is the shortest surface-to-surface separation distance between two substances,

n - is an exponent of D greater than zero,

Y - is the dimensional parameter of micro-material under consideration e.g. radius or length; conically included angle or a ratio of dimensional property,

x - is an exponent (greater than zero) of Y ,

N - is a constant greater than zero.

The negative sign (-) of the Van der Waals' forces shows that the forces are 'attractive'.

The problem statement in this research paper is: an investigation into the optimisation of geometrical parameters of interacting surfaces in order to improve efficiency and effectiveness in micro-material handling, using Van der Waals' forces.

When picking, the Van der Waals' forces between the gripper and the micro-work part should be higher than that between the pick-up position and the micro-work part. When releasing, the gripper forces should be lower than the placement position. 'Pick-up position' refers to the base material from where the micro-work part is lifted, and 'placement position' refers to the base material onto which the micro-work part is released.

2. EXPERIMENTAL DESIGN

This experimental design focuses on identifying how geometrical parameters affect the intensity of the Van der Waals' forces experienced between two interacting surfaces. Firstly, all specimens are washed in acetone, methanol, de-ionised water and then in 20% hydrofluoric acid solution using an ultrasonic bath. They are subsequently rinsed in de-ionised water. The washing removes any grease, oxide layers and other impurities from the specimens.

Secondly, the experiments are carried out on an electrostatic dissipating mat. The mat has accessories which include an anti-static wrist band to discharge the experimenter of any electrostatic forces, as well as an anti-static crocodile clip to discharge the apparatus and samples of any such forces. The experiments are performed in non-humid environments in order to eliminate

the effect of capillary forces. Non-ferrous materials are used to avoid the effect of magnetic forces. An atomic force microscope (AFM) is used to measure the intensity of the Van der Waals' forces experienced between the interacting bodies of different geometries. The corresponding formulae of the Van der Waals' forces with respect to geometrical parameters are shown in Table 2.

3. GEOMETRICAL PARAMETERS

Van der Waals' forces have been experimentally proven to be dependent on the shape or geometry of the interacting substances (Tanaka et al., 2008). Table 2 shows some common geometrical shapes and their corresponding Van der Waals' forces' expressions.

Table 2: Van der Waals' forces for a pair of interacting surfaces (Parsegian, 2006)

Geometry	Force
Two flat surfaces	$f = -\frac{A_H}{6\pi D^3}$ per unit area
Two spheres	$F = -\frac{A_H}{6D^3} \frac{R_1 R_2}{R_1 + R_2}$
Sphere - flat surface	$F = -\frac{A_H R}{6D^3}$
Cone - flat surface	$F = -\frac{A_H \tan^2 \theta}{6D}$
Cylinder - flat surface	$F = -\frac{A_H R^2}{6D^3}$

where:

A_H - is the Hamaker coefficient

D - is the shortest surface-to-surface separation distance

R - is the radius of the sphere or cylinder

Θ - is the half-cone angle

the negative sign (-) of the Van der Waals forces shows that the forces are 'attractive'.

It can be deduced from Table 2 that the greater the surface area of the interacting particles the greater the Van der Waals' forces will be (Oliveira, 1997).

Equations deduced from Table 2 and various literature sources are modelled in the subsequent sections with the view to optimising the manipulation of Van der Waals' forces in micro-material handling systems.

3.1. The analysis of the Van der Waals' forces with respect to radius

3.1.1. Sphere-sphere surface interaction

Figure 1 shows the sphere-sphere interaction where D is the shortest separation distance between the interacting surfaces, R_1 is the radius of the

smaller sphere and R_2 the radius of the bigger sphere.

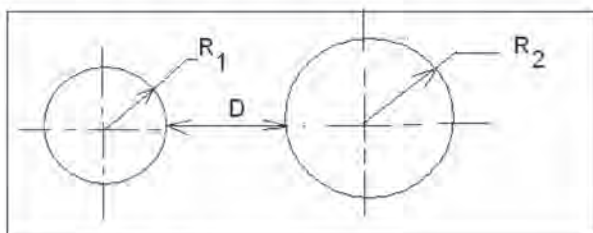


Figure 1: Sphere-sphere surface interaction

According to Fatikow et al. (2000), the Hamaker theory estimates that the Van der Waals' force, F (between two equal-sized spherical particles), is given as in equation (2) (Weber & Hrenya, 2007; Thoreson et al., 2006).

$$F = -\frac{A_H R}{12D^2} \quad (2)$$

where:

R - is the sphere's radius

A_H - is the Hamaker coefficient

D - is the shortest surface-to-surface separation distance between the spheres. As the radius increases, so the force increases. When the separation distance increases, the force decreases (Weber & Hrenya, 2007).

3.1.2. Sphere-flat surface interaction

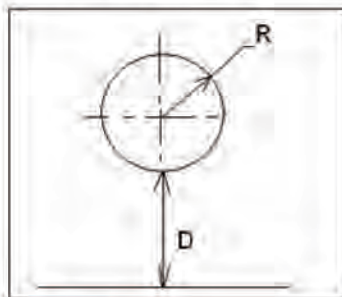


Figure 2: Sphere-flat surface interaction

Figure 2 is a schematic representation of the sphere-flat surfaces' interaction. Again the forces increase directly with the radius and decrease with an increase in separation distance (Gotzinger & Peukert, 2003).

The adhesive force between a spherical particle and a flat wall is given as equation (3) (Weber & Hrenya, 2007).

$$F = -\frac{A_H R}{6D^2} \quad (3)$$

For both sphere-sphere and sphere-flat surface interactions, the adhesive force approaches infinity as the separation distance approaches zero. This singularity incurred at particle contact is unrealistic and is avoided by imposing a "cut-off" distance, D_{cut} , as shown in Figure 3. A surface adhesion force model is used to calculate the adhesive force for separation distances below this cut-off distance. The adhesive force remains constant as separation distance decreases below D_{cut} (Weber & Hrenya, 2007).

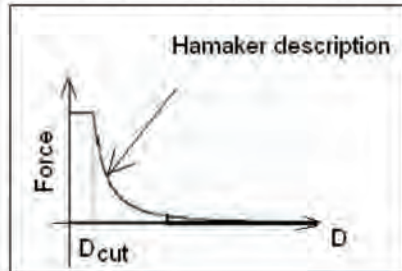


Figure 3: Variation of adhesive force with separation distance (Weber & Hrenya, 2007)

This region of constant adhesive force includes any "negative" separation distances that occur during actual particle contact (for example, overlaps stemming from the soft-sphere treatment of particles) (Weber & Hrenya, 2007).

3.1.3. Sphere-sphere, and sphere-flat interactive surfaces' comparison

Figure 4 shows the comparison between sphere-flat and sphere-sphere interactive surfaces as far as Van der Waals' force intensity and radius are concerned. R_1 is the radius of one sphere and R_2 of the other. The graphs are straight lines as long as R_2 is dependent upon R_1 , and R_1 is not constant. This is a case where the micro-gripper expands as the work piece expands (which is difficult to achieve in practice). It can be observed that double the Van der Waals' forces are experienced on a sphere-flat interactive surface as compared to sphere-sphere (where $R_2 = R_1$) interactions.

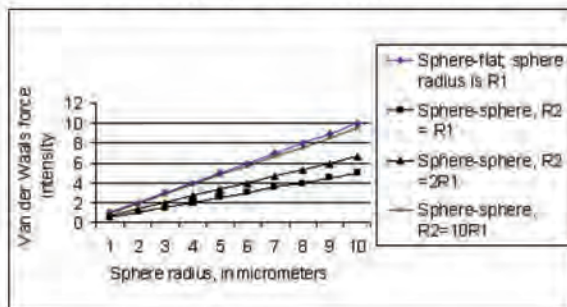


Figure 4: Effect of radius on the intensity of the Van der Waals' forces

As the radius R_2 increases to $2R_1$ and then to $10R_1$ (for the sphere-sphere interaction), the gradient of the force-radius curve increases approaching that of sphere-flat interactive surface, as shown in Figure 4. As R_2 increases to higher values, the rate of change of Van der Waals' forces becomes very small. Hence there is an optimum value of R_2 with respect to efficiency (Takeuchi, 2006). How can this be applied in micro-manufacturing with respect to picking and placement positions? The pick-up position of a micro-work part should be spherical (so as to reduce contact area and consequently the Van der Waals' force) and the placement position should be flat (resulting in more 'attractive' Van der Waals' force for the work piece).

Figure 5 shows a sphere-sphere interaction with the radius of the larger sphere, R_2 , increasing while the radius of the smaller sphere, R_1 , is constant at given values. As the radius R_2 increases, the Van der Waals' force intensity increases. The smaller the particle (that is, the smaller is R_1), the easier it is to 'pick' it.

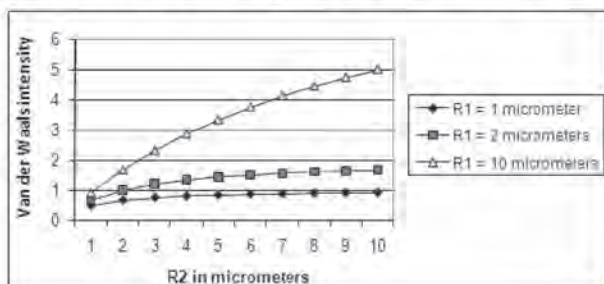


Figure 5: Sphere-sphere surface interaction

Therefore the gripper can be designed so that it expands pneumatically, like a balloon. This then increases its radius of curvature, the contact area and consequently, the adhesive force. This leads to a firm grip on a micro-work part. When releasing the work piece, the gripper reduces its radius by contracting, hence reducing the adhesive Van der Waals' forces.

3.1.4. Cylinder-flat surface

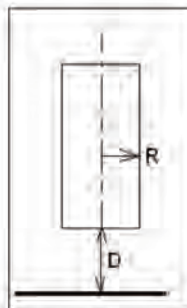


Figure 6: Cylinder-flat surface interaction

Figure 6 is a schematic representation of the interaction between a cylinder of radius R and a flat surface which is D micrometers away.

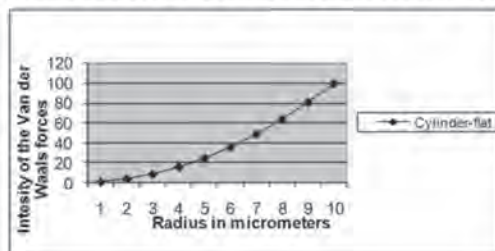


Figure 7: Cylinder-flat interactive surfaces

Figure 7 shows the plot of Van der Waals' forces against radius for a cylinder-flat surface interaction. The Van der Waals' forces in this case are more pronounced than in spherical interactions because the cylinder has a bigger contact area. This implies that the pick-up position should be spherical and the placement position cylindrical, for greater efficiency and effectiveness. Similarly, the gripper should be expandable in order to vary its radius. When picking a work piece, it should have a bigger radius than when releasing a work piece.

3.1.5. Sphere-sphere, sphere-flat, cylinder-flat interactive surfaces' comparison

Figure 8 shows the comparison of the sphere-sphere, sphere-flat surface, and cylinder-flat surfaces' interactions. The radius, R , of the elements increases from $1\text{ }\mu\text{m}$ to $10\text{ }\mu\text{m}$. It is evident that, for the same materials and separation distance equal to $1\text{ }\mu\text{m}$, the cylindrical surface exerts more Van der Waals' forces than the spherical surfaces when the radius is greater than $1\text{ }\mu\text{m}$.

Therefore, a cylindrical micro-gripper exerts more force than a spherical one. Hence, when large amounts of Van der Waals' forces are required in micro-material handling, a cylindrical gripper should be used.

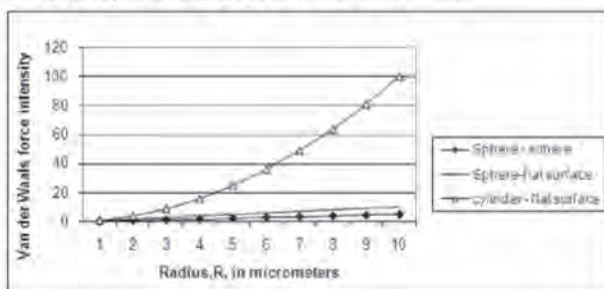


Figure 8: Comparison of three geometries

3.2. Cone-flat surface and cone angle analysis

Figure 9 shows the Van der Waals' forces exerted on a flat surface by a conical shape. The adhesive forces vary as the square of the tangent of the included-half-cone angle as indicated in Table 2. The Van der Waals' forces increase sharply after the 60° angle (semi-aperture angle) reaches an infinite at 90° (theoretically).

Consequently, the gripper can be made conical in shape so that its cone angle is varied accordingly. When picking, the included-half-cone angle should be greater than 60° and when releasing less than 60° as shown in Figure 10. The conical configuration can be achieved mechanically by having numerous pin-like structures conically mounted onto a diaphragm. The manipulation of the diaphragm (contraction or expansion) would vary the cone angle much like an umbrella mechanism. Furthermore, a centre pin which protrudes in and out of the peak of the cone angle may also be employed to increase the efficiency of the picking and releasing mechanism.

Similarly, the shape of the pick-up position can be manipulated. The pick-up position should have a small cone angle (to reduce the contact area and the adhesive force of the base material) and the placement position should have a large angle.

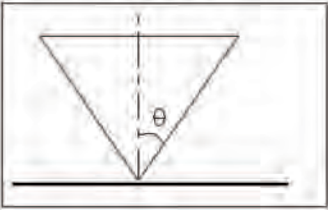


Figure 9: Cone-flat surfaces interaction

Figure 9 shows the cone with half-cone angle, θ , interacting with a flat surface.

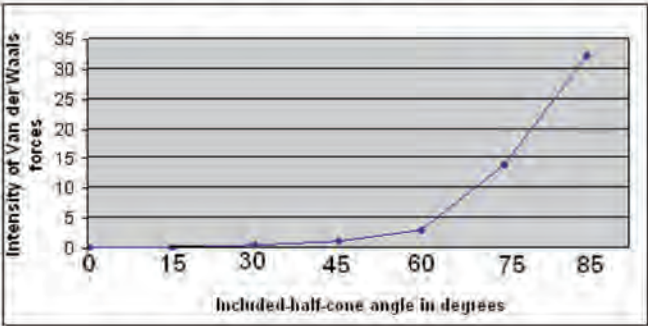


Figure 10: Cone-flat interactive surface

3.3. Van der Waals' force with respect to the separation distance

3.3.1. Flat-flat, sphere-sphere, sphere-flat, cylinder-flat, cone-flat interactive surfaces' comparison

Figure 11 shows the variation of Van der Waals' forces with respect to separation distance for flat-flat, and cylinder-flat interactive surfaces with reference to the equations in Table 2. All the other factors are considered constant and equal to a unit when integrated. The Van der Waals' forces decrease sharply since they vary inversely as the cube (third power) of separation distance (Kornvopoulos, 1996).

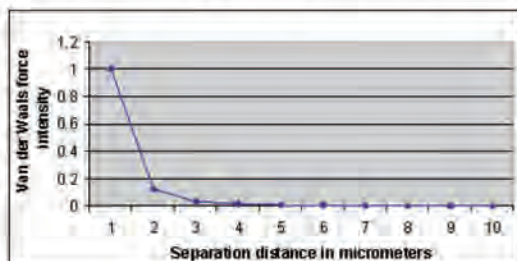


Figure 11: Force against separation distance for flat-flat and cylinder-flat interactive surfaces

In Figure 12, the adhesive forces for sphere-sphere and sphere-flat interactive surfaces vary as the inverse square of separation distance (as in Table 2). The reduction of the Van der Waals' forces in this case is less than with the cylinder-flat surfaces.

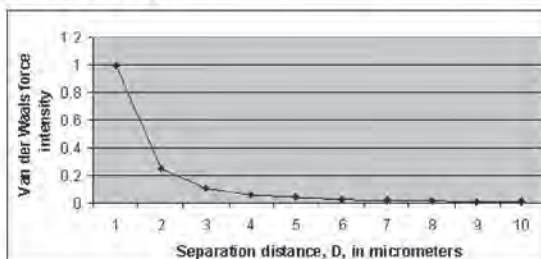


Figure12: Force against separation distance for sphere-sphere and sphere-flat interactive surfaces

Figure13 again shows the Van der Waals' forces between cone-flat surfaces and interactive surfaces. The reduction in the Van der Waals' forces is far less than in the last two cases because the adhesive forces are varying as the inverse of the separation distance (as in Table 2).

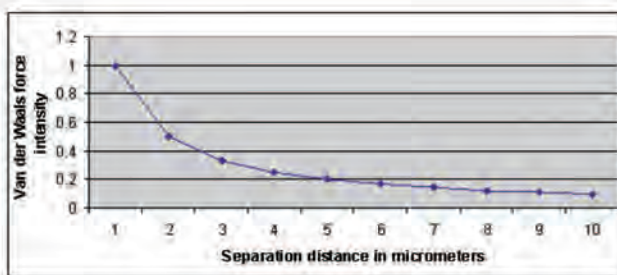


Figure 13: Force against separation distance for cone-flat interactive surfaces

3.3.2. Analysis of the different surface interactions with respect to separation distance

The last three figures were plotted on the same axes, as shown in Figure 14. All the other factors were considered constant and when integrated would produce a unit. Analysing Figure 14 (taking the force intensity at 1 μm as the comparison base), it is found that the 10% force intensity is reached at D equal to 10 μm , 3 μm and 2 μm for cone-flat, sphere-flat, and cylinder-flat surfaces, respectively. Therefore, a cone-flat interactive surface would be the best option for the maximisation of Van der Waals' forces for separation distances greater than 1 μm . Previous analysis with respect to the included-half-cone angle also proved that cone-flat interactive surfaces offered the optimum Van der Waals' forces' manipulability.

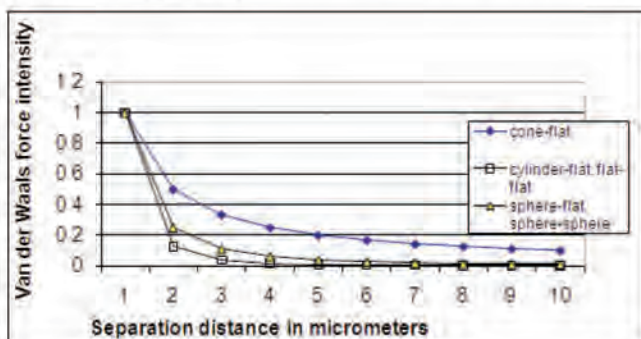


Figure 14: Comparison of sphere-sphere, sphere-flat, cylinder-flat, flat-cone and flat-flat interactive surfaces

It is evident from Figure 14 that the Van der Waals' force intensity drastically decreases as the separation distance, D , increases. As D becomes greater than 4 μm , the Van der Waals' force intensity is less than 10% (except for cone-flat interactive surfaces) as compared to the initial force when $D = 1 \mu\text{m}$. As the separation distance progresses to values greater than 4 micrometers,

the difference between the forces experienced becomes insignificant. Therefore, separation distances between the gripper and the micro-work part to be moved should preferably be less than 4 micrometers for an effective grip to be realised.

3.4. Surface roughness

Surface roughness refers to the uneven topography of a given substance. The effect of surface roughness has been studied and particles could be treated as 'smooth' when the surface asperities are less than $0.01\ \mu\text{m}$. The surface asperities drastically influence the Van der Waals' forces when they (surface asperities) are more than $0.1\ \mu\text{m}$ (Xie, 1997).

There are several approaches to the consideration of surface roughness. These include the asperity radius and the root-mean-square of the spacing of the asperities.

3.4.1. Surface roughness with respect to asperity radius

When two rough surfaces are in contact, the crests of the asperities would be in top-to-top contact as shown in Figure 15 (Li et al., 2006, DelRio et al., 2005).

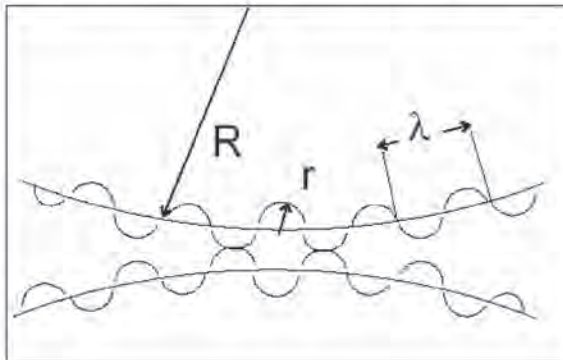


Figure 15: Objects with asperities in top-to-top contact

The objects in Figure 15 have radius, R ; asperity radius, r ; and asperity wavelength, λ (Rabinovich, 2000). The general formula for the adhesive Van der Waals' forces, F , (taking into consideration the existence of asperities at micro-level) is given in equation (4):

$$F = \alpha A \quad (4) \quad (\text{Li et al., 2006})$$

where:

α - is the intrinsic adhesiveness defined as the adhesive force exhibited on a

unit effective surface area (Li et al., 2006) measured in Nm^{-2} or $Kgm^{-1}s^{-2}$,
 A - is the effective surface contact area in m^2 .

Figure 15 infers that rough spherical surfaces have less contact area than flat surfaces (Rabinovich, 2000). Hence, in micro-material handling, the pick-up position should be curved and the placement position should be flat to increase the efficiency of 'picking up' and 'releasing' of micro-materials (Suresh & Walz, 1996).

Manipulability of the Van der Waals' forces can be realised by employing pin-like structures mounted onto a diaphragm and actuated by an intelligent gripper. These pins would contact the profiles of the asperities as shown in Figure 16. When 'picking up', sufficient pins protrude so that they form an elastic bond with the rough surface of the micro-work part. Upon releasing the work piece, sufficient pins retract to allow object releasing mimicking gecko setae (Filippov & Popov, 2006).

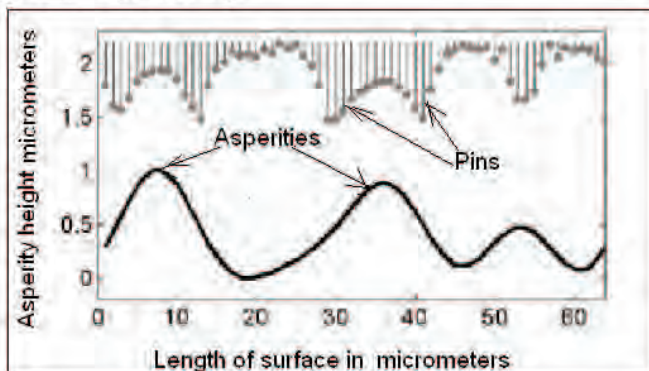


Figure 16: Diaphragm with pins (Filippov & Popov, 2006)

3.4.2. Surface roughness with respect to root-mean-square (*rms*) surface roughness

Rabinovich (2000) says Rumpf studied the effect of root-mean-square (*rms*) value surface roughness on the Van der Waals' force intensity. The noncontact and contact interaction of a spherical particle and flat surface were examined. Rumpf's equation is given as equation (5) and its bracket terms are defined in subsequent equations (6) and (7) (Li et al., 2006; Komvopoulos, 1996; Suresh & Walz, 1997; Eichenlaub et al., 2004).

$$F = \frac{AR}{6D^2} \left[\frac{1}{1 + R/1.48rms} + \frac{1}{[1 + 1.48rms/D]^2} \right] \quad (5)$$

$$\text{Rumpf's term 1 for noncontact interaction} = \frac{1}{1 + R/1.48rms} \quad (6)$$

$$\text{Rumpf's term 2 for contact interaction} = \frac{1}{[1 + 1.48rms/D]^2} \quad (7)$$

where:

rms - is the root-mean-square value of surface roughness of interacting surface

Equation (5) is also referred to as the Rumpf-Rabinovich's equation (Li et al., 2006).

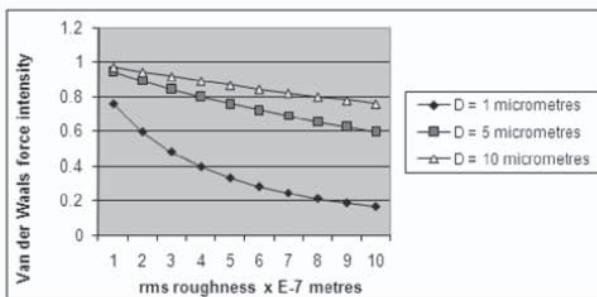


Figure 17: Effect of a surface roughness on Van der Waals' forces (using only the Rumpf's term 2, contact term)

An increase in the *rms* value at a constant separation distance, *D*, leads to a decrease in the Van der Waals' force intensity as shown in Figure 17. The smaller the radius of the particle, the more pronounced the decrease in the force. Therefore, the bigger the radius of the gripper the smaller the effect of the *rms* value (Rabinovich, 2000; Eichenlaub et al., 2006; Thoreson et al., 2006)

4. CONCLUSION

The analysis of the geometrical parameters of the different interacting surfaces has been completed. The flat-flat interactive surface has proven to exert the most Van der Waals' force compared to others, followed by cone-flat, cylinder-flat, sphere-flat and sphere-sphere interactive surfaces, respectively. A flat-surfaced gripper would be suitable for 'picking up' micro-work parts, but unsuitable for releasing. The conical micro-gripper proved to have higher Van der Waals' forces' manipulability when compared to others. When its half-cone angle exceeds 60° the Van der Waals' forces exerted increase sharply, and when below 60° the forces drop drastically, leading to an efficient and effective 'picking-and-placing' mechanism in micro-material handling. The sphere-sphere and sphere-flat arrangement proved to be difficult to

manipulate. It is recommended that the pick-up position of the work piece should be spherical and the placement position should be flat to allow for easy 'picking up' and 'releasing' of the micro-work part. On the other hand an increase in surface roughness has proven to decrease the Van der Waals' forces' intensity. The pick-up position should be rough and the placement position should be smooth for an efficient 'pick-and-place' cycle to be realised. It was also observed that pin-like structures mounted onto a diaphragm and actuated by an 'intelligent' gripper, improve the manipulation of the Van der Waals' forces. A large number of pins would be manoeuvred to contact the micro-work part during 'picking up' and would later be systematically retracted to afford 'release' in an efficient way.

A follow-up research paper would focus on the manipulation of Van der Waals' forces by the variation of the types of materials involved in micro-material handling systems.

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