THE APPLICATION OF VAN DER WAALS FORCES IN MICRO-MATERIAL HANDLING

S. MATOPE AND A. VAN DER MERWE

ABSTRACT

This paper investigates the challenges of employing Van der Waals forces in micro-material handling since these forces are dominant in micro-material handling systems. The problems include the creation of a dust-free environment, accurate measurement of the micro-force, and the efficient picking and placing of micro-work pieces. The use of vacuum suction, micro-gripper's surface roughness, geometrical configuration and material type are presented as alternatives to overcome the challenges. An atomic force microscope is proposed for the accurate measurement of the Van der Waals force between the gripper and the micro-work piece.

Keywords: Micro-material handling, Van der Waals forces, micro-work piece, micro-gripper, picking and placing.

1. INTRODUCTION

Following the market demand, the world of manufacturing research has shifted towards the manufacturing of microscopic products. Although miniature products are light and easy to handle (Raatz & Hesselbasch, 2007), Van der Waals forces play a significant role in the manufacturing of micro-products. They increase the effectiveness of grippers in work piece picking and holding because of their adhesive nature (Rollot et al., 1999). However, they make it difficult to release a work-piece. Therefore, this paper seeks to explore the nature of Van der Waals forces and how they can be positively manipulated in micro-manufacturing to grab and release on command.

Snapshots from a video (www.robots.com, 9 May 2008) show the picking and placing of pallets. The video depicts what happens at macro-scale when electromagnetism is used. This is in theory what would happen at micro-level when Van der Waals forces are manipulated. The robotic gripper should pick the object by Van der Waals forces as in Fig. 1a. Van der Waals attraction holds the material to the gripper during transfer as shown in Fig. 1b. Finally the work piece should be released efficiently as shown in Fig 1c, and in Fig 1d the robot retracts.

Figure 1a: Fanuc M-410iW Picking

Figure 1b: Transfer

Figure 1c: Place and release

Figure 1d: Robot retracts

2. DEFINITION OF VAN DER WAALS FORCES

Van der Waals forces can be simply defined as forces which exist between molecules, keeping matter as one entity (Fukuda & Arai, 1999). An advanced definition would be that Van der Waals are short-range forces, acting when surfaces are sufficiently close together, and are due to spontaneous electrical and magnetic polarisations that cause a fluctuating electromagnetic field within the medium and the gap between the surfaces involved (Debrincat et al., 2008; Zhang et al., 2007). Fig. 2 shows dipole molecules in particles or surfaces in contact or in close proximity experiencing the effect of Van der Waals forces (Tomas, 2007).

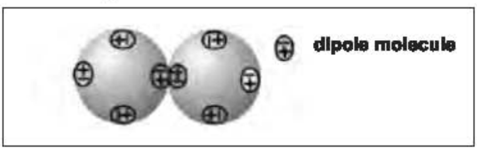

Figure 2: Van der Waals forces (Tomas, 2007)

It can be observed from Fig. 2 that a dipole is attracted to another dipole and the unlike poles pair and adhere to each other.

On the other hand micro-manufacturing refers to the processing of raw materials in the microscopic range, that is from 1 µm to 1mm range (Fukuda & Arai, 1999) using the appropriate micro-equipment.

3. THE BACKGROUND ABOUT THE DISCOVERY OF VAN DER WAALS FORCES

The first evidence of forces between molecules came from Johannes Diderik Van der Waals' 1873 PhD thesis on pressure, volume and temperature of dense gases (Parsegian 2006, pp 2). In 1937, HC Hamaker published an influential paper on Van der Waals interactions between large bodies (Parsegian 2006, pp 7). During 1948, HBG Casimir formulated the interaction between two parallel metal plates (Parsegian 2006, pp 9). In the 1950s, Lifshitz continued the work of Casimir by introducing a third media between the two parallel metal plates, instead of a vacuum (Parsegian 2006, pp 11-12).

4. FORCES IN ACTION AT MICRO-LEVEL

Research has revealed that at micro-level, the following adhesive forces among others are active: the Van der Waals force, electrostatic forces, surface tension force and capillary forces (Fukuda & Arai, 1999). It was observed that these adhesive forces have more effect on the manipulation of the micro-objects than do the gravitational forces (Fukuda & Arai, 1999).

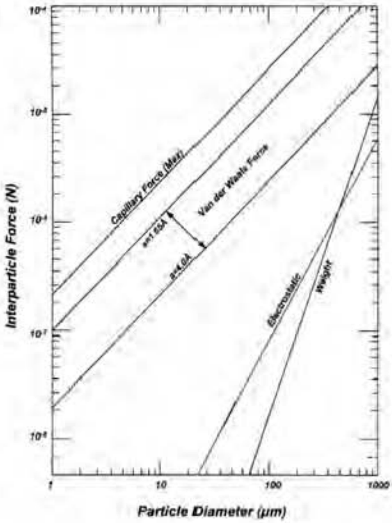

Figure 3: Theoretical inter-particle forces for single-point contact between equal spheres (in air), with particle weight plotted for comparison, where *a* is the asperity height and *A* is atomic distance (Fukuda & Arai, 1999).

From Fig. 3, it can be seen that Van der Waals forces are more prominent than electrostatic forces and gravity at micro-level when considering a dry environment (capillary force zero).

Furthermore, it has been proved that at small roughness values, in the micro-range, the adhesion is mainly due to Van der Waals dispersion forces acting across extensive non-contacting areas and that they vary with respect to the inverse of the square of the separation distance (that is, related to $1/D^2_{ave}$, where D_{ave} is the average surface separation). At large roughness values, in the micro-range, again Van der Waals forces at contacting asperities become the dominating contributor to the adhesion (DelRio et al., 2005). Debrincat et al. (2008) also support this notion when they assert that, once adhesion has taken place, the electrostatic force becomes of secondary importance while Van der Waals forces predominate. Experimental results have shown that it is the smaller particles that cause the particles to agglomerate, due to Van der Waals acting as a glue to hold larger particles together (Debrincat et al., 2008).

Therefore, the Van der Waals forces predominate at micro-level and should be studied in detail since they actively affect the micro-manufacturing environment more than other forces.

5. THE NATURE OF VAN DER WAALS FORCES AND IMPLICATIONS TO MICRO-MANUFACTURING

It was experimentally proven that Van der Waals forces do not vary linearly with the distance between the particles or surfaces under examination. Fig. 4 shows the non-linearity of the forces with respect to inter-atomic distances between two carbon nanotubes (Zhang et al., 2007). The Van der Waals forces are again complicated in that; they can either be repulsive or attractive depending on the inter-particle distance between the two items under examination as shown in Fig 4.

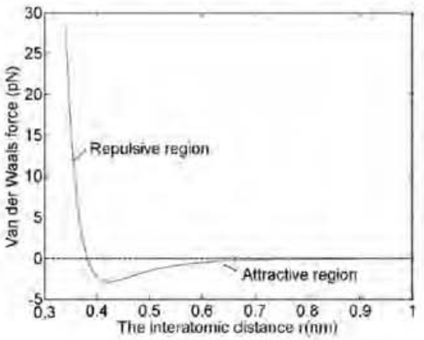

Figure 4: Van der Waals forces versus atomic distance in carbon nano-tubes

This figure indicates clearly that Van der Waals force is highly nonlinear (Zhang et al., 2007). Therefore, in micro-manufacturing, it is necessary to determine the region (for each specific material combination) in which the Van der Waals forces are attractive and repulsive so as to effectively manipulate them. One should also be aware that there is a critical separation distance between the particles where the Van der Waals forces are neither attractive nor repulsive, that is, where they have a zero value. Nonetheless, the Van der Waals forces are generally repulsive at nano-range and attractive in the micro-range. Fig. 5 shows the attractive forces between the printer-toner particles in the micro-range region.

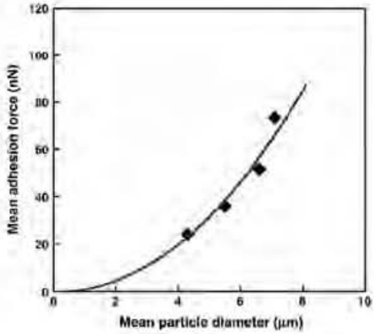

Figure 5: Relationship between the mean particle diameter and the mean adhesive force for printer-toner particles (Tanaka et al., 2008)

The particle-particle adhesive force in the printer-toner increased proportionately with approximately the second power of diameter (Tanaka et al., 2008) as shown in Fig.5. Therefore, adhesive force Van der Waals force increases rapidly with an increase in surface area of the particles because an increase in diameter leads to an increase in surface area of printer-toner. Hence in micro-manufacturing, optimum particle diameters have to be evaluated so as to realise effective grip of the micro-work pieces.

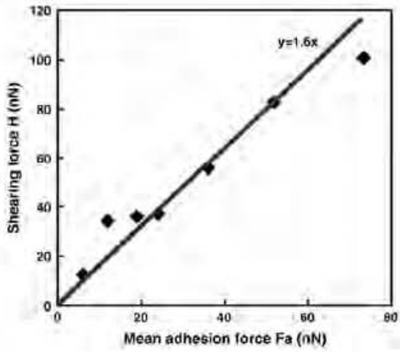

Figure 6: Relationship between the mean adhesion force, Fa, and the shearing force, H, for printer-toner particles.

Moreover, from Fig. 6, the shearing force, H, was larger than the adhesion force, Fa, and it was understood that the friction between the toner particles influenced H (Tanaka et al., 2008). Therefore it came be ascertained that in micro-manufacturing, the shearing force when micro-machining is being done should always be greater than the mean adhesive force between particles.

Furthermore, since the shearing force is directly proportional to the adhesive force at micro-level, it follows that the cutting forces during machining in micro-manufacturing are easily calculated using the factor of proportionality. Hence, a versatile metrological instrument in the form of an atomic force microscope can be developed to measure different types of forces experienced at this scale.

Since it has been observed that Van der Waals forces also depend on the geometry of the particles of surfaces under consideration (Tanaka et al., 2008), Table 1 shows the general formulas used for specific geometrical configuration of micro-materials.

Table 1: Van der Waals Interaction laws for most common object geometries (Fatikow et al., 2000)

Geometry	Force
Two flat surfaces	$f = -\frac{A_H}{6\pi D^3}$ per unit area
Two spheres	$F = -\frac{A_H}{6D^2}\frac{R_1 R_2}{R_1 + R_2}$
Sphere—flat surface	$F = -\frac{A_H R}{6D^2}$
Cone—flat surface	$F = -\frac{A_H \tan^2\theta}{6D}$
Paraboloid—flat surface	$F = -\frac{A_H}{12D^2}\frac{l_{xy}^2}{l_z}$
Cylinder—flat surface	$F = -\frac{A_H R^2}{6D^3}$

A_H is the Hamaker constant, D is the distance, R is the radius of the sphere or of the cylinder, θ is the semi-aperture of the cone, l is the semi-axis of the paraboloid. $A_H = \pi^2 C \rho_1 \rho_2$, where C is the constant in the atom–atom pair potential and ρ_1 and ρ_2 are the number of atoms per unit volume.

It is evident from Table 1 that the force of adhesion increases with an increase in contact surface area. Furthermore, the Van der Waals forces vary with the geometry of the surfaces in contact. Therefore, the geometries of the micro-work piece and the micro-gripper can be varied so as to optimise the manipulability of the Van der Waals forces at micron-level.

A further analysis of the surfaces in contact at micro-level reveals that micro-objects have some roughness which yields asperities. When two surfaces are in contact, the crests of the asperities on their surface are the ones which are in real contact at as shown in Fig. 7 (Li et al., 2006; DelRio et al., 2005).

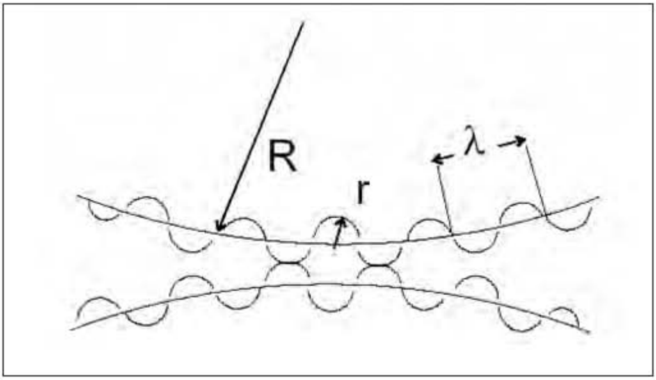

Figure 7: Particles with asperities in contact with a top-to-top contact approach

The particles in contact in Fig. 7 have radius, R; asperity radius, r; and asperity wavelength, λ. 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 1:

$F = \alpha . a$......................1 (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.

Intrinsic adhesiveness is a material property that is determined by particle roughness, Young's modulus, Poisson ratio, surface energy, and interfacial surface energy. It provides a quantitative characterisation of the adhesion tendency between small particles caused by Van der Waals force (Li et al., 2006).

Assumptions in the above equation are that:

- the particles are small, in micron range, and dry. Van der Waals attraction is the predominant inter-particle force;
- the asperities on a particle are equally sized and can be determined by root mean square values measured from the atomic force microscope (Li et al., 2006);
- when the asperities are in contact, a top-to-top contact approach is used, as illustrated in Fig. 7, and the contact area is elastically deformed (Li et al., 2006).

Therefore, the surface roughness of the substrate or base material, the micro-gripper and the micro-work piece can be varied so as to come up with an effective and efficient pick-and-place system in micro-manufacturing utilising Van der Waals forces.
Since Van der Waals forces are also affected by humidity, temperature, surrounding medium, surface condition, material, and relative motion (Tanaka

et al., 2008; Fukuda & Arai, 1999), there is a possibility that these parameters can be optimised in order to realise the efficient gripping and releasing of a miniature item during a micro-manufacturing process. Hence, experiments should be done on specific materials used in micro-manufacturing to identify these conditions.

6. MAJOR CHALLENGES IN THE MICRO-WORLD ENVIRONMENT

6.1. Dust-free environment

The environment for micro-manipulation should be clean and free of dust and small particles that could interfere with the microscopic objects being handled (Fukuda & Arai, 1999). Dust should not be generated in the micro-manipulation process. Abrasion should be avoided and most of the micro-manipulation tasks should be based on pick-and-place motion (Fukuda & Arai, 1999).

However, this is very difficult to achieve because micro-manufacturing work pieces are already at a micro-level and it is hard to distinguish between a dust particle and a micro-work piece.

6.2. Picking and releasing of the micro-work piece

When the Van der Waals adhesive force between the micro-work piece and base material is greater than that between the gripper and the work piece, the object remains stuck to the base material and cannot be picked (Fukuda & Arai, 1999). If the Van der Waals forces between the gripper and the micro-work piece are greater than that between the base material and the micro-object, then the work piece remains stuck to the gripper (Fukuda & Arai, 1999) and it cannot be released.

Evidently, the challenge is to control the Van der Waals forces between the micro-work piece, the gripper and the base material or substrate in micro-manufacturing.

6.3. Measurement of the Van der Waals forces

Force sensing down to ranges of micro-Newtons (μN) in micro-manufacturing systems raises unsolved problems (Fatikow et al., 2000). The fragility of micro-mechanical objects being manipulated in the micro-world demands the application of force sensors to avoid damaging the fragile micro-mechanical structures (Fatikow et al., 2000).

However, it is difficult to find suitable force sensors to detect these micro-objects. Investigations have started within this field to improve the capabilities of the micro-manufacturing systems by integrating force sensors into micro-robots (Fatikow et al., 2000).

7. ALTERNATIVE SOLUTIONS TO OVERCOMING THE CHALLENGES FACED IN MICRO-MANUFACTURING

7.1. Dealing with dust in micro-manufacturing

A possible solution would be to control the humidity of the micro-manufacturing environment so that dust is trapped by the dampness. Optimisation has to be done experimentally to realise the appropriate level of humidity that would lead to an effective and efficient micro-environment. Furthermore, the condensed water on surfaces in humid atmospheres helps in the lubrication of the manufacturing process. This incidentally reduces abrasion and then leads to a reduction in the generation of dust (Rollot et al., 1999). However, the surfaces should be corrosion resistant.

Micro-vacuum cleaners may also be used to suck away the dust particles. The application of pneumatics at micro-level is needed to identify the optimum suction pressures which remove nothing except the dust. Brownian motion and laws of flotation at micro-level have to be studied and applied, aided by experimental results.

Magnetic and electromagnetic forces may be used to attract ferrous dust generated during micro-machining. The strength of the magnetic and electromagnetic forces can be varied experimentally in order to reach the optimum values suitable for specific materials. The strength of these forces should not interfere with Van der Waals forces employed in the picking and placing of the micro-objects. Unfortunately, this method only applies to ferrous materials.

Electrostatic forces may be used to attract charged dust particles from the micro-manufacturing environment. However, the electrostatic forces should be manipulated in a manner avoiding interference with the material handling activities executed by Van der Waals forces.

7.2. Ways of improving the picking and placing of micro-work pieces

7.2.1. Varying the substrate or base material

The total force between a particle and a surface predominantly depends on the shape and texture of the particles (Sonnenberg et al., 2005; and Mizes et al., 2000). Hence the surface of the base material may be varied to improve the pick-and-place process. The coefficient of Van der Waals force between the base material and the micro-work piece should be low for picking, and high for releasing. This could be achieved by using different materials for the base material or by coating the other section of the base material with teflon which greatly reduces sticking.

7.2.2. Modifying the micro-gripper

To overcome the problems encountered during picking and placing, a special micro-end-effector could be developed. Such a gripper could have a modified surface configuration resembling that of a gecko's foot. Fig.8 shows a gecko moving on an inverted glass plate.

There is strong evidence that the adhesion ability of geckos is due to the Van der Waals interaction between a contacting surface and the hundreds of thousands of keratinous hairs or setae on a gecko's foot. Each seta is 30130 µm long and contains hundreds of 200500 nm projections or spatulae (Gao et al., 2005). The easy release is facilitated by the shape of the setae.

The gripper could be coated, heat-treated and have its roughness changed to resemble a gecko's setae, which would allow it to adhere and release easily as it moves upside down from one point to another (Takahashi et al., 2006: and **Huber** et al., 2007).

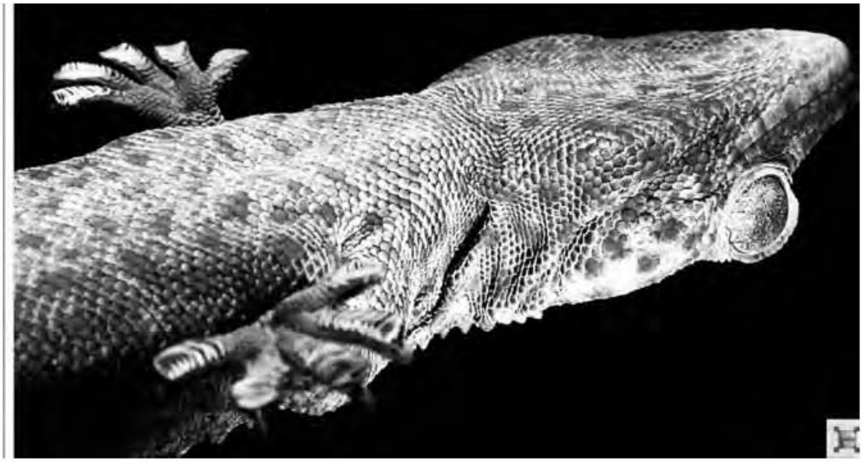

Figure. 8: Tokay gecko climbing while inverted on glass. Photo: K. Autumn (www.lclark.edu 2008)

The gripper could also be made to vibrate (Fukuda & Arai, 1999) in order to quickly release a micro-work piece, but accuracy of placement would be compromised.

The geometry of the gripper could be varied. For example, it could be micro-pyramidal or any other suitable shape depicted in Table 1 (Fatikow et al., 2000) which would optimise the micro-manipulability of the Van der Waals forces during picking and placing operations.

7.2.3. Variation of the micro-manufacturing environment

Other techniques which employ temperature change, moisture control with a micro-heater and pressure change can be administered to the micro-manufacturing environment to facilitate picking and releasing (Fukuda & Arai, 1999). It has been observed that the thickness of an adsorbent layer of water around a particle is approximately 0.35 nm (Debrincat et al., 2008). This film decreases the particle-particle separation distance leading to a significant increase in the Van der Waals force between them (Debrincat et al., 2008).

7.3. Measurement of the Van der Waals forces at micro-level

The measurement of Van der Waals forces became easier after the invention of the Atomic Force Microscope (AFM). The AFM measures force-versus-distance curves which provide valuable information on local material properties such as elasticity, hardness, Hamaker constant, adhesion and surface charge densities (Butt et al., 2005). The AFM allows experimentation on length, time, force and energy at micro- and nano-levels. These experiments can be carried out under natural conditions (Butt et al., 2007).

The AFM measures the force between its cantilever tip and the sample by monitoring the deflection, as shown in Fig. 9 (Butt et al., 2007; Butt et al., 2005).

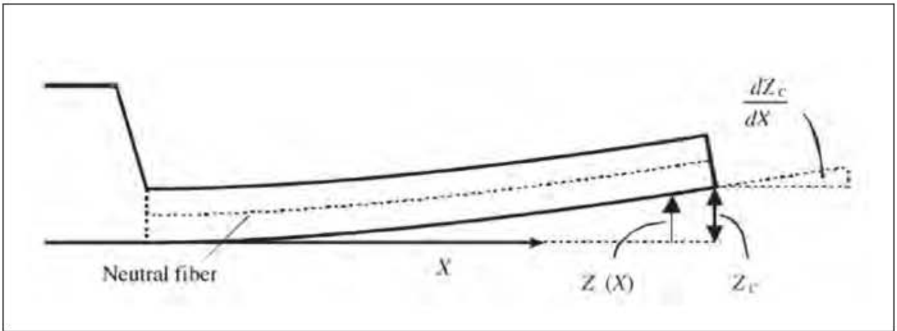

Fig. 9: Schematic side view of an AFM cantilever with a force at its end. X is the horizontal coordinate originating at the basis of the cantilever; Z(X) is the cantilever deflection at a position X; and Z_c is the cantilever deflection at its end

In a micro-manufacturing environment, some features of the AFM could be incorporated into the micro-gripper to supply information to the micro-robot as to whether a particle could be picked or released based on the Van der Waals forces being experienced, thus making the micro-robot intelligent. This improves the tactile sensing of the micro-robot so that detection of gripping and releasing of a micro-work piece is easily communicated.

8. CONCLUSION

This paper has explored the nature of the Van der Waals forces at micro-level and found them to be adhesive with an attractive effect on micro-work pieces. It has highlighted the challenges in the manipulation of Van der Waals forces during micro-material handling. Material types, topology and geometries of the micro-gripper, micro-work piece and the base material can be varied to improve the efficiency and effectiveness of a micro-material system. Strategies to eliminate dust in the micro-environment which included the application of humidity and vacuum systems were also discussed with the view of improving the efficacy of the micro-material handling system. The force sensing attributes of the atomic force microscope may be incorporated into a micro-gripper so as to make it artificially intelligent during mico-material handling. In a subsequent paper, optimisation of Van der Waals in micro-material handling through the manipulation of geometrical parameters will be considered.

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