STUDY ON APPLICABILITY OF ADHESIVE FORCES FOR MICRO-MATERIAL HANDLING IN PRODUCTION TECHNOLOGY.

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ABSTRACT

Micro-material handling and micro-assembly becomes increasingly important in large-volume manufacturing of products like sensors in automotive applications. Smaller dimensions of the micro-objects lead to problems with regard to the reliability of the manufacturing process because adhesive forces become predominant over gravity for objects whose dimensions are in the micro-range. In contrast to the common approach of minimizing those adhesive forces, this paper focuses on the use of the three main adhesive forces, van-der-Waals, electrostatic and surface tension forces, as gripping principles. These forces are compared to conventional vacuum grippers with regard to gripping forces and complexity of application. Modelling of the forces is executed for separation distances in the range of $1x10^{-12}$ m - $1x10^{-3}$ m. Even though vacuum forces dominate in magnitude over others within the whole range, there are several disadvantages of using them. On the other hand adhesive forces are advantageous in that they require little amount of energy and they do not mechanically strain the micro-parts being handled.

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1. INTRODUCTION

Industry has resorted to the use of vacuum forces in micro-material handling, but there are limitations in the extent to which these forces can be used as far as the dimensions of the micro-parts are concerned (Zech et al [1]). Also the required precision in picking and placing of the micro-object is rarely achieved (Lambert [2]). On the other hand adhesive forces namely electrostatic, surface tension and van-der-Waals forces are readily available for micro-part manipulation (Hesselbach et al [3], Lambert et al [4]). These forces dominate over gravity (Fearing [5]) in the micro-scale and hence are explored in this paper as to how effectively they can be used in micro-material handling. Their operation ranges are exposed as well as their technological applications.

2. ACTIVE FORCES IN THE MICRO-RANGE

Research has revealed that at micro-scale adhesive forces have more effect on the manipulation of the micro-objects than does the gravitational force (Fukuda & Arai [6]); Fearing [5]; Bohringer et al [7], Sanchez [8]). For masses less than the order of magnitude of 10^{-6} kg the force of gravity is less significant as compared to adhesive forces in many cases (as shown in figure 1) and the release of a micro-object from a gripper often becomes a great challenge (Sanchez [8]). Grippers employing vacuum force as an operating principle have their reliability reduced by the presence of adhesive forces in micro-material handling.

Fearing [5] compared the adhesive forces occurring in micro parts handling with mechanical grippers with gravity force as shown in Figure 1. Forces between a silicon sphere of density 2300 kg/m^3 and a flat plane were modelled. Gravity drops drastically as the micro-part's size and radius decreases. Capillary forces dominate over other forces in this micro range followed by van-der-Waals forces and then electrostatic forces (Fearing [5]; Bohringer [7]). In this analysis 1 % of the van-der-Waals forces are plotted for an atomically smooth surface (Fearing [5]) to compensate for the fact that van-der-Waals forces decrease rapidly with separation distance and also that they are greatly affected by surface roughness. This percentage also takes care of the effects of retardation. Even so, the van-der-Waals forces are more prominent than electrostatic forces and gravity at micro-level. However, as would be shown in the subsequent sections, vacuum forces predominate over adhesive forces.

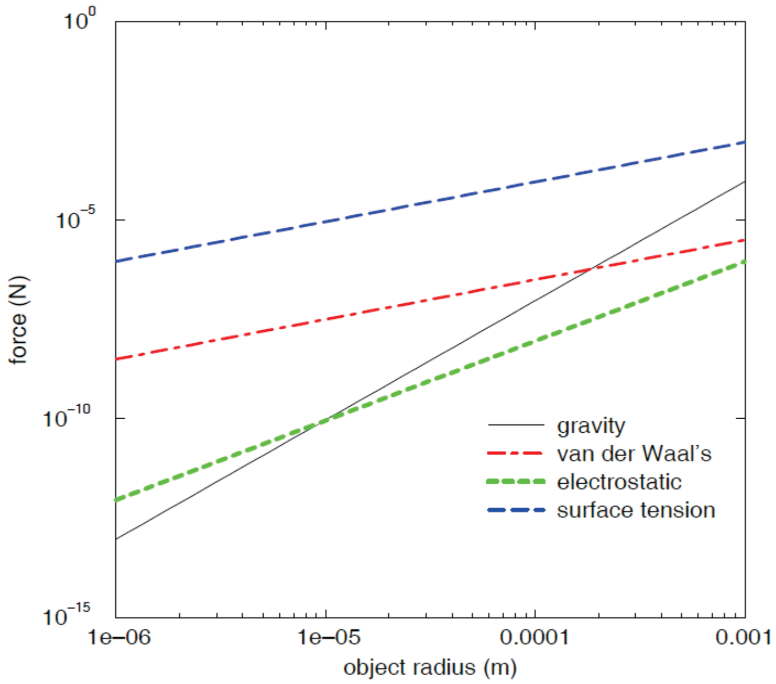

Figure 1: Comparison of forces acting in the micro-range as modelled by Fearing [5] and Bohringer et al [7]

3. COMPARISON OF ADHESIVE FORCES WITH RESPECT TO SEPARATION DISTANCE

The three adhesive forces and vacuum forces are modelled with respect to separation distance between the interacting surfaces. Micro-objects range from 10 mm down to 1 µm in dimensions (Lambert [2]) and these should be of mass not exceeding $1x10^{-6}$ kg (Sanchez [8]) in cases where gravity becomes less significant. Therefore, in this comparison, a flat micro-part (not a sphere as examined by Bohringer et al [7]) having a uniform cross-section and weighing $1x10^{-6}$ kg is considered. The materials compared are lead zirconate titanate (PZT) ceramic, polystyrene (PS), gold, copper, silicon, aluminium oxide (Al_2O_3), silver and diamond. The adhesive forces were modelled using analytical equations. The formulae used are as follows:

The van-der-Waals force equation for ideal flat surfaces is given by equation 1 (Parsegian [9], Bohringer [7])

$$F_{vdW} = -\frac{A_H}{6\pi D^3}A \ldots\ldots\ldots\ldots\ldots \qquad \text{Equation 1}$$

Where F_{vdW} – van-der-Waals force, A_H – Hamaker coefficient, D – separation distance, A - cross-sectional area of the micro-part.

The electrostatic force exerted between ideal flat surfaces can be calculated from equation 2

$$F_e = \frac{\varepsilon V^2}{2D^2}A \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 2}$$

Where F_e - Electrostatic force, V- Voltage difference between the micro-gripper and the micro-part, this is taken as 200V in this modelling, a parameter value practically used in micro-handling of piezo-ceramics with electrostatic grippers (Neugebauer et al [10]), A - cross-sectional area of the parallel plates represented by gripper and workpart. The cross-sectional area is taken as $1x10^{-4}$ m^2 for all the forces in this paper and is in line with the value used by (Neugebauer et al [10]), and D - separation distance

The surface tension force (also called capillary force) for two plates of same material such that their separation distance is small as compared to their length is given by equation 3(Lambert [19]),

$$F_s = \frac{2\pi\gamma}{D} R^2 \cos\theta \quad \text{............ Equation 3}$$

Where F_s - surface tension force, γ- surface tension constant, R – radius of the meniscus from the centre of the plates, D - separation distance. θ is the contact angle of a given liquid, water in this case, and since this paper is aimed at obtaining the limits, θ is taken to be equal to 0° so that a maximum value of cos θ = 1 is obtained.

The comparison of the adhesive forces is done in conjunction with gravitational and vacuum forces. The gravitational force, F_g, is given by equation 4.

$$F_g = \rho g V \quad \text{............ Equation 4}$$

Where ρ - density, g - gravitational acceleration, and V - volume.

Vacuum forces, F_{vac}, are modelled using equation 5 proposed by Dini et al [11] derived from Bernoulli's principle of fluid dynamics for a incompressible fluid of uniform flow (Dini et al [11]) .

$$F_{vac} = \frac{\rho Q^2}{2\pi D^2}\left[ln\frac{r_{ext}^2}{r_{int}^2} - \frac{1}{2}\left(\frac{r_{ext}^2 - r_{int}^2}{r_{int}^2}\right)\right] \quad \text{............ Equation 5}$$

Where ρ – density of air, Q – flow rate of air, D – separation distance, r_{int} - internal radius of vacuum pipe, r_{ext} – external radius of vacuum pipe.

The parameters used by Zesch et al [1] in the design of a pipette vacuum gripper are used for modelling as shown in Figure 2. The parameters are: air density, ρ – 1.22521 kg/m^3; air flow rate, Q = 1.2 x 10^{-4} m^3/s; internal radius of gripper, r_{int} - 2.5x10^{-5} m; and external radius of gripper, r_{ext} - 5.0x10^{-5} m (Zesch et al [1]) .

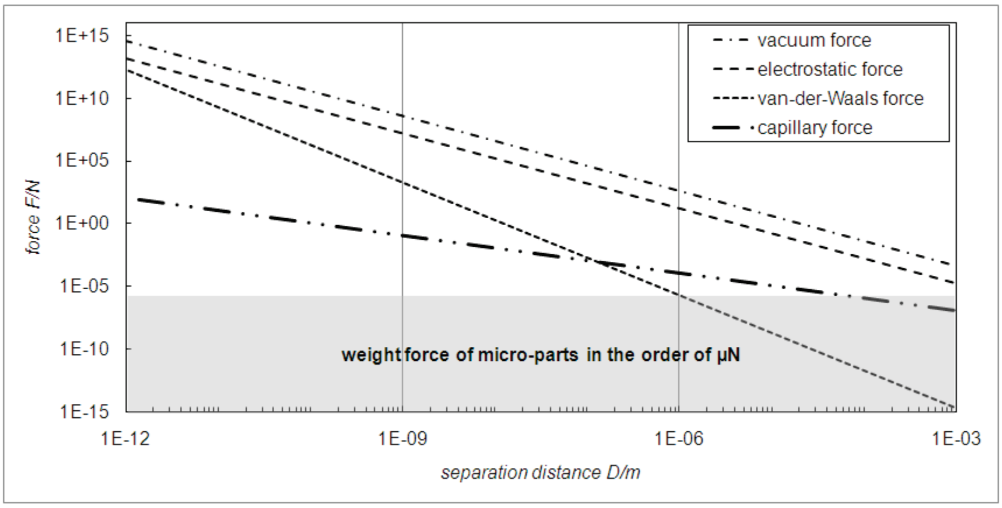

Figure 2: Comparison of gripping forces in the micro-range

It is evident from the modelling results in Figure 2 that vacuum forces predominate over others in the whole range of 1x10^{-12} m to 1x10^{-3} m, occupying the first position in magnitude and electrostatic the second. However, they cannot be used for a micro-workpart whose minimum dimension is equal or less than the internal radius of a gripper of size, 2.5x10^{-5} m.

In the $1x10^{-12}$ m to $1x10^{-7}$ m range van-der-Waals forces occupied the 3rd, surface tension 4th and as anticipated gravity the 5th. In the $1x10^{-7}$ m to $1x10^{-6}$ m range capillary force (surface tension) surpasses van-der-Waals forces coming 3rd, the latter 4th, and gravity 5th. As for the $1x10^{-6}$ m to $1x10^{-4}$ m sub-section, capillary force is 3rd, gravity supersedes van-der-Waals forces taking the 4th position and the latter 5th which is contrary to the postulations of (Sanchez [8]) and (Fearing [5]), maybe, because the plot is done against separation distance (instead of radius) and also that a flat micro-part is being considered in this case instead of a spherical one. The contrary is exhibited again in the subsequent sub-range. However, (Fearing [5]) also supports this when it says that van-der-Waals forces are short-range forces effective in the 0-100nm range.

Finally, in the $1x10^{-4}$m - $1x10^{-3}$m region, gravity predominates over capillary force taking the 3rd position and the latter 4th, and as expected the van-der-Waals forces occupy the 5th position.

4. LIMITATIONS FOR USE OF VACUUM FORCES IN MICRO-MATERIAL HANDLING

From the preceding section vacuum forces have proved to be strong in picking micro-materials as they exceeded the other forces in magnitude. They have been employed in handling micro-parts of dimensions not less than the internal diameter of the gripper of $2.5x10^{-5}$m (Zech et al [1]).

However, there are several limitations in using them. With the varying complexity of micro-parts, disadvantages of vacuum grippers include the following:

1. There is a limit to the size of their internal micro-hole construction since it is difficult to manufacture.
2. This in turn limits the size of micro-parts they pick since their dimensions have to exceed the internal diameter of the gripper or else they are sucked into the vacuum chamber. Zech et al [1] used their gripper in picking diamond particles ranging from 300µm down to 50µm, and no further than that, with a success factor of 75% (Zesch et al [1]).
3. Micro-parts cannot easily be released from them (Huang et al [12]). Zech et al [1] had to employ an external probe to release the other 25% of their diamond particles.
4. The precise release of a micro-part is hard to achieve (Zesch et al [1], Huang et al [12], Guoliang & Xinhan [13]).
5. Micro-parts are likely to be sucked into the vacuum channels clogging the system.
6. They impose high mechanical strain on micro-parts.
7. They do not work well with porous micro-materials (Vandaele et al [14]).
8. They do not work in a vacuum environment since they depend on outside pressure (Vandaele et al [14]).
9. They require a pneumatic system, in some cases, which includes pumps, valves and controllers (Huang et al [12]).
10. They are not suitable for collapsible and soft materials which easily get drawn into the vacuum channels jamming the system (Vandaele et al [14]).

These disadvantages of vacuum forces lead to the exploration on the applicability of adhesive forces in micro material handling. Each force is examined in the subsequent sections with the objective of optimising its use in micro-material handling operations.

5. EMPLOYMENT OF ADHESIVE FORCES IN MICRO-MATERIAL HANDLING

For an effective micro-material handling system to be realised, the appropriate adhesive force upon which the gripping principle is based should be selected and the gripper has to be adapted to the gripping task. This can be realised by maximising the selected force and minimising all other active forces. In many cases, attention has to be paid in particular to the releasing of the micro-workparts because of decreased effect of gravity compared to the gripping forces. The subsequent sub-sections show approaches for adapting and optimising given micro-material handling systems to particular gripping tasks.

5.1 Surface tension gripper

A surface tension actuated gripper consists of at least two interacting surfaces with a liquid in between. Water is used often in the surface tension actuated gripper because it is readily available in liquid form, appears in the atmosphere as vapour and is stable in both phases at ambient conditions. When picking a micro-part the interface tension of the liquid between the surfaces of the micro-gripper and the micro-part should be higher than the interface tension of the liquid between micro-part and the substrate of the pick-up position. Since the resulting surface tension force depends on the contact area, to improve reliability in picking, the interactive surfaces between the micro-gripper and micro-part should be larger than that between the part and the substrate. In cases where picking of a micro-material is a problem, a hydrophilic coating is applied on the gripping surface so that the contact angle is reduced to minimum to allow the exertion of a stronger surface tension force on the micro-part so as to realize grip.

When releasing, the interface tension of the liquid between the gripper and micro-part should be less than that between the micro-part and the placement position's surface. To improve release, the contact area between the micro-part and the placement position substrate should be greater than that with the gripper (Lambert [2]). A micro-heater and a dry stream of nitrogen, as mentioned earlier, may be used to aid release. A hydrophobic coating may be integrated in a reconfigurable micro-gripper to reduce the surface tension on a micro-part during the release operation (Arai et al [15]). Capillary forces have been used in the handling of 0.3mm and 0.5mm diameter balls (Lambert et al [4]).

In some troublesome cases, the gripper and the micro-particle are immersed into a liquid medium to change the equilibrium so as to release a micro-object (Weisenhorn et al [16]. Another option would be to release the micro-part in a vacuum since surface tension forces are reduced to a zero value in such an environment (Lambert [2]).

Limitations of capillary forces are that they cannot work in a vacuum, they form an oxide layer on corrosive materials, cannot work for contact angles of 90^o (as in the case of water and silver), and cannot work for contact angles greater than 90^o (as in hydrophobic cases for example, water on Teflon makes a contact angle of 180^o) since they become repulsive. On the other hand electrostatic forces do not have these disadvantages.

5.2 Electrostatic force gripper

An electrostatic gripper basically consists of one (unipolar) or two (bipolar) electrodes. Their working principle is the accumulation of opposite charges on gripper surface and micro-part surface. For a reliable picking, the voltage and the interactive surface area between the micro-gripper and micro-part should be optimised. In cases where gripping force is insufficient for picking electrode configuration can be changed, voltage can be increased or the micro-part's material can be changed to one with higher permittivity to allow higher electrostatic forces to be exerted on the micro-part.

For releasing, the voltage-supply is switched off and micro-parts fall of the gripper by gravitational force. In case of an unsuccessful release due to residual charges, parts and gripper can be grounded to support the release (Lambert [2], Feddema et al [17]). If it happens that parts are still not released after this, the part should make contact with placement position so that the adhesive van-der-Waals forces may lead to the final release of a micro-part. Conductive materials that do not easily form insulating oxides may also be incorporated in an electrostatic micro-gripper to act as part of an ejection mechanism (Fearing [5]). However, this is very difficult to achieve at micro-scale.

Electrostatic forces have been used in the handling of automotive piezo-ceramic sensors of 10mm length (Neugebauer et al [10]), metallic cylinders of diameters within the range of 0.25-1mm and length of 1-4mm (Fantoni [18]), glass spheres of 100-800µm diameters (Hesselbach et al [3]). However, they are not suited for sensitive integrated circuits' (IC) components (Piers [19]).

Limitations of electrostatic forces are that they require a dielectric coating, they cannot work in aqueous conditions or liquid immersions, they leave residual charges on micro-workparts after operation, and they require electrical supply or other charging means. It should be noted that the disadvantages of electrostatic and surface tension forces do not apply in the case of van-der-Waals forces.

5.3 Van-der-Waals force gripper

Van-der-Waals forces are inherent in nature and they are experienced when at least two surfaces interact. There are three main strategies of manipulating the van-der-Waals force. These include the variation of the interacting material types, geometrical configurations and surface roughness. Focusing on the material type, for reliable picking of micro-workparts the micro-gripper should have a significantly higher value of the Hamaker Coefficient than the substrate of the picking position. As for the release of a micro-workpart the reverse applies, the micro-gripper should have a significantly lower Hamaker Coefficient value than the placement position's substrate. Van-der-Waals forces were used in the production of wall-climbing robots of masses of at least 0.1 Kg (Murphy et al [20], Murphy et al [21]).

To improve the reliability of van-der-Waals forces in a micro-material handling system, the geometrical configuration of the interacting surfaces should be systematically varied. For an efficient picking to be realised, the substrate of the picking place should be convex to reduce the contact area and the gripper surface should be flat to increase the area of contact and hence exert more force than the latter. When releasing, the placement position should have a larger contact area on the micro-part than the gripper (Parsegian [9]).

The third strategy is to employ variation in surface roughness. The rougher the surface the less the van-der-Waals forces exerted, the smoother the surface the more the van-der-Waals forces (Fearing [5], Vogeli & von Kanel [22], Zhou & Nelson [23], Rabinovich et al [24], Lambert & Delchambre [25]). For an effective picking the gripper should have a less value of the root-means-square (*rms*) than the picking position's substrate in order for a greater force to be exerted on the micro-part by the gripper. As for an efficient release, the placement position's substrate should have a less *rms* value than the gripper's.

For these strategies to realize optimum efficacy other forces should be eliminated or minimized. Electrostatic forces can be eliminated by grounding all equipment of any such force (for example the use of an anti-static mat as shown in the experiment in Figure 3). The surface tension force can be reduced by employing a micro-heater to heat up the environment so as to reduce the humidity level (Fukuda & Arai [6]) or by passing a continuous flow of dry nitrogen (Fearing [5], He et al [26], Zhou & Nelson [23]). The electrostatic and surface tension forces may also be eliminated by immersing the interacting surfaces into a liquid.

Limitations of Van-der-Waals forces are that they require a very clean environment, and they are generally short-range forces (Israelachvili [27]).However, the advantages of Van-der-Waals forces over other adhesive forces are that, they are applicable to all materials, can work in a vacuum, can work in aqueous conditions, are applicable in all states of matter, and they do not require an external energy source. Since Lambert [2] indicated that the application of van-der-Waals forces in micro-material handling has not yet been exploited thoroughly, experimental work on the application of van-der-Waals forces is explained in the following section so as to benefit from the highlighted advantages.

5.4 Experimental description on van-der-Waals forces

Polyurethane has been used in the design of wall-climbing robots because it exerts a lot of van-der-Waals forces on given surfaces (Murphy et al [20], Murphy et al [21]). Therefore, the first group of experiments was executed on two grades of polyurethane (one of a shore hardness of 30 and other of 60). The aim was to find their applicability in micro-material handling operations. Each grade was supplied in two parts stated as A and B. The parts were thoroughly mixed for at least 3 minutes as per manufacturer's specifications (Advanced Materials Technology (Pty) Ltd). A releasing agent was sprayed onto the interior walls of the moulds to allow easy removal of the product after curing. After pouring, the moulds were cured in a 70^0C oven for more than 24 hours (the time corresponding to the manufacturer's specifications). The moulded parts were removed from the moulds and were used as interactive surfaces for micro-material handling operations.

Experiments proved that both grades of polyurethane could pick different types of micro-materials from several types of surface (which include wood, glass, metals, Perspex, polyvinyl chloride (PVC) and other polymer materials). Square micro-parts of 10 mmx10 mm with thickness less than 500 µm, and made of silicon coated with copper were picked. It was observed that polyurethane of 60 shore hardness exerted less van-der-Waals forces than that of 30 shore hardness. Therefore, in a picking-and-placing cycle the former was used for the gripper's interactive surface and the latter for the releasing place as shown in Figures 3 to 5. The figures show a micro-part picked by a micro-gripper (made of polyurethane of shore hardness value of 60) from an anti-static mat (supplied by RS Components Company) and released onto the polyurethane interactive surface of 30 shore hardness. The anti-static mat and crocodile clip discharged the pick-up place, micro-part, releasing place and the micro-gripper of any electrostatic charge which could interfere with the van-der-Waals forces.

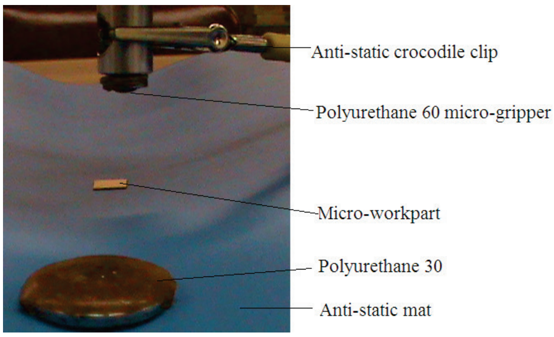

Figure 3: Initial arrangement before picking

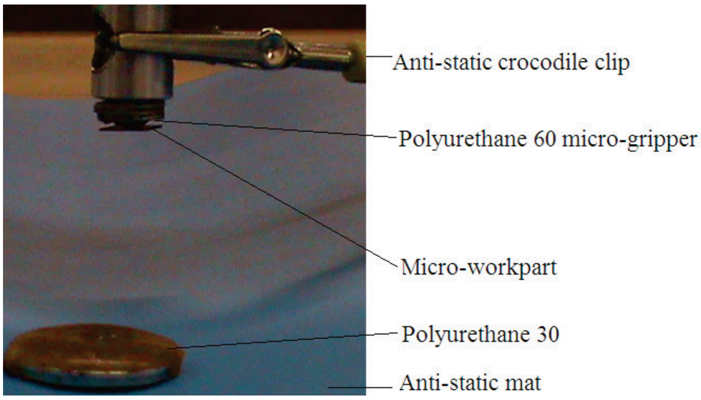

Figure 4: Pick-and-transfer by the van-der-Waals gripper

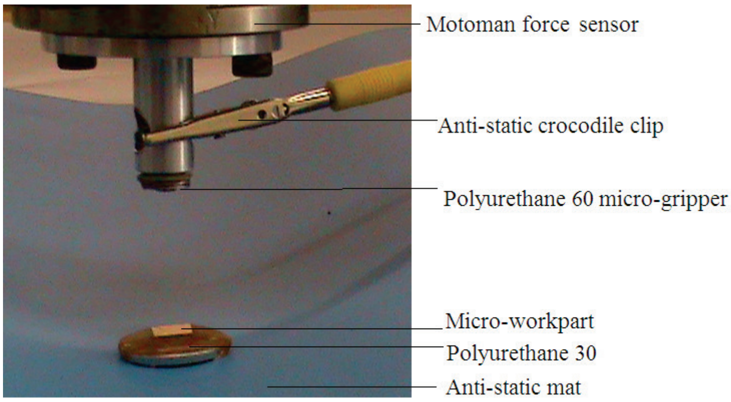

Figure 5: Placement of the micro-work part

The second group of experiments was conducted on two electron-beam-evaporation (e-beam) coatings of copper on silicon substrates. These types of materials were selected because they are widely used in sensitive integrated circuits (IC) of electronic devices where the application of van-der-Waals forces would be a preferred option given the limitations of electrostatic and surface tension forces highlighted earlier.

The first e-beam deposited copper coating was executed for 5 minutes (Cu 5) and the other for 20 minutes (Cu 20). The coatings had root-mean-square (*rms*) surface roughnesses of 2.72 nm and 217 nm. An Atomic Force Microscope model Asylum MFP 3 D-Bio with version 6.22A software was used to measure the actual van-der-Waals forces exerted by the e-beam deposited samples. Its cantilever had a silica sphere (at the end) of a radius of 2.5 µm with an *rms* surface roughness value of 0.2 nm. The spring constant, *k*, of the cantilever was 0.27 N/m. The velocity of approach and retract of the silica sphere was 2 µm/s. The aim of the experiment was to validate the applicability of van-der-Waals force in picking-and-placing operations by varying the surface roughness parameter. The experimental conditions were as follows: the temperature was 23^{o}C, atmospheric pressure was 101.325 kPa and the humidity level was 20%.

The amount of van-der-Waals forces exerted by the e-beam coatings was determined from the retracting curves as pull-off forces. Initially, the AFM silica sphere would be in contact with the sample under examination and then separated from it, generating a retracting curve of the van-der-Waals forces,F, (in nN) against jump-off distance, H, (in nm). The Cu 5 exerted a larger van-der-Waals force of 26 nN (as in Figure 6) as compared to 17.5 nN of Cu 20 (as in Figure 7). Therefore, the Cu 5 coating can be used as a gripper's interactive surface for picking micro-parts from a Cu 20 base. In cases where Cu 20 is used as the gripper's surface, then the releasing place should be made of Cu 5 for a reliable release. Hence, the rougher the surface the less the van-der-Waals forces exerted as evidenced by the experimental results.

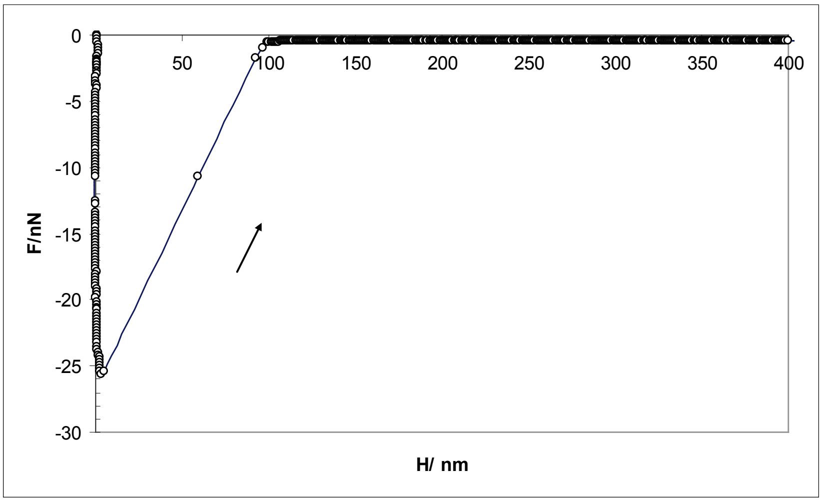

Figure 6: Retracting curve for Cu 5

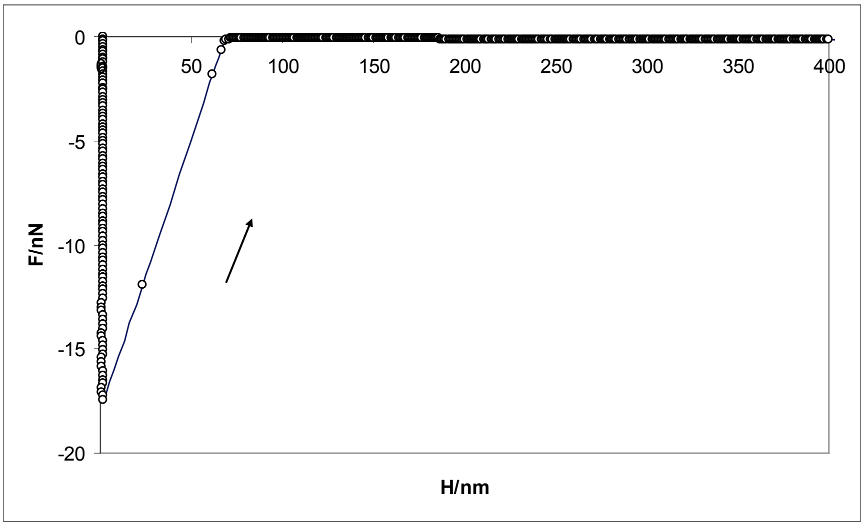

Figure 7: Retracting curve for Cu 20

6. CONCLUSION

A comparison on the application of vacuum forces and the three main adhesive forces in micro-material handling was executed. The adhesive forces considered are van-der-Waals, surface tension and electrostatic forces. These forces predominate over gravity in the manipulation of micro-objects. Modelling of the forces is executed for separation distances within the $1x10^{-12}$ m - $1x10^{-3}$ m range for selected interactive surfaces. Vacuum forces dominate in magnitude over others in this whole range and electrostatic forces come second. In the sub-range of $1x10^{-12}$ m - $1x10^{-7}$ m Van-der-Waals forces come third in magnitude and surface tension forth. In the $1x10^{-7}$ m - $1x10^{-6}$ m range capillary force (surface tension) surpasses van-der-Waals forces coming third, the latter fourth, and gravity fifth. As for the $1x10^{-6}$ m - $1x10^{-4}$ m sub-section, capillary force is third, gravity supersedes van-der-Waals forces taking the fourth position and the latter fifth. In the last sub-range of $1x10^{-4}$m - $1x10^{-3}$m, gravity predominates over capillary force taking the 3rd position and the latter 4th, and as expected the van-der-Waals forces occupy the 5th position. This anomally of the last two sub-sections where gravity supersedes the indicated adhesive forces is attributed to the fact that separation distance is the comparison base {instead of radius (Fearing [5], Bohringer [7])}, a flat micro-part {instead of a spherical one (Fearing [5], Bohringer [7])} of mass $1x10^{-6}$kg (Sanchez [8]) is considered and also the fact that van-der-Waals forces are short-range force which are mainly effective in the 0-100nm range (Fearing [5], Bohringer [7]). Since the vacuum grippers exert a large force, they are suited for very large parts whose dimensions do not exceed the internal radius of the gripper, otherwise clogging would happen. Hence they are not suitable for sub-micron objects. Electrostatic forces are also very strong depending on the supply voltage and they can handle a wide range of micro-objects, but cannot work in aqueous conditions. Surface tension grippers have the advantage of self-alignment and are suitable for transfer and positioning of micro-objects, but cannot work under vacuum conditions. On the other hand, van-der-Waals forces can work in these conditions and they are always active even when the operating principle of the gripper is not based on them. They are mostly suitable for the handling of small micro-parts of any material type, geometrical configuration and surface roughness. Experiments provided evidence that different magnitudes of van-der-Waals forces are exerted by different types of materials. Two type of polyurethane of shore hardness 60 and 30 can be used for micro-material handling purposes with the former suitable for the gripper's material and the latter for the releasing place. Copper e-beam coatings of different surface roughness also showed significant differences in the amount of van-der-Waals forces they exerted. The Cu 5 with a 2.72 nm *rms* value exerted 26 nN, and Cu 20 (of 217 nm *rms* surface roughness value) exerted 17.5 nN proving that the former can be used for the placement area's surface and the latter for the gripper's interactive surface in the handling of micro-parts, for example sensitive IC components of electronic devices.

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