Decision Support System for Van-Der-Waals Forces Actuated Micro-Material Handling Operations

S. Matope and A.F.Van der Merwe
Department of Industrial Engineering
University of Stellenbosch, 7600, South Africa

Abstract

Adhesive forces, which include Van-der-Waals forces, play a decisive role in the micro-material handling of micro-parts involved in the assembly of micro-components. This paper presents a decision support system (DSS) intended for the effective utilisation of Van-der-Waals forces in micro-material handling operations. The DSS takes advantage of three parameters: material type, geometrical configuration and surface roughness; upon which the Van-der-Waals forces depend. It develops three basic strategies, depending on these parameters, to deal with relatively simple micro-handling tasks. For complicated micro-material handling operations it presents hybrid strategies. Four alternatives of the hybrid strategies are proposed to cater for the variable complexities experienced in micro-material handling operations. The paper also stipulates the criteria under which the identified strategies are functional.

Keywords:
Decision support system, Van-der-Waals forces, micro-material handling.

1. Introduction

Little work, if any, has been done towards the development of a decision support system (DSS) for the application of Van-der-Waals forces in micro-material handling operations. This paper explores a DSS for micro-material handling operations which employ Van-der-Waals (VdW) forces as their gripping principle. The DSS is developed based upon three parameters on which Van-der-Waals forces are depended. These are: material type, geometrical configuration and surface roughness.

2. Theoretical background

Nature, as in the case of geckoes, is utilising Van-der-Waals forces in scaling walls of various inclinations, even including inverted planes (Autumn, 2003; Glassmaker et al, 2004). Murphy et al 2011 have also employed Van-der-Waals forces in developing wall-climbing robots of 0.185 kg masses. Matope et al (2010), Matope et al (2011), Matope et al (2012a) have shown that Van-der-Waals forces can be used for micro-material handling operations when the handling strategies are developed based on the parameters upon which the Van-der-Waals forces depend. One of such parameters pointed out by Parsegian (2006) and Israelachvili (2011) is material type. Each material has a specific Hamaker Coefficient (Parsegian, 2006; Israelachvilli, 2011). Some metals, for example silver, have relatively higher Hamaker Coefficients than aluminium, and materials like Teflon have the lowest value (Parsegian, 2006). However, it should be noted that the Hamaker coefficients of solid materials in air are generally of the order of 10^{-19}J (Bergstrom, 1997, Parsegian, 2006, Israelachvili, 2011)

Geometrical configuration is another parameter upon which Van-der-Waals forces depend (Parsegian (2006), Israelachvili (2011), Van der Merwe and Matope (2009), Matope and Van der Merwe (2010), Matope et al (2011), Matope et al (2012a)). For an example, the non-retarded Van-der-Waals force, *F*, between two equal-sized spherical particles (sphere-sphere) is given as in Equation 1(Weber W. M., Hrenya M. C., 2007; Thoreson, E.J., Mart, J. and Burnham, N.A., 2006; Fatikow, S., Seyfried, J., Fahlbusch, S., Buerkle, A., Schmoeckel, F., 2000).

$$F = -\frac{A_H R}{12L^2} \quad (1)$$

Where R is the sphere's radius, A_H is the Hamaker coefficient, L is the shortest surface-to-surface separation distance between the spheres. As the radius increases, the force increases.

The Van-der-Waals forces for a sphere-flat surface interaction (sphere-plane) are given by Equation 2 (Parsegian, 2006, Takahashi, K., Berengueres, J.O.L., Obata, K.J., Saito, S., 2006; Weber W. M., Hrenya M. C., 2007; Thoreson, E.J., Mart, J. and Burnham, N.A., 2006).

$$F = -\frac{A_H R}{6L^2} \tag{2}$$

Where R is the radius of the sphere, A_H is the Hamaker coefficient, L is the shortest surface-to-surface separation distance between the spheres. As the radius increases, the force increases. Equations 1 and 2 were developed based on known, approximate specific energy (given per unit area) of Van-der-Waals interaction between two planes (Derjaguin 1934) related to the geometry of interacting objects.

When two flat surfaces are interacting, the flat-flat surface interaction (plane-plane) is shown by Equation 3 (Fatikow, S., Seyfried, J., Fahlbusch, S., Buerkle, A., Schmoeckel, F., 2000; Israelachvili, 2011).

$$F_{pp} = -\frac{A_H R}{6L^3} \tag{3}$$

Where F_{pp} is the Van-der-Waals plane-plane force per unit area. This equation was obtained by differentiating the specific energy expression with respect to the distance L.

Comparing Equation 1 and 2, sphere-plane force is twice as large as sphere-sphere force. As for the plane-plane interaction, Van der Merwe and Matope (2010) analytically modelled the Van-der-Waals forces exerted by different geometrical configurations and found that it (plane-plane) exerts the largest Van-der-Waals force as compared to other configurations.

Rabinovich et al (2000a) and Rabinovich et al (2000b) revealed that surface roughness is another parameter upon which Van-der-Waals forces depend on. In some cases surface roughness is found to override the effect of material type (Matope et al, 2012b) and geometrical configuration. This happens when the root-mean-square (*rms)* surface roughness value is larger than 1-2 *nm* and the Hamaker coefficient is of the order of 10^{-19} *J* for a given material. It should be noted that *rms* surface roughnesses of the micro-parts can be varied (for manipulation purposes) for any given material, whilst the Hamaker coefficient is always constant for a specific material (Matope et al, 2012a).

A micro-material handling operation actuated by Van-der-Waals forces consists of four elements: the picking position, micro-part to be handled, micro-gripper and placement position. The micro-material handling system has three main pairs of interactive surfaces which are between: a) the placement position and the micro-part, b) the micro-part and the micro-gripper, and c) the micro-part and the placement position.

The criteria for a reliable pick-transfer-place cycle of a micro-part in micro-material handling system is that: the picking place should exert less force on the micro-part than the micro-gripper (for picking to take place), and the placement position should exert more force on the micro-part than the micro-gripper (for an effective release operation to be achieved), (Matope et al, 2011). It should be emphasized that for picking to be realised, the combined weight of the micro-part and the Van-der-Waals forces exerted by the picking position should be less than the Van-der-Waals forces exerted by the micro-gripper. The picking position must be firmly supported on its base so as to avoid its being picked together with the micro-part. For a reliable release of a micro-part, the placement position should exert greater Van-der-Waals forces than the combined effect of the weight of the micro-part and the gripper's Van-der-Waals forces (this covers cases in which the micro-part is released onto inverted walls). In addition to that, the gripper and the placement position should be firmly supported in order for a transfer of the micro-part to take place.

3. Experimental Findings

An electron beam evaporation method was used to prepare four samples using a high vacuum electron beam evaporator (Varian 3117 model) as detailed in earlier publications by the authors in Matope et al (2011), Matope et al (2012a) and Matope et al (2012b). An Atomic Force Microscope (Asylum Research MFP3D AFM, Santa Barbara, CA) with colloid probe (Ducker et al, 1992) was used to measure the interaction forces between the e-beam deposited films and silica spheres glued onto cantilevers, again as detailed by the authors in their previous publications (Matope et al 2012a, Matope et al 2012b). Some experimental findings on five samples (which were published by the authors earlier) are considered in this case as shown in Table 1.

Table 1: The Van-der-Waals forces, Hamaker coefficients and surface roughness of experimental samples

Sample	Hamaker Coefficients, zJ (Parsegian, 2006)	*rms* surface roughness value, nm (Matope et al, 2012b)	Experimental Van-der-Waals force*, nN (Matope et al, 2012b)
Copper, Cu 5.1	400	2.72	24
Copper, Cu 5.2	400	1.50	28
Copper, Cu 20.2	400	0.90	36
Silver, Ag 20.1	500	1.41	111
Silver, Ag 5.1	500	0.5	314

*Force was measured between silica sphere probe of 2.5 μm radius and flat metallic samples

The alpha-numeric labelling of samples in Table 1 is explained as follows: the alpha part refers to the chemical symbol of the material, the first number refers to the e-beam deposition time in minutes and the second number refers to the batch number. For example: Cu 5.1 refers to a copper material, e-beam deposited for 5 minutes, batch number 1; Cu 20.2 refers to a copper material, e-beam deposited for 20 minutes, batch number 2.

From Table 1 it is observed that, for a given type of material (for example copper sample), as the surface roughness increases, the Van-der-Waals force decreases (in agreement with Rabinovich et al, 2000a; and Rabinovich et al, 2000b). Furthermore, it is evident that materials of higher Hamaker coefficients exert larger Van-der-Waals forces than those of less Hamaker coefficients (in agreement with Parsegian (2006) and Israelachvili (2011)).

4. Strategies and Decision Support Systems for using Van-der-Waals Forces in Micro-Material Handling Systems

Based on the experimental findings and literature review, four main strategies for employing Van-der-Waals forces are developed. These are based on the controllable properties of the interacting surfaces, namely; material type, geometrical configuration and surface roughness variations. It should be noted that material type is the fundamental parameter upon which Van-der-Waals forces are based because all interacting surfaces in a micro-material handling operation are made of a specific type of material. The second parameter, geometrical configuration, then builds on the material type because each interacting surface has a specific geometry. The third parameter, surface roughness, builds on the geometrical configuration as shown in Figure 1.

Four main strategies of employing Van-der-Waals forces in micro-material handling systems are presented in this paper based on the three mentioned parameters (Figure 1). These strategies are referred to as Strategy 1 (based mainly on material type), Strategy 2 (based mainly on geometrical configuration), Strategy 3 (based mainly on surface roughness) and Strategy 4 (a hybrid strategy based on at least two of the parameters upon which Van-der-Waals forces depend). A decision support system (DSS) is also developed, as illustrated in Figure 2, to aid in the identification of the correct strategy to use in a given micro-material handling situation.

The first step in the synthesised DSS is task definition. This includes the identification of the material type, geometrical configuration and surface roughness of the interacting surfaces in the micro-material handling system under consideration. Next is the selection of the correct strategy governed by the pick-transfer-place criteria as discussed in the ensuing sections. These strategies are developed for a flat surfaced micro-part (to be handled) of uniform *rms* surface roughness values on both sides.

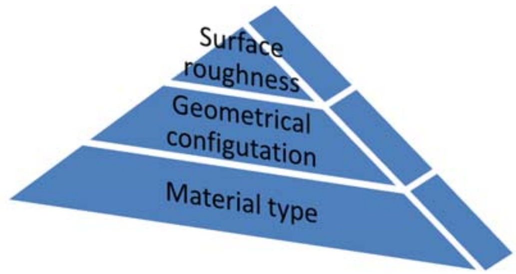

Figure 1: Strategical hierarchy of parameters for VdW force actuated micro-material handling operations.

The fundamental strategy, Strategy 1, employs only the variation of material type for Van-der-Waals force micro-material handling operations. In this strategy the geometrical configuration and the surface roughness of the interacting materials are correspondingly equal or the same. This strategy requires that material types be logically varied in order to improve the reliability of a pick-transfer-place cycle. Since the exerted Van-der-Waals forces vary directly as the Hamaker coefficient of a given material (Equations 1, 2, and 3) the micro-gripper should exert a higher Van-der-Waals force (by having a higher Hamaker coefficient) on the micro-part than the picking place. For an effective release to be realised, the material of the placement position should exert higher Van-der-Waals forces on the micro-part than the micro-gripper. For example, given the Hamaker coefficients of silver, copper and aluminium as 500 zJ, 400 zJ and 145 zJ respectively (Parsegian, 2006), a reliable micro-material handling system would have copper gripper picking a micro-part from an aluminium surface and transferring it onto a silver base. Upon contact the silver base would detach the micro-part from the copper gripper.

In micro-material handling operations where the interacting materials are of the same material type and of equal *rms* surface roughness values, Strategy 2 should be employed. This strategy utilises the logical variation of the geometrical configuration of interacting materials for an effective micro-material operation to be realised. Since Van-der-Waals forces vary directly as the interactive area between the objects involved, this strategy requires the picking position to have less interactive area than the micro-gripper on a given micro-part as shown in Figure 3 (Stage 1). Subsequently, the placement position should have a greater interactive area than the micro-gripper for an easy release of the micro-part to be realised as in Figure 3 (Stages 3 and 4).

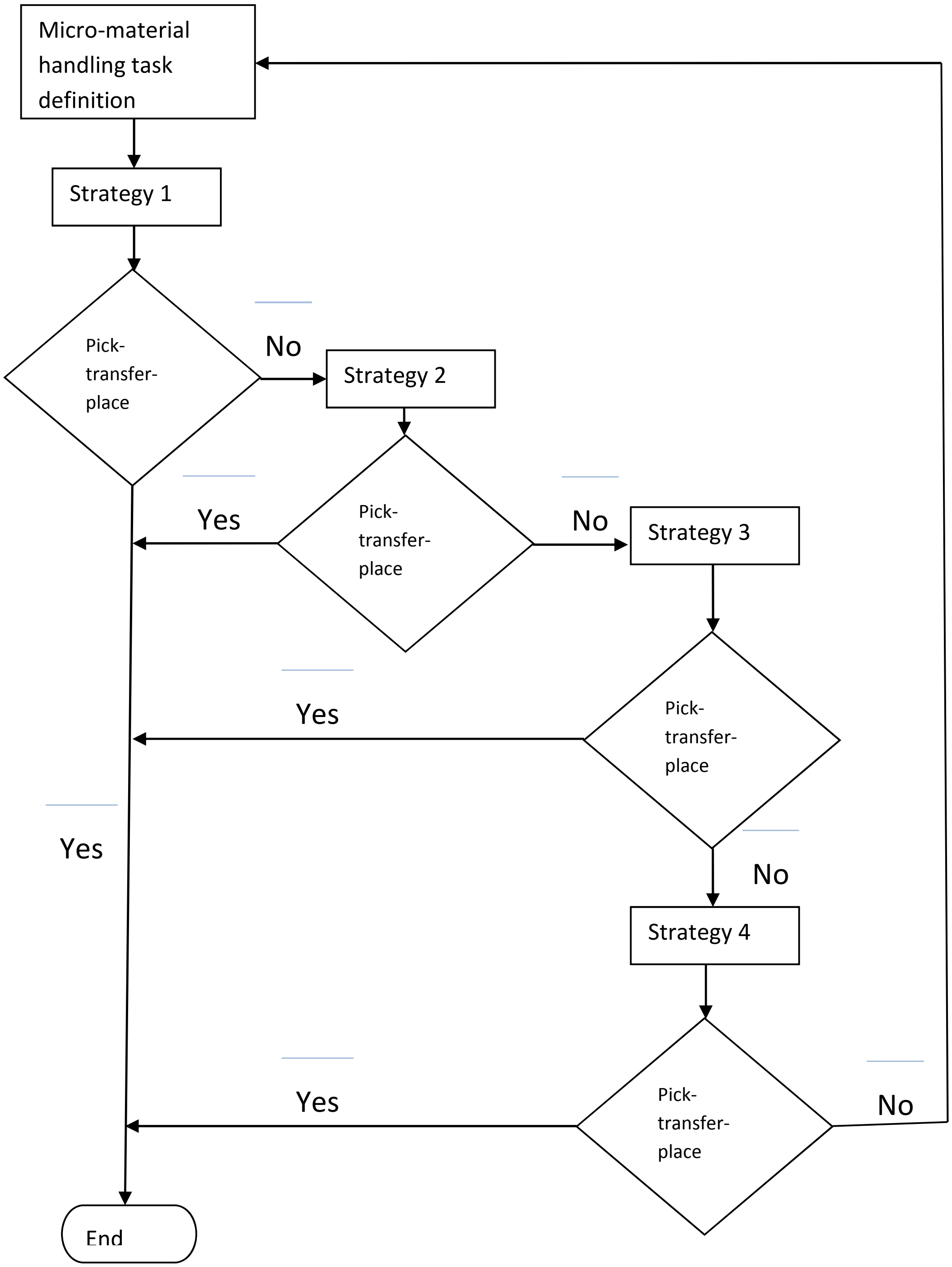

Figure 2: DSS for micro-material handling strategies employing VdW forces

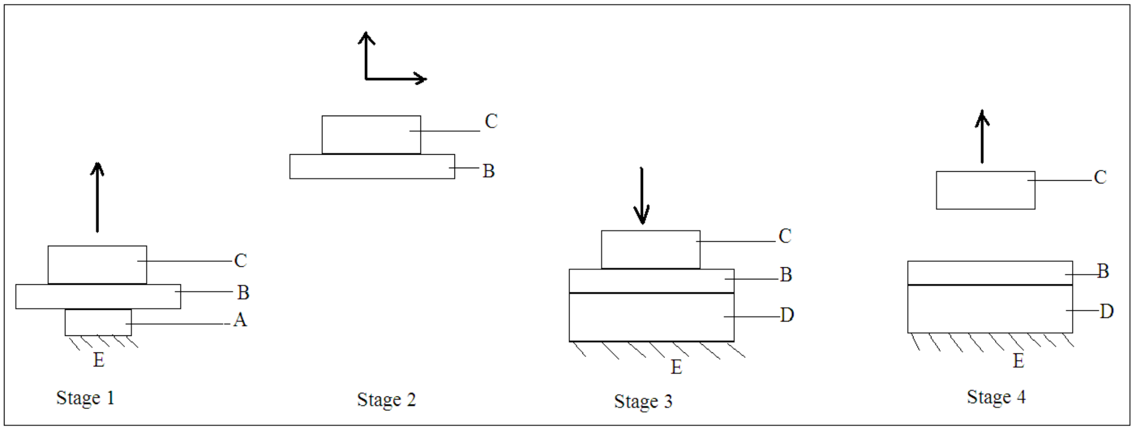

Figure 3: Flat geometries in which the interactive contact area is increased for material handling purposes

In Figure 3; Stage 1 is the initial picking phase, Stage 2 is the transfer phase, Stage 3 is the placement phase, and Stage 4 is the micro-gripper's release phase. The arrows show the direction of motion. A is the picking position, B is the micro-part to be handled, C is the micro-gripper, D is the placement position, E is the surface on which A and D are fixed. The micro-gripper C has a greater interactive area on micro-part B than that of picking position A; and the placement position D has a greater interactive area on B than that of micro-gripper C. It should be noted that both A and D should be fixed and immovable on their base E for an effective micro-material handling operation to be realised.

Another option would be to have a spherical picking position, a cylindrical gripper and a flat placement position in order to have a progressive increase in contact area as in Figure 4. In this case the micro-part would be flat on both sides.

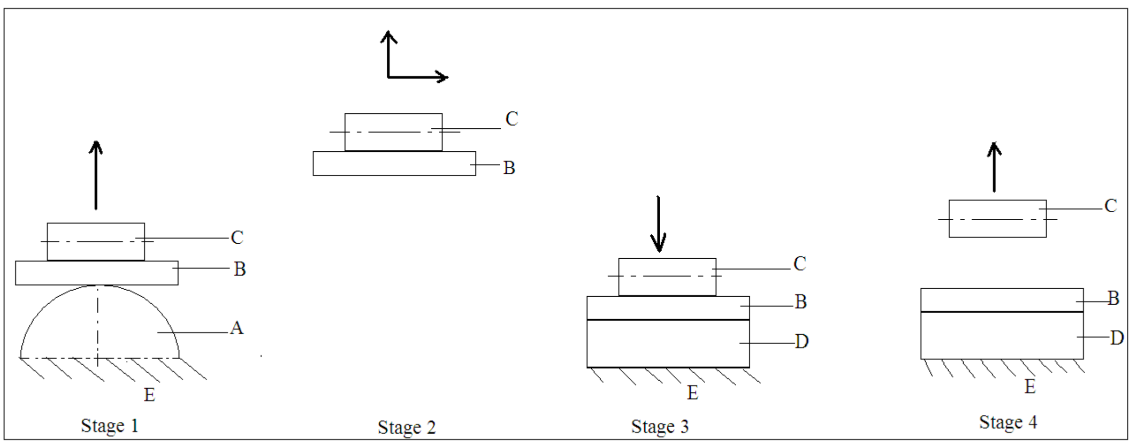

Figure 4: Geometrical configuration's variation for a reliable micro-material handling operation

In Figure 4; the picking place, A, is spherical; micro-gripper, C, is cylindrical; placement position, D, is flat; and the micro-part, B, to be handled is flat. The arrows show the direction of motion. The spherical picking place exerts less Van-der-Waals forces on the micro-part because it makes a point contact (less area of contact) with the micro-part; while the cylindrical micro-gripper exerts a larger force on the micro-part because it makes a continuous line contact with it (micro-part). The flat placement position affords a larger gripping area on the micro-part than the cylindrical micro-gripper; this leads to the release of the micro-part because the placement area exerts more force on the micro-part than the micro-gripper by virtue of its larger interactive area.

In cases where the interacting surfaces are of same material type, same geometry and of equal area; surface roughness variation can be employed as Strategy 3. Since it has been proven that Van-der-Waals forces decrease as *rms* surface roughness values increase (Rabinovich et al, 2000a and Rabinovich et al, 2000b), the interactive surface area of the picking position should be rougher than that of the micro-gripper, for a micro-part to be picked. For a reliable release to be achieved, the interactive surface area of the micro-part with the placement position should be smoother (have a lower *rms* value) than that with the micro-gripper. The applicability of this strategy can be explained using Ag 20.1 and Ag 5.1 samples of equal interactive area which have *rms* surface roughness values of 1.41 nm and 0.5 nm, respectively, and exert corresponding Van-der-Waals forces of 111 nN and 314 nN (as in Table 1). The Ag 20.1 can be used for the interactive surface of the picking position and the Ag 5.1 for the placement position. A micro-gripper of silver of medium surface roughness (between 0.5 and 1.41 *rms* roughness) which exerts Van-der-Waals forces of medium magnitude (between 111 nN and 314 nN) would be used in this case.

Nevertheless; some micro-material handling operations could be so complex that one pure strategy may not be reliable. The fourth option would be to use a hybrid strategy, termed Strategy 4, which is a combination of at least two previously mentioned strategies, as shown in the matrix Table .

Table 2: Matrix table for Strategy 4 showing options of hybrid strategies

	Strategy 2 (Geometry)	Strategy 3 (Surface roughness)
Strategy 1 (Material type)	Strategy 4-1 (Strategies 1&2)	Strategy 4-2 (Strategies 1&3)
Strategy 2 (Geometry)	Not a hybrid	Strategy 4-3 (Strategies 2 &3)
Strategy 3 (Surface roughness)	Already considered as Strategy 4-3 (Strategies 2 &3)	Not a hybrid
Strategy 4-1 (Strategies 1&2)	Already considered as Strategy 4-1 (Strategies 1&2)	Strategy 4-4 (Strategies 1, 2 &3)

The hybrid strategy consists of four sub-strategies, categorized as Strategy 4-1 (a combination of Strategy 1 and Strategy 2), Strategy 4-2 (a combination of Strategy 1 and Strategy 3), Strategy 4-3 (a combination of Strategy 2 and Strategy 3) and Strategy 4-4 (a combination of Strategy 1, Strategy 2 and Strategy 3) as shown in Table 2. Figure 5 (which is similar to Figure 2) shows the corresponding decision support system for the hybrid strategies.

As in the first DSS, the micro-material handling task definition is also initially conducted in this second case (Figure 5). For micro-material handling operations in which the interacting surfaces are of equal *rms* surface roughness values, hybrid Strategy 4-1 would be used. In this case; the picking position, micro-gripper and placement position would be made separately of different materials. Their geometrical configurations are designed such that the interactive area of the micro-part with the picking place, micro-gripper and the placement position, should increase successively as indicated in Figure 3 or Figure 4; and the interactive Hamaker coefficients of the interacting materials should correspondingly increase; in order to achieve a reliable pick-transfer-place cycle.

When a material handling operation involves surfaces of same geometrical configuration and same interactive area, hybrid Strategy 4-2 should be used. In this option; the interactive surface of the micro-part with the picking place, micro-gripper and the placement position would be made of different materials, of increasing Hamaker coefficients, respectively; and of successively decreasing surface roughness. For example, considering the samples used in this paper, a suitable combination would be Cu 5.1 and Ag 5.1, of decreasing *rms* surface roughness values of 2.72 nm and 0.5 nm, respectively. Their empirical Van-der-Waals forces are accordingly 24 nN and 314 nN. Therefore; in this option, the interactive surfaces of the picking position and the placement position should be Cu 5.1, and Ag 5.1, respectively. In this scenario, the micro-gripper should be made of a material of medium Hamaker coefficient and surface roughness within the limits imposed by Cu 5.1 and Ag 5.1.

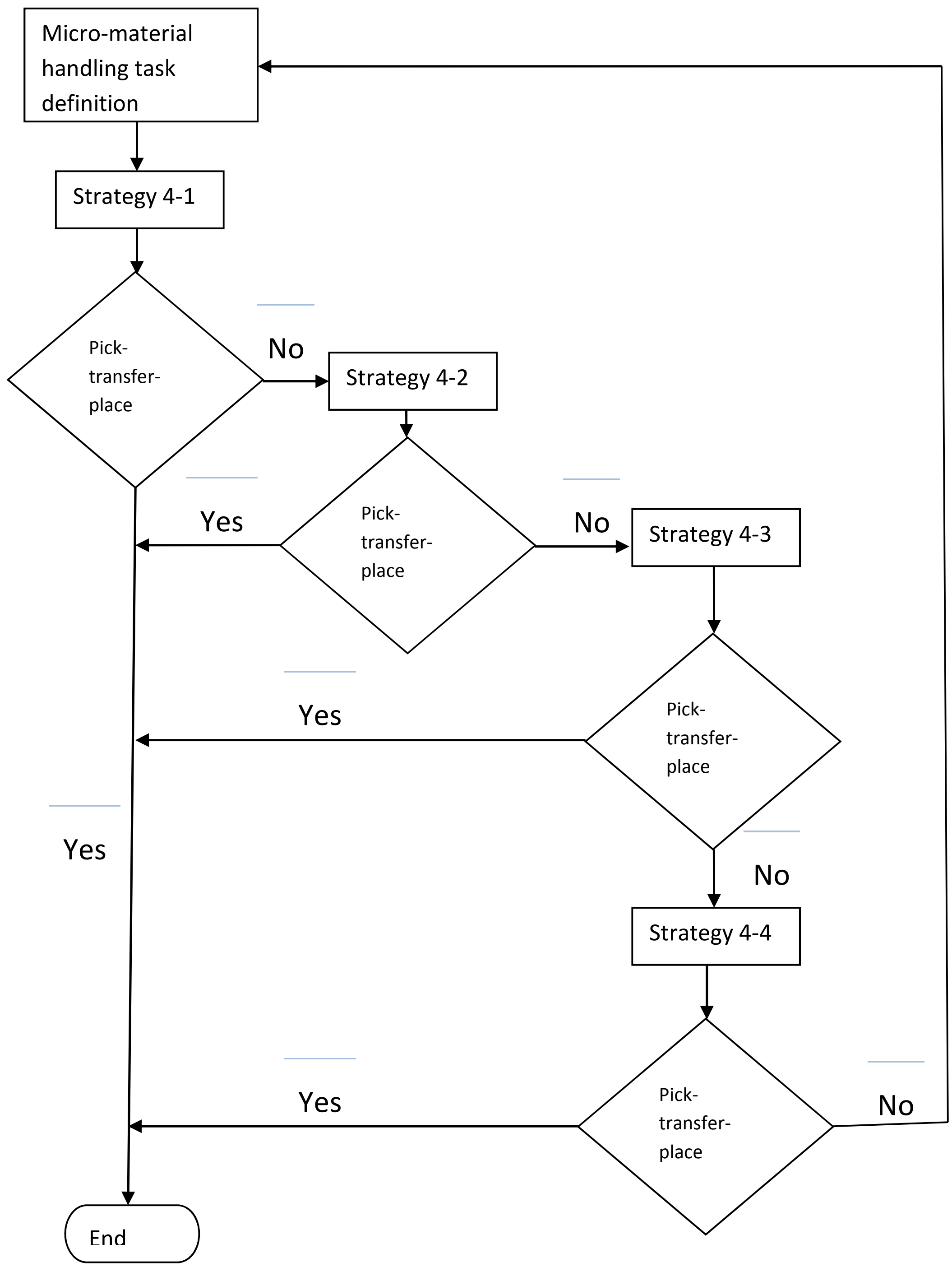

Figure 5: DSS for hybrid material handling strategies employing VdW forces

In cases where the interacting surfaces in a micro-material handling operation are of the same type, Strategy 4-3 would be suitable. Strategy 4-3 of the hybrid strategies combines Strategy 2 and Strategy 3. In this case, when a similar material is used for all micro-material handling of components; then the interactive geometrical areas of the micro-part with the picking position, micro-gripper and placement position should increase successively.

However; their *rms* surface roughness values should decrease correspondingly, for an effective micro-material handling operation to be realised. For example; the samples of copper namely; Cu 5.1, Cu 5.2 and Cu 20.2; of corresponding *rms* surface roughness values of 2.72 nm, 1.5 nm, 0.9 nm; and their geometrical configurations being spherical, cylindrical and flat, respectively as in Figure 4; would correspondingly be used for the picking position, micro-gripper and placement position's interactive surfaces to achieve a reliable micro-material handling system.

In complicated micro-material handling cases where the interacting surfaces are of different materials, geometrical configurations and surface roughnesses. Strategy 4-4 would be appropriate. Strategy 4-4 of the hybrid strategies combines all the three fundamental strategies: Strategy 1, Strategy 2 and Strategy 3. The choice of material should ensure that the interactive Hamaker coefficients of the micro-part with the picking position, micro-gripper and placement position should increase successively. The geometrical configurations should ensure that the interactive areas of the micro-part with the picking position, micro-gripper and placement position should increase successively. However, *rms* surface roughness values should decrease correspondingly for a reliable micro-material handling system to be realised. The example in Strategy 4-2 can be modified into Strategy 4-4 by adding a geometrical configuration element so that the Cu 5.1 picking place is spherical, and the Ag 5.1 placement position is flat as in Figure 3. In this situation, the micro-gripper should be made of a material of medium Hamaker coefficient and surface roughness within the limits demarcated by Cu 5.1 and Ag 5.1; and would have a cylindrical configuration as in Figure 3.

5. Conclusion

This paper highlights decision support system intended for use in Van-der-Waals forces actuated micro-material handling systems. The DSS is developed based upon strategies which are founded on the parameters upon which Van-der-Waals forces depend. These parameters are material type, geometrical configuration and surface roughness. Among the basic strategies, founded on one variable parameter, are: Strategy 1 based on material type, Strategy 2 on geometrical configuration, and Strategy 3 based on surface roughness. These strategies are individually appropriate for specific and relatively simple micro-material handling operations. For complicated micro-material handling operations, a hybrid strategy that depends on at least two variable parameters would be suitable. The hybrid strategy presented in this paper consists of four options which are: Strategy 4-1 (a combination of Strategy 1 and Strategy 2), Strategy 4-2 (a combination of Strategy 1 and Strategy 3), Strategy 4-3 (a combination of Strategy 2 and Strategy 3) and Strategy 4-4 (a combination of Strategy 1, Strategy 2 and Strategy 3). In all these strategies, the Van-der-Waals forces are logically increased in subsequent interactive surfaces to ensure a reliable pick-transfer-place cycle of a micro-material handling operation.

Acknowledgements

The authors greatly appreciate the input they got from Prof Y.I. Rabinovich.

References

Autum K., Sitti M., Liang Y.A., Peattie A.M., Hansen W. R., Sponberg S., Kenny T.W., Fearing R., Israelachvili J.N., Full, R.J., Evidence for Van- der- Waals' Adhesion in Gecko Setae. *99*, pp. 12252-12256. National Academy of Sciences (PNAS), 2002.

Bergstrom, L., Hamaker constants of inorganic materials. *Advances in Colloid and Interface Science, 70*, 125-169, 1997.

Ducker, W.A., Senden, T.J., Pashley, R.M., Measurement of forces in liquids using a force microscope, *Langmuir*, 8, pp. 1831–1836. http://dx.doi.org/10.1021/la00043a024, 1992.

Fatikow, S., Seyfried, J., Fahlbusch, S., Buerkle, A., Schmoeckel, F., A flexible microrobot-based microassembly station. *Journal of Intelligent and Robotic Systems, 27*, 135–169, 2000.

Fearing, S., Survey of Sticking Effects for Micro-parts Handling. *IEEE/RSJ International Workshop on Intelligent Robots & Systems (IROS)*, (pp. 212-217). Pittsburgh, 1995.

Glassmaker N. J., Jagota A., Hui, C. Y., Kim, J., Design of Biomimetic Finterfaces:1. Making contact. *Journal of the Royal Society Interface, 1*(1), 23-33, 2004.

Israelachvili, J., Van der Waals Forces between particles and Surfaces. In J. Israelachvili, *Intermolecular and Surface Forces (Third Edition)* (pp. 253-389). London: Academic Press, Elsevier.

Israelachvili, J. (2011). Van- der-Waals' Forces Between Particles and Surfaces. In J. Israelachvili, *Intermolecular and Surface Forces (Third Edition)* (pp. 253-389). London: Academic Press, Elsevier, 2011.

Matope, S., Van der Merwe, A.F., Nemutudi R., Nkosi, M., Cele, M., and Maaza, M., Micro-material Handling through the Manipulation of Van-der-Waals forces by the Generation of a Predetermined Surface Topology. *24th SAIIE Annual Conference*, (pp. 101-110). Pretoria, 2010.

Matope, S., Van der Merwe, A. F., Nkosi, M., Maaza, M. and Nemutudi R., Micro-material Handling Employing E-beam Generated Topographies of Copper and Aluminium. *South Africa Journal of Industrial Engineering, 22* (2), 175-188, 2011.

Matope S., Rabinovich, Y. I., Van der Merwe, A.F., Micro-material handling employing e-beam coatings of copper and silver, *South African Journal for Industrial Engineering*, Vol. 23 (1), pp. 114–121, 2012a.

Matope S., Rabinovich, Y. I., Van der Merwe, A.F., Van der Waals interactions between silica spheres and metallic thin films created by e-beam evaporation. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, Volume 411, pp. 87–93. http://dx.doi.org/10.1016/j.colsurfa.2012.07.006, 2012b.

Murphy M. P., Kute C., Mengüç Y. and Sitti M., Waalbot II: Adhesion Recovery and Improved Performance of a Climbing Robot using Fibrillar Adhesives . *The International Journal of Robotics Research, 30(1)* , 118–133, 2011.

Parsegian, V., *Van der Waals forces: A handbook for biologists, chemists, engineers, and physicists.* New York: Cambridge University Press, 2006.

Rabinovich Y. I, Adler J. J., Ata A., Singh R.K. , Moudgil B. M., Adhesion between Nanoscale Rough Surfaces. I. Role of Asperity Geometry. *J. Colloid Interface Surf., 232*, 10-16, 2000a.

Rabinovich I. Y., Adler J. J., Ata A., Singh K. J., and Moudgil M.B., Adhesion between Nanoscale Rough Surfaces II. Measurement and Comparison with Theory. *Journal of Colloid and Interface Science, 232*, 10–24, 2000b.

Takahashi, K., Berengueres, J.O.L., Obata, K.J., Saito, S. Geckos' foot hair structure and their ability to hang from rough surfaces and move quickly. *International Journal of Adhesion & Adhesives, 26*, 639–643, 2006.

Thoreson, E.J., Mart, J. and Burnham, N.A., The role of few-asperity contacts in adhesion. *Colloid and Interface Science, 298*(1), 94-101, 2006.

Van der Merwe, A.F. & Matope, S., The Physical Design of Micro-Grippers Actuated by Van- der Waals' Forces for Use in Micro-Material Handling. *Proceedings of the 23rd SAIIE Annual Conference*, (pp. 178-188). Pretoria, 2009.

Van der Merwe, A. F. and Matope, S., Manipulation of Van-der-Waals Forces by Geometrical Parameters in Micro-material Handling. *Journal for New Generation Sciences, 8*(3), 152-166, 2010.

Weber W. M., Hrenya M. C., Computational study of pressure-drop hysteresis in fluidized beds. *Powder Technology, 177*, 170–184, 2007.

Bibliography

Stephen Matope is a Senior Lecturer in the Department of Industrial Engineering at Stellenbosch University. He has published several journal and conference papers on the application of Van-der-Waals forces in micro-material handling. His research interests are in micro-manufacturing. He holds a PhD in engineering obtained at Stellenbosch University.

Andre F. Van der Merwe is an Associate Professor in the Department of Industrial Engineering at Stellenbosch University. He is also the head of the Advanced Manufacturing Research Group in the Industrial Eng. Dept. He has published several journal and conference papers on the application of Van-der-Waals forces in micro-material handling. His research interests are in advanced manufacturing. He holds a PhD in engineering obtained at Stellenbosch University.