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Robot Skin with Integrated Micro Rubber Suction Cups Adhering Rough Surfaces

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Abstract— **The aim of this research is to realize a functional adhesive robot skin with integrated micro suction cups, which has two new functions involving adaptive adhesion to rough/curved surfaces and anisotropic adhesion. This skin can be applied to various robot mechanisms such as robot hands, wall climbing robot feet and so on.**

In this report, the robot skins have been successfully developed to realize the higher adaptive adhesion by modifying materials and integration density of suction cups. The suction cups on 10mm × 10mm area realize the adhesion to surfaces with 145μm RMS roughness and with gap of 900μm in height.

I. Introduction

FUNCTIONAL microstructures for adhesion and friction have recently been developed by several robot researchers with inspired by the living beings [1-7]. In nature, a lot of small animals lighter than 100g in weight have adhesive microstructures on their bodies for climbing walls. For example, geckos employ hierarchical micro/nano scale hairs to realize adhesives force caused by van der Waals' force [1-3]. Some other insects such as ladybugs and flies utilize the wet adhesion related to surface tension with the secretory fluid [4-6]. Some other insects use micro spines for hooking [7].

Especially, for the wall climbing robots, the adhesives with microstructures are superior to the conventional adhesive mechanisms with normal dimension because of the fewer limitations in range of applicable surfaces [14]. Generally, the magnetic mechanisms and the mechanical grasping mechanisms are applied only on ferromagnetic surface and on surfaces which have bumps to be grasped, respectively. Even the vacuum adhesion [13,15,16] which has been the most popular method is actually used for climbing on the very smooth surface such as window glass.

Compared with these typical adhesive mechanisms, biomechanically mimicked microstructures have higher potential abilities applicable to wide variety of surfaces for actual applications. However, the developed robot skins with microstructures still have the following further requirements for practical uses; one is higher adhesion force enough to apply the skins for wall climbing robots with heavier weight and the other is wider range of applicable roughness on surface for the skin to adhere.

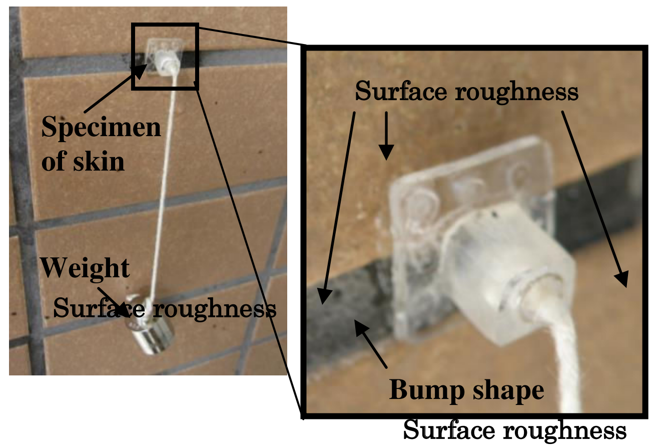

Fig.1. Adhesive skin on 10mm x 10mm in size consisting integrated suction cups; It adheres on a rough surface with bumps. The magnification image shows the skin realize the higher adaptive adhesion.

To obtain these adhesive properties, we have focused on suction cups made from elastic materials, which work as microstructure on the robot skin base. The suction cups in this report mean that they work with no pumps but work with vacuum generated during the motions of their pushing and peeling. For realizing the adhesion to walls, the suction cups are pushed on the surface by applied load to empty the internal air of the cups. After sealing, by releasing the load, negative pressure inside the cups is utilizable ideally with the outer atmosphere pressure of 100 kPa.

In our previous report [8], we have proposed the concept of functional adhesive robot skins with the integrated micro suction cups, which realizes the new functions involving adaptive adhesion to rough/curved surfaces and additional anisotropic adhesion for the on/off control of adhesive state. The potential properties of both functions were confirmed by conducting the fundamental experiments. These results clearly show that the skin with micro suction cups is suitable for the wall climbing robot feet.

Considering the previously reported skins, this paper represents the improved development of the skin for the higher adaptive adhesion to even rough surfaces as shown in Fig.1. It is realized by modifying materials and integration density of suction cups on the skin base.

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This paper is organized as follows. Section 2 presents the working principle of the integrated micro suction cups, and three models with different integration densities have been simulated using nonlinear finite element method. Section 3 represents the fabrication process using the micro rubber molding methods. The experimental results and verification with the fabricated specimens are presented in Section 4. Finally, in section 5, the summary of the results in this paper are shown.

II. WORKING PRINCIPLE OF SUCTION CUPS

A. Structure of Adhesive robot skins

Adhesive robot skins consist of micro suction cups and the rubber skin base on which the cups are integrated, as shown in Fig.2.The cups are connected to the base with connection pillars, as shown in Fig.2 (a).When the pushing/ peeling load are applied on the rubber skin base, the connection pillars deform as a sealer to adapt the roughness and the shapes of the wall. Therefore, the integration density has a big influence on adaptive adhesion property. The reason of the phenomenon is described in the details in section II.B.

The integration density is defined with the diameter of the integrated suction cups and the number of cups on rubber skin base, which is 10mm x 10mm in this report. In previous report [8], we have designed the suction cup as the non-dimensional model with non-linear FEM analysis. This means that the value of the cup diameter decides the values of the other parameters in the suction cups.

We have designed three models with different integration density, single cup, density A, and density B, as shown in Fig.2 and Table I. These models are 10mm, 2mm, and 0.5mm in cup diameter of cups and 1, 9, and 144 in cup number, respectively.

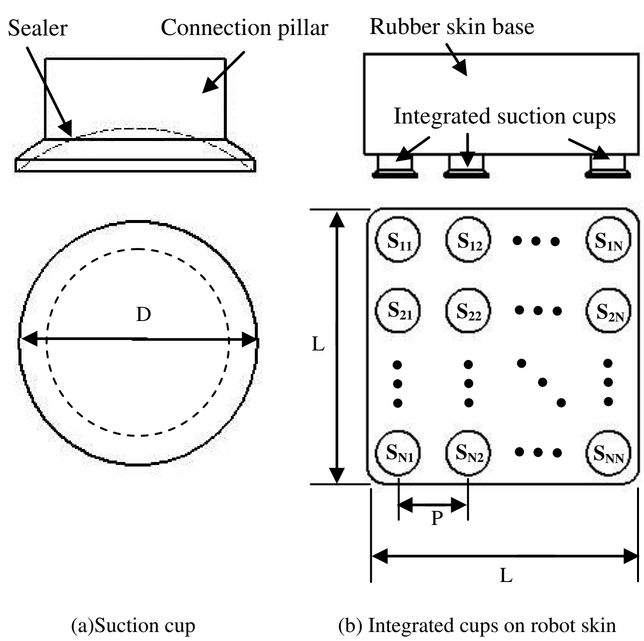


Fig.2. Structure of the developed skin with integrated micro suction cups

Table 3.1
Three models discussed in this paper, each has different integration density of micro suction cups. The rubber skin base is 10mm x 10mm.

	Diameter *D* [mm]	Number of cups
Non-integrated density (Single cup)	10	1
Integrated density A	2	9
Integrated density B	0.5	144

B. Adhesion mechanisms for integrated micro suction cups

Skins with integrated micro suction cups can adhere to rough surfaces due to two factors according to roughness types. The first factor works for roughness smaller than the cups and the second factor for roughness larger than the cups. The concept is illustrated in Fig.3.

About the first factor for adhering to surfaces with relatively smaller roughness to micro cups, each suction cup is required to deform to suit to the roughness to realize the sealing state. It is important for the cups to adapt the roughness with utilizing the rubber softness and the liquid surface force [9]. Generally speaking, the ideal sealing means the realization of strong sealing performance to high vacuum pressure and wide sealing area.

About the second factor for relatively larger roughness, the rubber base on which micro suction cups are integrated is required to deform to make most cups keep the vacuum even if some cups cannot remain sealing.

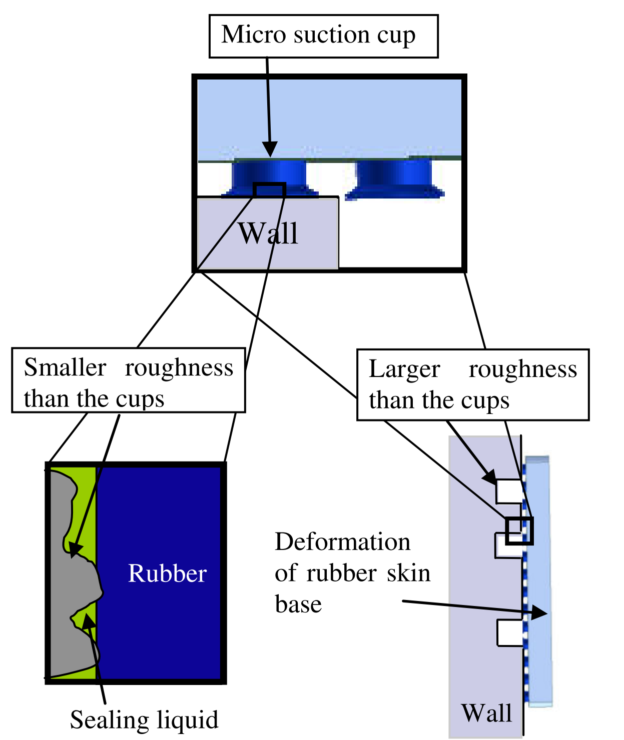


Fig.3. Working principle of integrated micro suction cups

C. *Non-linear FEM analysis for integration densities*

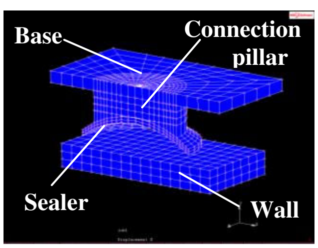
To confirm the adaptive adhesion property of the integrated suction cups shown in Section II.A., three types of skins with different densities have been analyzed by nonlinear finite element method software (Marc, MSC corp.) [8]. Material, geometrical, and boundary non linearity is considered in the analysis. Analysis results are shown in Figs.4 and 5.

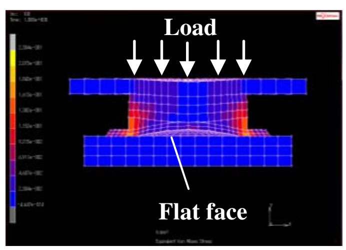
Single suction cup on a flat-surface was analyzed with a simplified 3D half model as shown in Fig.4 (a). Pushing load higher than 0.06 kPa realizes good deformation of the cup as shown in Figs. 4 (b) and 4 (c), resulting in good adhesive force. But

When the applied load on the top face of connection pillar is 0.06kPa, the contact area between the cups and the flat surface shows the largest value as shown in Fig.4 (b). The internal stress distribution of the sealer for the smaller loads is shown in Fig.4(c). This result shows the shape adaptability of a single suction cup to roughness relatively smaller the cup size.

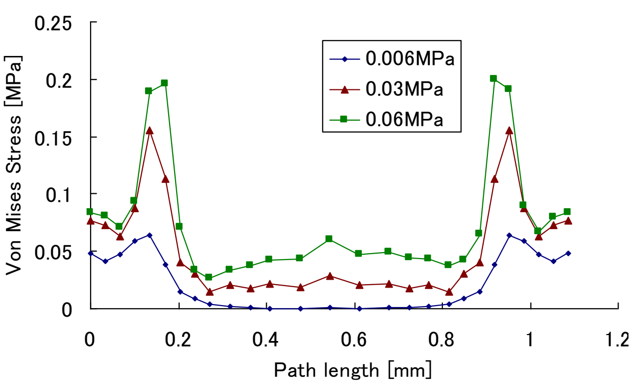
Shape adaptability of the integrated suction cups on walls with roughness relatively bigger than the cup diameter is shown in Figs.5. Each analysis model consists of an integrated suction cups fabricated on a rubber base and a surface with 300μm bump in height.

As shown in Figs.5 (b) and (c), they work well to show good adaptability to the bump, where we can find some cups around the bump don't work as suction cups because of the difficulties of the air-sealing while other cups with some



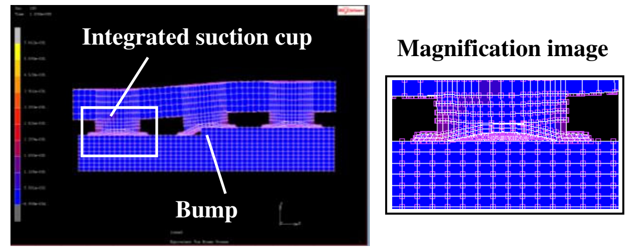


(a)Model of suction cup (b) Simulation result

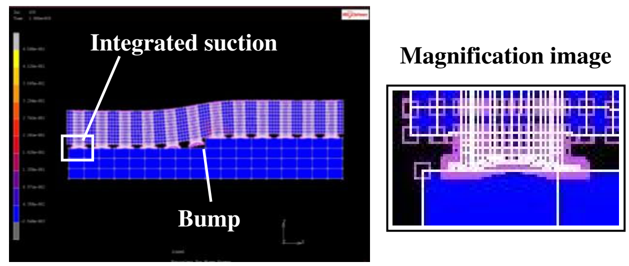


(c)The internal stress distribution of sealer with changing the load applied on the face of the connection pillar

Fig.4. FEM simulation results of single cup deformation



(a) Integration density A



(b) Integration density B

Fig.5. FEM simulation results for integrated suction cups

distance from the bump works well to maintain the adhesion force.

III. FABRICATION OF SPECIMENS

The specimens of skins have been fabricated by using the micro rubber molding method which is shown in detail in previous report [8]. This fabrication method is superior to the general MEMS methods in this case because of easily realizing 3-dementional spherical shell structure of the suction cups. In the method, the unique molds fabricated by mechanical machining process are used for the molding as shown in Fig6. The molds and the cups were made of aluminum and silicone rubber, respectively. The two types of the silicone rubber materials (Shin-Etsu Silicones, RTV rubber); KE-1308 and KE-1603 are used for modifying the adhesion properties, which is described in the details in Section IV.C.

The fabricated specimens are shown in Fig.7, such as the non-integrated suction cup (single cup) in Fig.7 (a), the skin

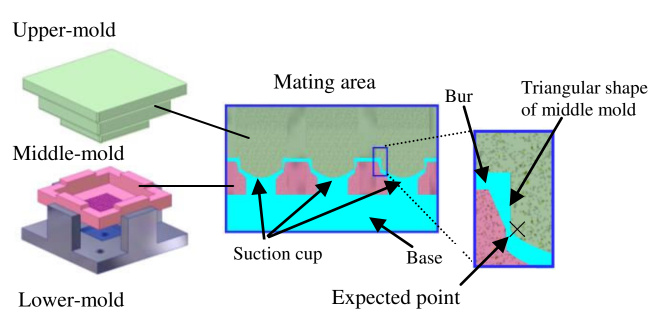


Fig.6. Micro rubber molding method for the integrated micro suction cups [8]

integrated with the density A in Fig.7 (b), and the skin integrated with the density B in Fig.7(c).

(a) Suction cup (b) Skin with density A (c) Skin with density B

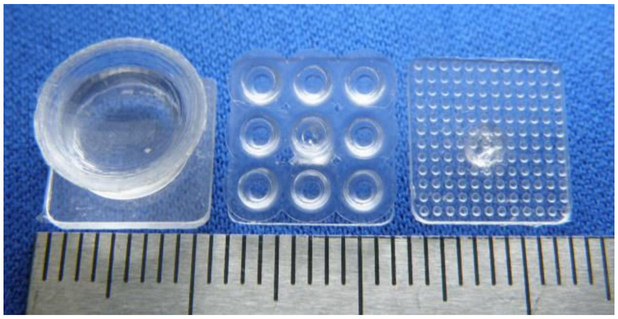


Fig.7. Fabricated specimens of the suction cup and the skins

IV. Experiments

A. Experimental set up

To accurately evaluate adhesion properties to rough surfaces , the adhesion forces of the developed skins were measured using the experimental set up shown in Fig.8.

The basic set up is shown in Fig.8 (a). The tensile testing apparatus with the force sensor is used to pull off the adhesive skins on a plate at 0.25 mm/s with a thin thread. Five times pull-off tests are done for one condition and these peak values of peeling force are averaged to be defined as adhesion force. To compare the properties of the specimens with the different sizes, the adhesion forces are converted to the adhesion pressure by dividing the pulling force by the initial contact area of the cups and dummy wall plates.

The experiments are made for several different plates shown

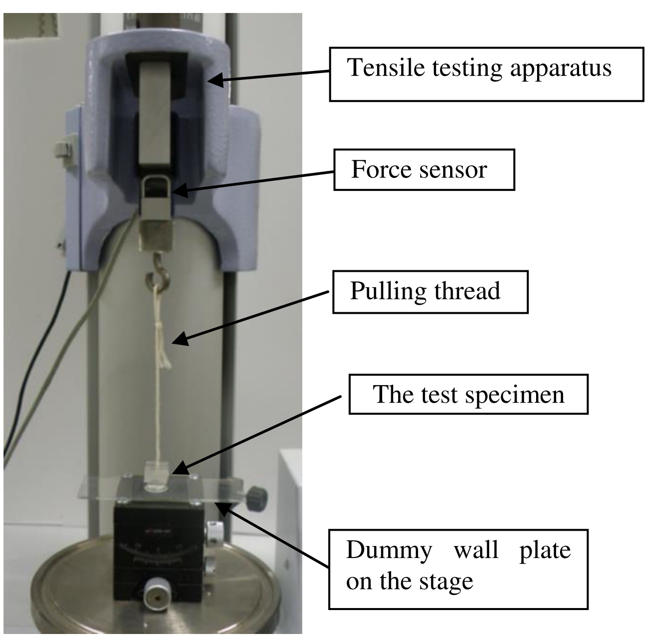
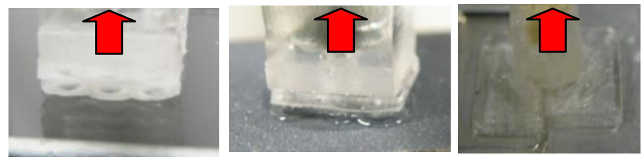


Fig.8. Experimental set up for the evaluation of adhesive force



(a) Smooth glass (b)Abrasive paper (c)Bump

Fig.9.Sevral different plates for preparing dummy walls

in Figs.9 (a), (b), and (c); a smooth glass plate, abrasive papers with several different roughness, and plates with different height-bumps.

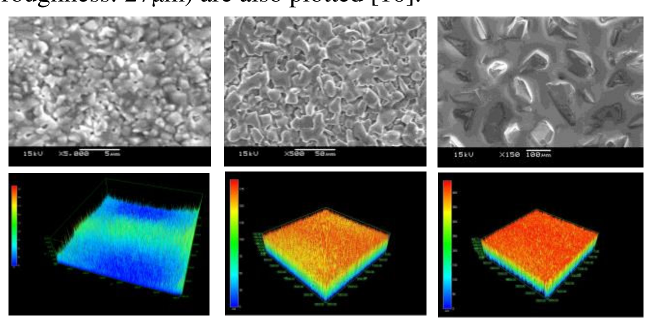
B. Defined roughness of the dummy walls

We used several dummy walls on which the developed skins adhere such as a glass plate for smooth wall, abrasive papers for small roughness and bumped metal plates for big roughness.

Generally, small roughness is defined with the value of RMS (root-means-square) amplitude roughness. To quantify the roughness, we prepared the dummy wall with commercially available abrasive papers and films. On their surfaces, they have uniform particles with the diameter standardized by ISO, as shown in Fig.10.

Bigger roughness in this paper means a kind of surface shape such as bumped or curved surfaces. We prepared aluminum surfaces with a bump fabricated with machine processing. An example is shown in Fig.11. Each plate has a bump with the height from 100μm to 900μm.

A scanning laser microscope was used to measure the surface roughness of these dummy walls for scan length of 3500μm. The dummy walls are plotted in Fig.12 based on the RMS surface roughness and the height of shape bump. In the addition to the walls, the actual living environment walls such as the glass wall (RMS roughness: 0.02μm), the painted drywall (RMS roughness: 20μm), and the wood walls (RMS roughness: 27μm) are also plotted [10].



(a) #10000 (b)#1000 (c)#180

Fig.10. SEM images (upper) and 3D profile images (lower) of roughness with abrasive papers

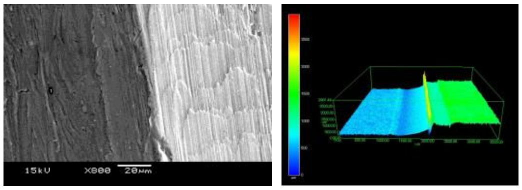


Fig.11. SEM image (left) and 3D profile image (right) of the bump

C. *Adhesive condition of suction cups*

The adhesive performances of the skins depend on sealing property of cups. The air leakages are suppressed by the two methods; the use of sealing with very soft rubber material and the coating with sealing liquids. To know how much these methods cause higher performance, we have conducted the exploratory experiment with the non-integrated suction cup under the following different conditions.

(1)Condition 1: Suction cups made from softer rubber (KE-1308, Hardness Durometer A: 8) with no liquid

(2)Condition 2: Suction cups made from harder rubber (KE-1603, Hardness Durometer A: 28) with no liquid.

(3)Condition 3: Suction cups made from the harder rubber with coating water (Surface tension: 72mN/m [11]).

(4)Condition 4: Suction cups made from harder rubber with coating liquid detergent (Surface tension: 30mN/m [12]).

Water and detergent are used in conditions 3 and 4, which work to increase the air-sealing properties due to their surface tension.

Experiments were made five times for each condition and the results are shown in figures with average marks and error bars.

Figure 13 shows the relationship between RMS surface roughness and the adhesion force of one suction cup under dry condition wet condition using water and wet condition with laundry liquid. From the graph, it is found that wet adhesions of suction cup are superior to dry adhesion. In particular, we have adopted the experimental condition4 using the liquid detergent to estimate the following experiments.

Suction cups with hard rubber realize high adhesive force for smaller roughness but their force drops suddenly for roughness bigger than a critical roughness. On the other hand, suction cups with softer rubber show smaller force but they show no sudden force drop.

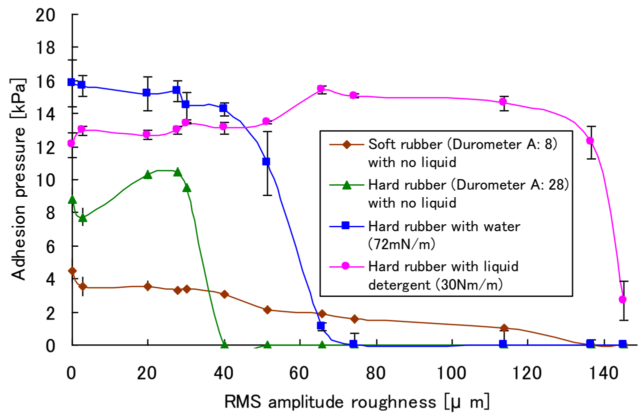


Fig.13. Relations between RMS surface roughness and adhesion force of a suction cup under dry and wet conditions

D. *Adhesion properties of skins*

In order to estimate the adhesion properties of skins to rough surfaces, the two tests have been done using the specimens with the different integration densities of micro suction cups.

Figure14 shows the relationship between RMS roughness of the dummy walls and adhesion force of the skins with integrated suction cups. As shown in the figure, for the small roughness under 150μm, higher integration density causes the narrower range of applicable surface roughness. This is because the clearances between cups and roughness from which air comes into the internal of cups have worse effect on sealing performance. This can be understood that the roughness becomes relatively bigger for the highly-integrated smaller cups. However, the skin with the highest density B can maintain stable adhesion until surface roughness is 40μm.

Figure 15 shows the relationship between the height of uneven surface and the adhesion force. This shows the adhesive properties for the roughness relatively bigger than the cup size. It is found that the integration of micro suction cups have excellent advantage of adhesion property to the rough surface much larger than the cups. The adhesion of the

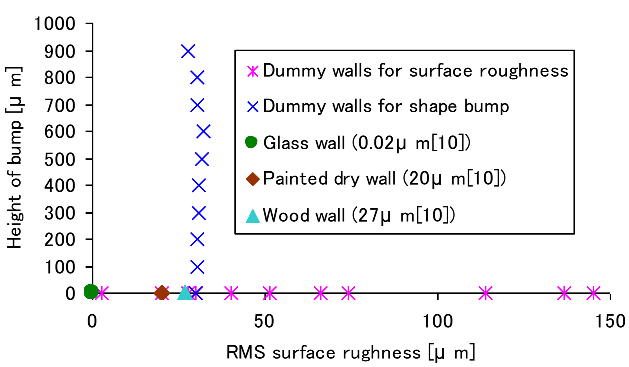


Fig.12. Roughness of the dummy walls and the actual living environment walls

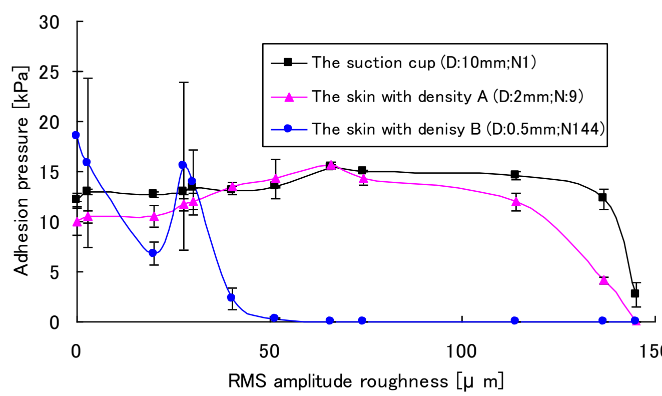


Fig.14. Relations between RMS surface roughness and adhesion force of the three size types of specimens with suction cups.

non-integrated suction cup becomes unstable when the height of a bump is 200μm and then disabled. On the contrary, the skins with integrated micro suction cups can maintain stable adhesion until the height of a bump is 900μm.

Considering these results we concluded that integrated suction cups work well for surfaces with roughness and bumps which are very different in size from the cup dimensions.

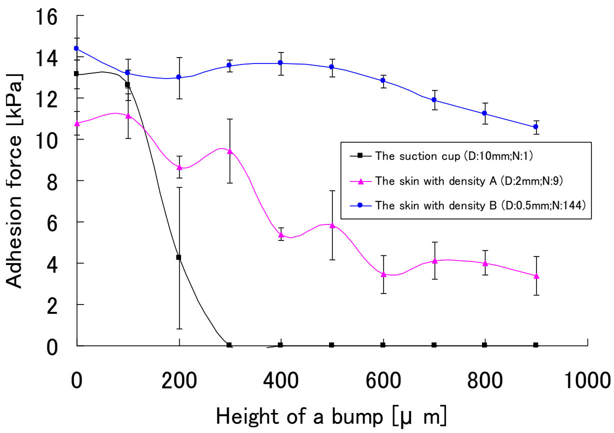


Fig.15. Relations between the height of the bump and adhesion force of the three size types of specimens with suction cups.

V. CONCLUSION

The adhesive robot skins with integrated micro rubber suction cups have been successfully developed to realize the higher adaptive adhesion to rough surfaces than the previously reported skins. To our knowledge at present, no other adhesive microstructures developed for climbing robots' feet can maintain stable adhesive state to wider range of applicable roughness on the surfaces than these improved skins. We have no discussions on shear forces in this report, but this robot skin realizes shear force [9] due to the friction between the cups and surface to have the potential as a robots sole skins.

The results of this paper are summarized as follows;

(1)We have proposed the working principle of integrated suction cups on rubber skin base, which realizes the adhesion to rough surfaces.

(2)By modifying materials and integration density of suction cups, the skins have been designed using nonlinear FEM analysis and fabricated with micro molding method,

(3)Evaluation experiments for the adhesion properties of the skins have been done using the proposed dummy walls which can quantify the roughness to apply suitably on our actual living environment walls.

(4) The adaptive adhesion with the suction cups on 10mm x 10mm area to surfaces with 145μm RMS roughness and with the gap of 900μm in height is confirmed by the experiments.

(5) Surface tension of liquids works very much to increase the adhesive force.

(6) Suction cups with hard rubber realize high adhesive force for smaller roughness but their force drops suddenly for roughness bigger than a critical roughness.

(7) Integrated suction cups work well for surfaces with roughness and bumps which are very different in size from the cup dimensions.

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