Study on Liquid Management Technology in Water Tank for Propulsion System Utilizing Aluminum and Water Reaction (Improvement of Liquid Acquisition Performance by Hydrophilic Coating in Metallic Tank)

著者	IMAMURA Takuya, SUGIOKA Masatoshi, HIGASHINO Kazuyuki, IMAI Ryoji
journal or publication title	International Journal of Microgravity Science and Application
volume	35
number	1
page range	350103-1-350103-6
year	2018-07-31
URL	http://hdl.handle.net/10258/00009659

doi: info:doi:10.15011//jasma.35.350103

Int. J. Microgravity Sci. Appl., **35** (1) (2018) 350103
DOI: 10.15011//jasma.35.350103

IIII Review IIII

Study on Liquid Management Technology in Water Tank for Propulsion System Utilizing Aluminum and Water Reaction
(Improvement of Liquid Acquisition Performance by Hydrophilic Coating in Metallic Tank)

Takuya IMAMURA [1], Masatoshi SUGIOKA[2], Kazuyuki HIGASHINO[2] and Ryoji IMAI [1]

Abstract

In order to use hydrogen as a fuel for spacecraft propulsion system, utilization of aluminum and water reaction system is considered. Liquid-gas separation is necessary for water tank in this propulsion system. The purpose of this study is to confirm the applicability of water to the surface tension liquid acquisition mechanism in tank by improving wettability using a silica coating. It was demonstrated that silica coating could improve the wettability of water against metallic material applied to practical tanks. By the microgravity experiment using drop tower facility, it was confirmed that water in tank could be acquired on the liquid outlet by vane device with silica coating.

Keyword(s): Al-Water Reaction, Liquid Management, Water tank, Surface Tension, Microgravity, Drop Tower, Hydrophilic Coating

Received 19 December 2017, Accepted 10 January 2018, Published 31 January 2018

1. Introduction

Currently hydrazine is used as fuel for the spacecraft propulsion system. Hydrazine has high ignitability and can realize high specific impulse for thruster system, however, it is extremely harmful to the human body. Therefore, high safety is required for operation [1]. Hydrogen is harmless to the human body, therefore is promising as one of alternative fuels. We are studying to produce hydrogen by stirring and reacting aluminum powder and water in a reactor [2]. Furthermore, we are aim to develop a satellite propulsion system to which this hydrogen production method is applied [2]. In this system, aluminum and water are mixed in the reactor to produce pressurized hydrogen for the thrusters [3]. Also, as an advantage of utilizing the aluminum and water reaction, there are some points as follows;

(1) The product obtained by the reaction of aluminum and water is only hydrogen and aluminum hydroxide harmless to the human body.
(2) In the aluminum and water reaction, it is possible to produce hydrogen on demand and it is not necessary to store hydrogen in a tank for a long time. In addition, the aluminum and water reaction does not require handling of high pressure gas on the ground.

Under microgravity, the liquid in the tank is driven along the inner wall, and the gas-liquid interface is greatly curved. This is because the surface tension becomes remarkable under microgravity. In addition, since the direction of acceleration is unstable, it is difficult to acquire the liquid at the liquid outlet. Therefore, in order to discharge liquid or gas individually from the inside of the tank, measures to enable gas-liquid separation in the tank are necessary. An example of such a tank is a vane type surface tension tank. This tank has a liquid acquisition mechanism by surface tension [4) - 6)].

In this study, we are studying the development of liquid management technology in water tank and the supply system of aluminum powder and water to reactor. In previous experiments, subscale water tank made of transparent acrylic resin with hydrophilic were prepared [7]. This coating was applied to improve liquid acquisition capability for water which has generally poor wettability on solid wall. Evaluation tests were conducted under microgravity conditions by using drop tower facility. Liquid behaviors in a water tank under microgravity were observed and it was confirmed that liquid acquisition was successfully realized [7]. Continuously we target to evaluate liquid acquisition characterizes for metallic vane tank with hydrophilic coating in microgravity conditions.

2. Outline of Experiment

2.1 Outline of Microgravity Experiment

In this experiment, we used the 50 m drop shaft facility "COSMOTORRE" owned by Uematsu Electric Co., Ltd. This facility has 40m in a free fall distance and can obtain 2.5 sec in microgravity duration. Experimental device is mounted on a drop capsule shown in **Fig. 1**. This capsule has a double structure, therefore the outer capsule can suppress the influence of the air

1 Course of Aerospace System Engineering, Muroran Institute of Technology, 27-1, Mizumoto-cho, Muroran, Hokkaido 050-8585, Japan.
2 Aerospace Plane Research Center, Muroran Institute of Technology, 27-1, Mizumoto-cho, Muroran, Hokkaido 050-8585, Japan.
(E-mail: r_imai@mmm.muroran-it.ac.jp)

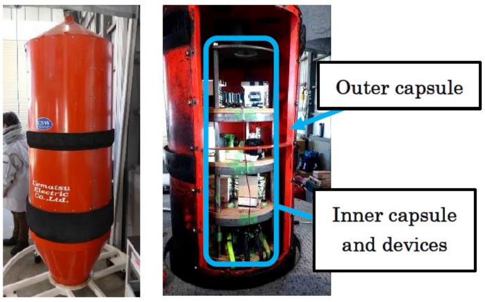

Fig. 1 Drop capsule and experimental devices installed on the capsule.

resistance on the inner capsule on which the experimental device is installed, and it is possible to obtain a microgravity environment of about 10^{-3}G.

2.2 Experiment Contents of Water Tank and Device Outline

In this study, application of vane type surface tension tank was considered. However, since water has a large contact angle with the solid surface, that is wettability is very poor, therefore it is difficult to drive liquid using surface tension under microgravity. As a method for improving the wettability of water, silica coating which forms a glass thin film on the solid surface was utilized. In previous research, it has been confirmed that wettability by silica coating in vane type surface tension tank made of acrylic resin was improved, and capturing water on tank outlet was realized [7]. In present study, microgravity experiments were conducted using a vane type surface tension tank made of metallic material similar with the practical one.

2.2.1 Water Tank Details and Experimental Device

Details of the vane type tank made of metallic material used in this experiment and details of the experimental device mounted on the drop capsule are described hereafter.

Figure 2 shows details of vane type tanks made of metallic material. Diameter and volume of tank are 50 mm and 65 mL respectively. In order to make observation of the interior of the tank, 1/3 area of the front portion in the tank is made of transparent acrylic resin. The material of metallic part of the tank and the vane are stainless steel SUS304. The silica coating agent was "Silica Shield" manufactured by Excia Co., Ltd [8]. The coating is applied only to the metallic part and the vane. This is because if the wettability of the acrylic portion is improved the liquid also reaches there, which causes deterioration of visibility. We prepare two kinds of vanes with 5 mm and 2.5 mm in height of thin plates. Higher thin plates is expected to have stronger acquisition characteristics of water since capillary force is larger than with low thin plates. We investigate the effect of height of these thin plates.

Figure 3 shows details of experimental device. Video images are taken from the front of tanks to observe the liquid behavior inside the tank. The experimental device was designed to be equipped with two tanks in order to make it possible to obtain the results of two experimental conditions in one free falling.

2.2.2 Experimental Conditions

Table 1 shows experimental conditions. Pure water was used as the test liquid, and liquid volume of this experiment was set to be 18 ml, same amount in previous experiment by using silicone oil as test fluid [9]. In order to improve the visibility of the liquid in the tank, the test liquid was colored by food red.

2.2.3 Details of Silica Coating

As mentioned above, previous research has confirmed that improvement of wettability by silica coating was effective for acquisition of water by microgravity experiment using vane type

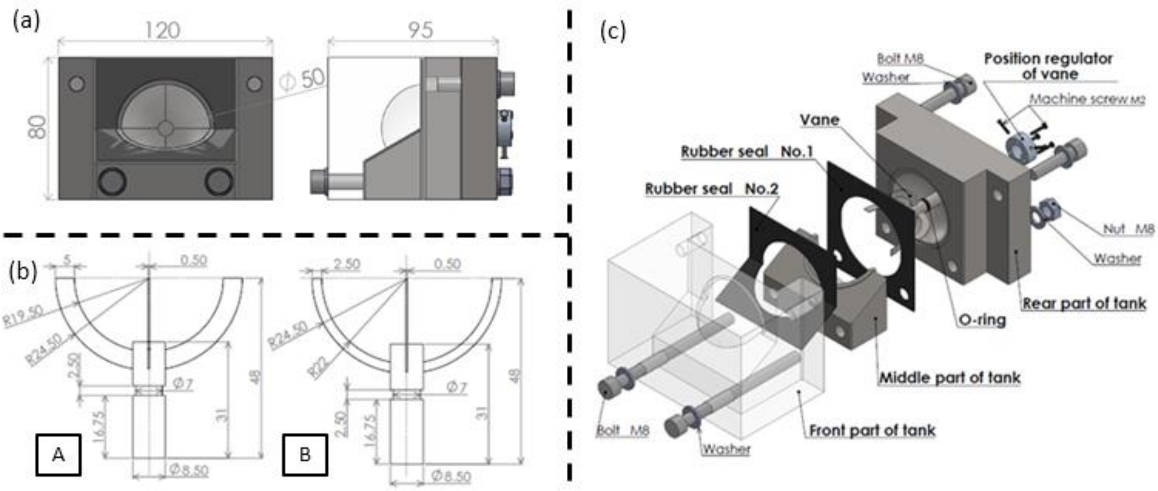

Fig. 2 Overview of water tank: (a) entire view of water tank, (b) vane configuration, (c) exploded view of water tank.

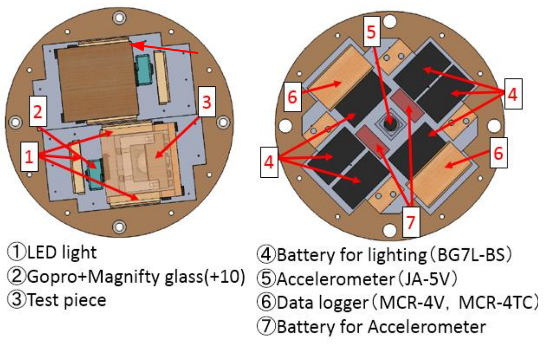

Fig. 3 Details of experimental device.

Table 1 Experimental conditions.

Condition number		No.1	No.2	No.3	No.4
Vane		A	B	B	A
Liquid volume ml		18	18	18	18
Liquid	Substance	Pure Water			
	Coloring	○	○	×	×

surface tension tank made of acrylic resin [7]. However, there was a problem in the durability of wettability by the coating, such as the effect was lost when the first experiment was finished. Various types of Silica Shield are prepared depending on the application, and in all of them, heating is recommended to convert the coating agent into silica in order to obtain a favorable wettability characteristics. However, because the coated object was made of acrylic resin in previous experiments, it could not withstand heating. Therefore, silica conversion was carried out at room temperature. This was considered to be a cause of poor durability.

Since the metallic vane type and tank is used in this experiment, silica conversion by heating is possible. Therefore, type of Silica Shield having high characteristics for improving wettability through silica conversion by heating is selected. In addition, the effect obtained by Silica Shield varies depending on the film thickness after completion of coating, therefore by applying the coating agent at several times, we search for the optimum film thickness that can obtain the required effect. Therefore, after selecting the liquid agent type, we search for the number of times of coating that can obtain better wettability. For the test piece, SUS304 (Size: W 23 × D 50 × T 2) which is the same material as the tank is used. After completion of the coating, contact angle of water against test piece is measured to search for the type of Silica Shield and the number of times of coating that favorable wettability can be obtained. The coating procedure is as follows.

(1) Degrease the test piece with ultrasonic washing machine and wiping by ethanol.
(2) Apply the coating agent, dry to the extent that it does not become sticky.
(3) Repeat the process of (2) and apply the coating agent at several times.
(4) Using an electric furnace, heat at 350 °C for 60 min.
(5) Cool sufficiently the test piece, lightly polish the coated surface with a cloth wetted with pure water and finish it.

2.2.4 Experiment of Selecting the Optimum Silica Shield

Three types of Silica Shields such as SSN-SD50, SSL-SD100, and SSL-SD500 are used for selection. Characteristics of the three Silica Shields are shown in **Table 2**. SSN-SD50 can convert silica at normal temperature, and was used for acrylic tanks in previous research [7]. In the several types of Silica Shield, the SSL-SD100 and the SSL-SD500 are capable of silica conversion at a relatively low temperature, and the recommended heating temperature is 250 °C or higher. Selection of low temperature silica coating aims to prevent thermal deformation of tank and vane material. SSL-SD100 and SSL-SD500 have different film thicknesses of the products themselves, and the film thickness of the coating after completion of coating becomes thicker for SSL-SD500. In the coating procedure described in 2.2.3, the heating temperature is set at 350 °C, this is because in the purpose of improvement of hydrophilic, it is recommended to heat at 300 °C or higher in the above three types.

This experiment is carried out twice to confirm reproducibility. Results of contact angle measurement are shown in **Table 3**. Images of droplet on solid wall in the second measurement are shown in **Fig. 4**. Experimental results show that the wettability of SSN-SD50 was not improved completely, and the wettability could be improved significantly in the other two types. And it turned out that the SSL-SD100 was particularly improved. From these results, it was found that the optimum type of Silica Shield for silica conversion by heating was SSL-SD100.

Table 2 Characteristics of coating agent liquid.

Liquid type	SSN-SD50	SSL-SD100	SSL-SD500
Silica conversion temperature	At room temperature	100°C~	100°C~
Recommended heating temperature	At room temperature	250°C~	250°C~
Film thickness	Thin	Thin	Thick

Table 3 The contact angles in the absence of coating and the contact angle for each liquid type.

Liquid type		without coating	SSN-SD50	SSL-SD100	SSL-SD500
Contact angle deg	1st	32.49	43.16	10.55	10.96
	2nd	31.97	33.80	6.01	9.29

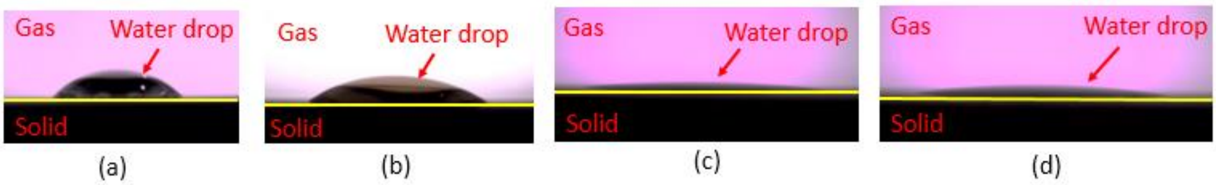

Fig. 4 Images of droplet on solid wall in the second measurement in liquid type selection experiment: (a) without coating, (b) SSN-SD50, (c) SSL-SD100, (d)SSL-SD500.

Table 4 Experimental conditions for optimum coating number.

Test pieces	No. 1	No. 2	No. 3
Number of coatings	5	7	10
Liquid type	SSL-SD100		
Heating temperature	350℃		
Heating time	60min		

Table 5 Experimental conditions for optimum coating number.

Test pieces		Not coating	No. 1	No. 2	No. 3
Number of coatings		Not	5	7	10
Contact angle deg	1st	47.70	14.85	10.88	12.93
	2nd	47.83	17.32	11.31	10.59
	3rd	45.30	14.75	11.51	11.20
Average contact angle deg		46.94	15.64	11.23	11.58

2.2.4 Search for Optimum Number of Application of Silica Shield

Experimental conditions are shown in **Table 4**. This experiment was carried out three times to confirm reproducibility. The experimental results are shown in **Table 5**. From the results, it was confirmed that the contact angle became relatively smaller with repeating number of coating for Silica Shield. The average contact angle was almost the same when the number of applications was 7 and 10. As a property of Silica Shield, hydrophilic characteristics was enhanced with increasing film thickness, however, risk of cracking increased. From this fact, we determined the number of application of Silica Shield to be 7 times as the optimum value.

3. Experimental Results

Firstly, the liquid behavior inside the vane type tank was checked in high wettability case. **Figure 5** shows the microgravity experimental results in a vane type surface tension tank using silicone oil (kinematic viscosity 1 mm^2/s) which is well known to have high wettability [10]. Silicone oil is colored with a dye (Oil Green 502), however the tank wall and vane surface are not coated. As shown in **Fig. 5**, the liquid spreads over the entire inner wall of the tank immediately after entering the microgravity. And as time elapsed, it was found that liquid was gradually captured near the liquid outlet.

The acrylic part of the tank used in present experiment is not coated. From this fact and the above mentioned experimental results, it is expected that the liquid does not move to the acrylic part, however is captured on the vane side in this experiment.

Based on the above results, discussion will be made for each experimental condition.

3.1 Results and Consideration of Experiment No. 1

The experimental result of Experiment No. 1 is shown in **Fig. 6**. From this figure, we can see that contact line of liquid surface against tank wall moved toward liquid outlet, which was the behavior in early period after entering microgravity condition.

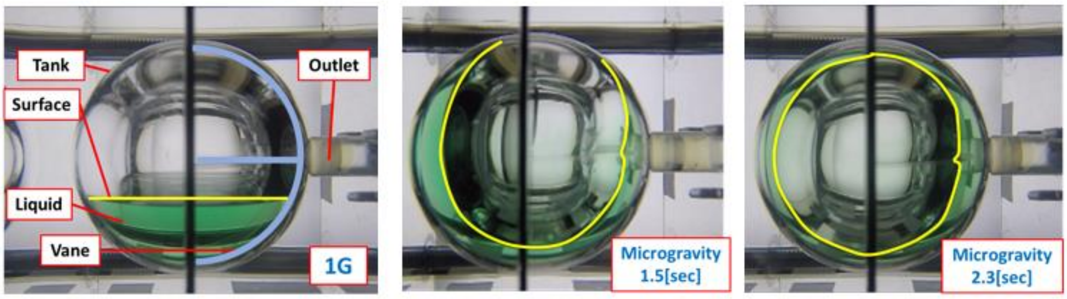

Fig. 5 Experimental result of vane type tank made of acrylic.

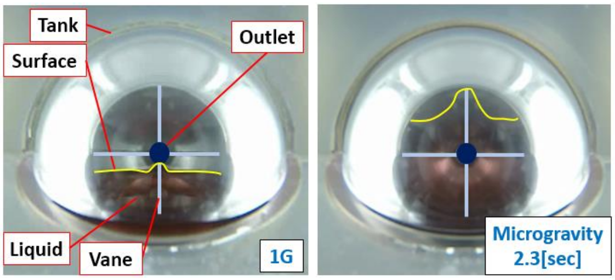

Fig. 6 Liquid behavior in Experiment No. 1.

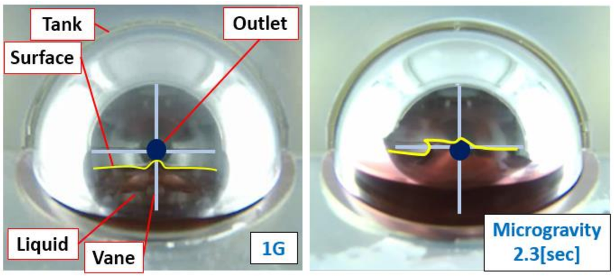

Fig. 7 Liquid behavior in Experiment No. 2.

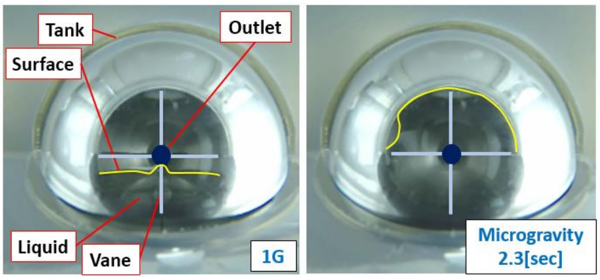

Fig. 8 Liquid behavior in Experiment No. 3.

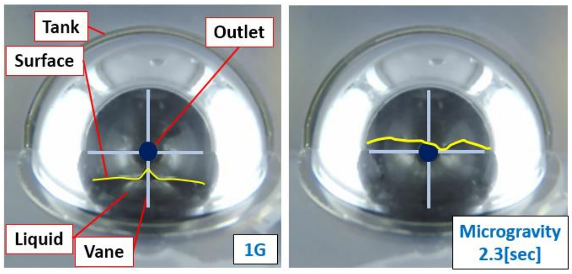

Fig. 9 Liquid behavior in Experiment No. 4.

Afterward water will be captured on the vanes and liquid outlet in longer duration similar with silicon oil case shown in **Fig. 5**. From this result, it was confirmed that the silica coating was also effective also for a tank made of metal.

3.2 Results and consideration of Experiment No. 2

The liquid behavior in Experiment No. 2 is shown in **Fig. 7**. From this figure, we can see that water was could not be driven and captured on liquid outlet sufficiently. There are two possible causes as follows;

(1) Since the height of vane B used under this condition was lower than the vane A used in the Experiment No. 1, the acquired amount of the liquid by the vane was decreased.

(2) The undissolved powder of food red was adsorbed on the coating surface and adversely affected the wettability and surface tension.

Cause (2) will be further explained as follows. Glass originally has a large surface tension (surface free energy), and has a property that gases, liquids and fine particles and are easily adsorbed to the surface [11]. In addition, substances having closer surface tension value are easily adsorbed. Water and glass are an example of this case, therefore glass is easy to be wet with water. In this study the solid surface was vitrified by silica coating in order to promote the adsorption of water, and the wettability was improved. However, the surface tension reduced as impurities was adhered. From the above mentioned fact, we suppose water could not be captured under this experimental condition since the undissolved powder of food red adhered to water and the coating surface as impurities, therefore reduced surface tension.

3.3 Results and consideration of Experiment No. 3

The liquid behavior in Experiment No.3 is shown in **Fig. 8**. Experiment No. 3 was conducted in order to identify the cause of the malfunction of liquid acquisition function as the experimental result of Experiment No. 2. In this experiment food red wasn't used in water. From **Fig. 8**, we can see that water was acquired near the liquid outlet. Furthermore, in comparison with the result of Experiment No. 1 shown in **Fig. 8**, it was found that the test piece of Experiment No. 3 would be able to acquire more water. Previous studies have shown that the larger vane could acquire larger amount of water [7]. From these facts, it is important not only that the wettability of the tank surface is improved but also impurities are not contaminated to realize acquisition of water.

3.4 Results and Consideration of Experiment No. 4

The liquid behavior in Experiment No. 4 is shown in **Fig. 9**. From this figure, water rose on the vane surface, but it was not acquired sufficiently in 2.3 seconds in microgravity duration. It turned out that driving of water was not ceased, and the microgravity condition ended just after the liquid surface reached the position shown in **Fig. 9**. From these results, it is considered that water can be acquired even if the amount of liquid was small if the microgravity duration was longer. This was because the area of the vane in contact with water in the initial state was small since the amount of liquid was small, therefore it took longer time to perform acquisition on the liquid outlet.

4. Conclusion

We are now considering application of hydrogen produced by aluminum and water reaction on spacecraft propulsion system. In present study, experimental equipment and test piece were prepared, and microgravity experiments were conducted by drop tower facility. By this experiment the liquid acquisition mechanism of the water tank was investigated. The experimental results and future task are summarized as follows;

(1) It was shown that silica coating was effective also for the vane type surface tension tank made of metallic material close to practical device.

(2) It was shown that impurities contained in water possibly affected wettability and surface tension badly. The liquid capturing function might be supressed due to this effect.

(3) Evaluation tests with longer duration microgravity condition using a larger simulation tank has to be conducted.

Acknowledgements

We are deeply grateful to Uematsu Electric Co., Ltd.

References

1) E.W. Schmidt: Hydrazine and Its Derivatives: Preparation, Properties, Applications, 2 Volume Set, Wiley-Interscience, (2001).
2) Y. Kanda, S. Kondo, S. Ooya, T. Kobayashi, Y. Uemichi, K. Higashino and M. Sugioka: J. of Chemical Engineering of Japan, **44** (2011) 803.
3) K. Kondo, K. Higashino and M. Sugioka: Proc. of The 53rd Conference on Aerospace Production and Power, JSASS-2013-0033, Okayama, Mar. (2013).
4) J.R. Rollins, R.K. Grove and D.E. Jaekle, JR: 21st Joint Propulsion Conference, AIAA-85-1199, Monterey, (1985).
5) D.E. Jaekle, JR: 27th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA-91-2172, Sacramento, (1991).
6) F.T. Dodge: Southwest Research Institute, San Antonio, TX, USA (2000).
7) R. Imai, T. Imamura, M. Sugioka and K. Higashino: Microgravity Science and Technology, **29** (2017) 475.
8) S. Katsumasa and T. Okawa: Jap. J. of Multiphase Flow, **28** (2014) 466.
9) R. Imai, T. Ideta, K. Yamada, K. Hana and K. Mitani: Proc. of the Space Science and Technology Conference, **46** (2002) 287.
10) K. Takahashi, K. Inaba and K. Kishimoto: J. of the Adhesion Society of Japan, **50** (2014) 235.
11) K. Hukuyama: J. of The Surface Finishing Society of Japan, **60** (2009) 21.