A Non-Contact Holder Using Airflow*

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When products requiring careful handling such as semiconductor wafers and food (hereinafter called “workpieces”) are transported in manufacturing processes, problems can occur due to malfunctions that degrade sanitary conditions during the transport of workpieces through contact. An excellent device for transporting workpieces is a pneumatic non-contact holder (hereinafter called “holder”). However, this device has a disadvantage in that, although the vertical force on the workpiece can be controlled, it is not possible to control the horizontal force. As such, the workpiece is sometimes unstable and slides away from the holder. We changed the shape of the diffuser in the holder, and observed the behavior of the workpiece held by the holder. We measured the holding force and the pressure distribution for several holders in order to determine the influence of the diffuser shape on the behavior of the workpiece.

Keywords: Pneumatic, Non-Contact, Airflow, Holding Force, Pressure Distribution

1. Introduction

Objects such as semiconductor wafers and glass substrates are normally transported using direct-contact end effectors¹⁾. However, surface scratching, particle contamination and electrical charging can occur due to the direct contact between the handling device and the workpiece, leading to the possibility of a reduction in production efficiency and reliability. Non-contact transport methods have been proposed to address these problems, and methods using electromagnetic power and supersonic motion have already been developed. However, problems such as restrictions on the type of workpiece material and difficulties in stabilizing the workpiece floating position remain to be addressed²⁾. The pneumatic non-contact holder shown in Fig. 1 is liked in semiconductor manufacturing processes³⁻⁴⁾ because it has the following five advantages: (A) there is no chance of contamination or damage to a workpiece, and objects such as food can be transported under sanitary conditions, (B) it generates low heat or no magnetic field, (C) it is applicable to a variety of workpiece materials, (D) it does not require a control loop to obtain a stable state⁵⁻⁶⁾, and (E) it is durable and requires no maintenance. There are several types of the holder, including Bernoulli and vortex holders. The holder, which is introduced in this paper, uses a Bernoulli mechanism⁷⁾ and is referred to as the Bernoulli holder.

Fig. 1 Non-contact holding by Bernoulli holder

1.1 Bernoulli Holder

Figure 2 shows a schematic diagram of a Bernoulli holder. Compressed air is supplied from a supply port of the holder, and escapes to the atmosphere through the space between the holder and the workpiece. Negative pressure forms at the space between the holder and the workpiece according to Bernoulli's theorem, because the airflow from the holder decelerates and becomes equal to atmospheric pressure. Atmospheric pressure acts on the side of the workpiece opposite the holder, so the workpiece is moved toward the holder due to the pressure differential. However, the holder can hold the workpiece without contact, because a layer of air flowing between the holder and the workpiece is maintained.

Our previous study⁸⁾ revealed that by constructing a chamfer, called a diffuser, on the edge of the holder, a Bernoulli holder can stably hold a workpiece without letting it slide away from the holder. As shown in Fig. 3, when a workpiece slides toward the right, a pressure differential occurs at both ends of the workpiece. The speed of the airflow at the side closest to the center of the holder is higher, and so negative pressure occurs at this side. In contrast, the airflow at the side farthest from the center of the holder escapes along

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the diffuser due to the Coanda effect and the pressure around this side of the workpiece becomes equal to atmospheric pressure, and so the workpiece is pushed toward the negative pressure side. Thus, the holder with the diffuser can prevent workpieces from sliding away from the holder.

Fig. 2 Principle of Bernoulli holder

Fig. 3 Principle of hydrodynamic force on sliding workpiece

1.2 Purpose of Present Study

As described above, the holder holds a workpiece using the hydrodynamic force generated by the pressure differential. However, although such holders can control the force on a workpiece in the vertical direction, they cannot control the force acting in the horizontal direction. Therefore, a workpiece may slide away from the holder. To prevent this, a guard is often installed in such holders. However, if the side of a workpiece touches the guard, the workpiece sometimes breaks. The purpose of the present study is to find a holder shape that can completely prevent the workpiece from sliding away. Therefore, we changed the shape of the diffuser in the holder, and observed the behavior of the workpiece held by the holder. We measured the holding force and the pressure distribution for several holders in order to determine the influence of the diffuser shape on the behavior of the workpiece.

2. Nomenclature

E	:	Supply energy
P	:	Supply pressure (absolute pressure)
P_a	:	Atmospheric pressure (absolute pressure)
Q	:	Supply flow rate

3. Experimental Equipment and Methods

3.1 Holder

Figure 4 shows a cross section of the Bernoulli holder considered here. The holder is cylindrical and has an outer diameter of 40 mm and a height of 36 mm. The primary components of the holder are Body-A, the deflector, and Body-B. Compressed air supplied to the holder flows between Body-A and the deflector and exits from the nozzle, which has an opening of 0.2 mm. The air is directed toward the space between the holder and the workpiece and flows near the diffuser. In this study, we changed the shape of the diffuser in Body-B in order to examine its influence on the behavior of the workpiece. In Fig. 4, a and b indicate the diffuser width and height, respectively, and θ indicates the angle of the diffuser in degrees and is calculated using $\theta = \arctan(b/a)$. Table 1 lists the dimensions of the diffusers considered here. In this paper, we focus on the width and the angle of the diffuser.

Fig. 4 Structure of Bernoulli holder

Table 1 List of components of holder

Holder Name	Width a (mm)	Height b (mm)	Angle θ (degrees)
H-1	6	0.17	1.6
H-2	9	0.25	
H-3	6	0.34	3.2
H-4	9	0.50	
H-5	6	0.50	4.8
H-6	9	0.75	
H-7	6	0.66	6.3
H-8	9	1.00	
H-9	6	0.74	7.0
H-10	9	1.11	
H-11	6	0.84	8.0
H-12	9	1.26	
H-13	6	1.00	9.5
H-14	9	1.50	
H-15	9	2.00	12.5

3.2 Experimental Facilities

Figure 5 shows the pneumatic circuit used in this experiment. Air is compressed by the compressor, and water, dust, etc., in the air are removed by a filter. The air flows through a solenoid valve, a regulator, a flow meter, and a pressure gauge before entering the holder, and then exits from a nozzle. Figure 6 shows the system used in this experiment. The holder is fixed to vertically moving electric slider. Using this system, we observe the behavior of the workpiece held by the holder. The holding force and the pressure distribution for several holders are measured by the experimental apparatus shown in Fig. 7. The holder is fixed to the apparatus, and we measure the holding force for the surface plate by using the load cell which is fixed to the top of the holder. The distance between the holder and the surface plate (hereinafter called “clearance”) can be adjusted by the micrometer at the top of this apparatus. The small hole on the surface plate is connected to a U-shaped tube manometer. The other side of the U-shaped tube manometer releases air into the atmosphere, so the pressure at the surface of the surface plate can be measured by reading the height difference of the liquid in the tubes. We measure the pressure distribution radially by moving the holder horizontally.

Fig. 5 Pneumatic circuit of holder

Fig. 6 Experimental system

Fig. 7 Experimental apparatus

Figure 8 shows the workpieces that were used in this experiment. The workpieces are thin disks made from acrylic resin and have a thickness of 1 or 3 mm and a diameter of 30, 35, or 40 mm.

Fig. 8 Experimental workpieces

3.3 Experimental Methods

(i) Preventing test of workpiece's sliding away

After holder holding workpieces were vertically moved by an electric slider, we investigated how long each holder could stably hold a workpiece without dropping it. First, by using the experimental system shown in Fig. 6, the workpiece was placed on the stage, and the holder was brought close to the workpiece at a clearance of 0.15 mm. The airflow pressure was adjusted in advance. During the few seconds after the airflow exited, the holder moved to a height of just above 150 mm at a speed of 30 mm/s. In this test, the supply pressure was only 30 or 40 kPa. The measurement time was from the moment that the holder completely rose until the workpiece slid away from the holder. These measurements were conducted 10 times under the same conditions. If the workpiece slid away from the holder before the holder completely rose, the recorded time was 0 s. If the workpiece was held for more than 60 s, the measurement was considered significant, because such a holder can be considered to be useful in factories.

(ii) Measurement test of holding force

We measured the holding force while changing the clearance with the experimental apparatus shown in Fig. 7. In this case, we adjusted the supply pressure and the supply flow rate so that the supply energy was about 30, 60, 100, or 200 W. The supply energy E is given by:

$$E = P_a \times Q \times \ln \left(\frac{P}{P_a} \right) \quad (1)$$

Equation (1) is the energy equation for compressible flow. If the supply pressure is 40 kPa, the supply energy for all the holders in the present study is about 60 W, because the supply flow rate is about the same.

(iii) Measurement test of pressure distribution

To characterize the influence of the diffuser shape on the pressure distribution, we measured the pressure distribution radially. In order to compare the results as clearly as possible in this test, we used a supply energy of 60 W and a clearance that gave the maximum holding force. Our previous study ⁹⁾ revealed that the pressure distribution differs depending on the line along which the pressure distribution is measured, because of the asymmetry of the internal holder structure. Therefore, we measured the pressure distribution radially along six different lines.

4. Results

For the fifteen holders listed in Table 1, we conducted the tests described above. The results are as follows.

4.1 Preventing Test of Workpiece's Sliding Away

Table 2 shows an example of the results for holder H-14. The values indicate the time in seconds from the moment that the holder completely rises until the workpiece slides away from the holder. This is called the holding time. The ○ symbol indicates that the measurement time exceeded 60 s.

Table 2 Holding time of holder H-14 (unit: seconds)

Workpiece		Supply Pressure (kPa)	Supply Flow Rate ($\times 10^{-4} \text{ m}^3/\text{s}$)	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Thickness (mm)	Diameter (mm)												
3	30	30	14.3	○	○	○	○	○	○	○	○	○	○
		40	17.2	○	○	○	○	○	○	33	16	○	○
	35	30	14.8	○	○	○	○	○	○	○	○	○	○
		40	17.0	○	○	○	○	○	○	○	○	○	○
	40	30	14.3	○	15	28	○	16	3	○	○	21	18
		40	16.5	○	○	○	○	2	○	○	○	16	12
1	30	30	14.5	○	○	○	○	○	○	○	○	○	○
		40	17.0	○	○	○	○	○	○	○	○	○	○
	35	30	14.3	0	0	0	0	0	0	0	0	0	0
		40	16.5	3	0	0	0	0	0	0	0	0	0
	40	30	14.3	26	0	0	16	38	0	0	0	23	0
		40	16.5	31	○	○	○	34	○	0	○	26	○

It can be seen that the holding time depends on the dimensions of the workpiece.

Table 3 shows the results of a probability analysis for the fifteen holders. The ○ symbol indicates that the holder could hold the workpiece with a probability of 100% for more than 60 s for supply pressures of 30 and 40 kPa. The △ symbol indicates that the holder could hold the workpiece with a probability of 100% for more than 60 s for supply pressures of either 30 or 40 kPa. The × symbol indicates that the holder could not hold the workpiece with a probability of 100% for more than 60 s for supply pressures of either 30 or 40 kPa.

It can be seen that the holding time for the holder also depends on the diffuser shape. Holders with diffuser angles that were too large or too small could not hold the workpiece for a long time. For a small diffuser angle, the effect on the workpiece was small. On the other hand, for a large angle, flow separation seemed to occur at the diffuser. Onitsuka et al. thought that a flow separation occurs in a flow path with a diffuser angle of 8.0° and over ¹⁰⁾. Therefore, in this test, nearly the same results were obtained. Moreover, for an angle of 3.2, 4.8, 6.3, or 7.0°, holders with a diffuser width of 9 mm could prevent the workpieces from sliding away better than holders with a diffuser width of 6 mm. The reason for this is

considered to be that when a workpiece slides, holders with the diffuser width of 9 mm can more immediately affect the workpiece. In holders H-4, 8, and 10, the workpieces seemed to contact the holder because the workpieces vibrated. Therefore, holder H-6 could most stably hold the workpieces without contact while preventing them from sliding away.

4.2 Measurement Test of Holding Force

To examine the influence of the diffuser angle on the behavior of the workpiece, we conducted a measurement test of the holding force and the pressure distribution for holders H-2, 6, and 15 whose the angles of the diffuser are quite different. Figures 9-11 show the holding force characteristics.

Fig. 9 Holding force characteristics of holder H-2

Fig. 10 Holding force characteristics of holder H-6

Fig. 11 Holding force characteristics of holder H-15

It can clearly be seen that a holder generates a higher holding force as it is supplied with more energy. The holding force initially increases with increasing clearance, but then decreases towards zero. It was found that the holding force could be negative in the case of a very small clearance (less than about 0.08 mm), because the surface plate is pushed downward by the collision with the airflow from the holder. Figure 12 shows a comparison of the maximum holding force for the holders.

The maximum holding force for holder H-6 with a diffuser angle of 4.8° was the greatest, regardless of the magnitude of the supply energy.

Fig. 12 Maximum holding forces of holders H-2, 6, and 15

Table 3 Results of all holders

<div>Diffuser</div> <div>Workpiece</div>					Angle (degrees)																							
					1.6			3.2			4.8			6.3			7.0			8.0			9.5			12.5		
					Width (mm)																							
					6		9		6		9		6		9		6		9		6		9		9			
					Holder Name																							
					H-1	H-2	H-3	H-4	H-5	H-6	H-7	H-8	H-9	H-10	H-11	H-12	H-13	H-14	H-15									
Thickness (mm)	3	Diameter (mm)	30	Mass (g)	2.46	×	×	×	○	○	○	○	○	×	○	×	△	×	△	×								
					3.35	×	×	○	○	○	○	○	○	×	○	△	△	○	○	×								
					4.25	×	×	○	○	○	○	○	○	×	○	×	○	○	×	×	×							
	1	Diameter (mm)	30	Mass (g)	0.83	×	×	×	○	×	○	×	○	×	○	×	△	×	○	×								
					1.09	×	×	×	○	○	○	○	○	×	○	×	○	×	×	×	×							
					1.49	×	×	○	○	○	○	○	○	×	○	×	△	×	×	×	×							

4.3 Measurement Test of Pressure Distribution

Figure 13 shows the pressure distribution for holders H-2, 6, and 15. In this figure, the pressure is the average for each measurement line.

Fig. 13 Pressure distributions of holder H-2, 6, and 15

It was found that a large negative pressure occurs in the region inside the nozzle in each holder. Also, the magnitude of the negative pressure greatly decreases when the distance from the center of the holder becomes about 9.5 mm. Moreover, positive pressure occurs because the airflow from the nozzle exits obliquely and collides with the surface plate when the distance from the center of the holder is about 10.0 mm. The pressure becomes negative in the region outside this point, and then decreases to atmospheric pressure. For holder H-6, a large negative pressure occurs in the region outside the nozzle over a relatively wide range. Also for holder H-6, the holding force, which is calculated by integrating the pressure radially, is the largest for the three holders.

5. Conclusions

In this study, we examined the influence of the diffuser shape on the behavior of a workpiece. Our purpose was to determine the holder conditions that can completely prevent the workpiece from sliding away from the holder. The following conclusions were obtained:

1. A holder with a diffuser which has an optimized shape can prevent the workpiece from sliding away from the holder.
2. The diffuser shape affects the holding force and the pressure distribution, and also the hydrodynamic force that acts on the sliding workpiece.

As a future task, we need to investigate in more detail the mechanism underlying the diffuser effect. We intend to measure the holding force and the pressure distribution in situations where the workpiece slides. We also plan to determine the velocity and pressure distributions around the workpiece using numerical analysis, with the intention of developing a holder that can more stably hold workpieces.

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