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Control of line width with active nano fountain pen (ANFP) for nano manufacturing

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Abstract

In this paper, modeling of ANFP (active nano fountain pen) and a nano size line control system with ANFP based on fuzzy algorithm is developed. It was found that line width is affected directly with initial mass of meniscus; velocity of patterning and concentration of ink directly affect line width. The control algorithm using the result of modeling successfully shows that the speed of patterning is increased and a variation of line width is possible compared with DPN (dip pen nano lithograph) and FPN (fountain pen nano lithograph). The control of line width system with ANFP is developed by using fuzzy algorithm. Finally, it is shown that it is possible to develop an effective control of variant line width with the same speed.

Keywords: ANFP (Active Nano Fountain Pen); Line width; Fuzzy algorithm

1. Introduction

As it is different from existing imprinting methods in nano manufacturing pattern research, improving technology using AFM (atomic force microscope) is getting into the spotlight. DPN and FPN are come to this method.

The invention of DPN makes molecular ink (for example, Octadecanethiol acid - ODT, 16 - Mercaptohexadecanoic acid - MDHA, alkanethiol), possible in being written with high resolution on the surface substrate (for example., gold, mica).

The disadvantages of DPN are that it must immerse an AFM tip into a solution, then the molecular ink will be coated on the tip; the ink will be written when the tip is contacted to the surface substrate; during time the ink adhering on the tip will be used up, it means to continuously make pattern we have to re-immerse the tip in ink again. These disadvantages make DPN pattern with halting time [1-3].

Therefore, duration is the only factor for controlling line width [4]. In the case of DPN, because duration time arrives at hundreds seconds to do line width control, there is a limitation in process efficiency.

In order to overcome the disadvantages of DPN, a new technique called FPN that is a match of DPN with a micro fluidic system [5] has been developed. The micro fluidic system consists of two micro channels and a high-capacity reservoir, that contains ink. Ink from the reservoir travels through microchannels by capillary action force; then ink is deposited at the tip. When the tip contacts substrate, molecular inks go through the tip to form a meniscus; after that if the tip moves, the pattern is made. However, it is hard to control the initial meniscus with FPN. It cannot make various patterns rapidly. An ANFP is introduced to make up for the weak points of FPN. Recent work by Lee showed a conception of ANFP [6, 7]. An ANFP can control the mass of the meniscus with pressure and velocity of the tip with time. An ANFP has a membrane connected with the tip to pump ink. When the tip is in contact with the substrate, membrane pumps a chamber, so ink contained in chamber flows.

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At this time, the initial meniscus is controlled by this pumping, it makes various patterning rapidly. In this case, some effects that are the velocity of patterning, initial mass of meniscus, the diffusion of ink, the coefficient of diffusion, the concentration, the relative humidity, etc form the line width. A modeling of line width for ANFP was introduced by Hwang about upper effects [8].

In this paper, the results of modeling and open Loop fuzzy algorithm are introduced to control line width based on modeling. Because the error between line width and reference line width cannot be sensed by using an existing AFM, open-loop fuzzy control algorithm was used.

2. Modeling

2.1 Working principle

Fig. 1 depicts the schematic of ANFP. A tip is connected in the channel. When the tip is attached to substrate, pressure occurs and it causes the mass of channel to change as shown in Fig. 2 [6]. so ink can flow out at tip. It is possible that the initial meniscus can be controlled.

In this paper, the purpose is to investigate and control the effects of varying velocity of the tip, concentration and diffusion rate of ink to line width. Fig. 3 [8] illustrates a block diagram of the whole system. Z means vertical direction between the tip and surface substrate. When the tip contacts the surface substrate, the pressure of the microfluid in microchannels should change, which causes the amounts of molecular inks to be changed. G_meniscus was used to describe this phenomenon. G_meniscus means mass of meniscus that comes out in tip.

When the tip is contacting the substrate; whether the effective force of the tip is strong or weak, it affects the shape of the meniscus because the mass of the meniscus is changed depending on the effective force. Due to time, the effective force approaches to a constant value then the shape of the meniscus is stable.

There are some forces that dominate the system: van der Waals force, capillary force, and surface tension force. The van der Waals force is very important to consider and investigate the adhesive phenomenon of molecular ink, but in this study, the purpose is to control the line width of the ink; the force is very small compared with other forces. Thus, it is omitted.

The tip moves on the X–Y surface plane by X-Y plotter force. At this time the total force applied to the tip is G_tip. Firstly, line width is made by G_ line width; secondly, under the diffusive phenomenon of ink, the line width will be spread. After a period of time, the line width does not spread more; it reaches

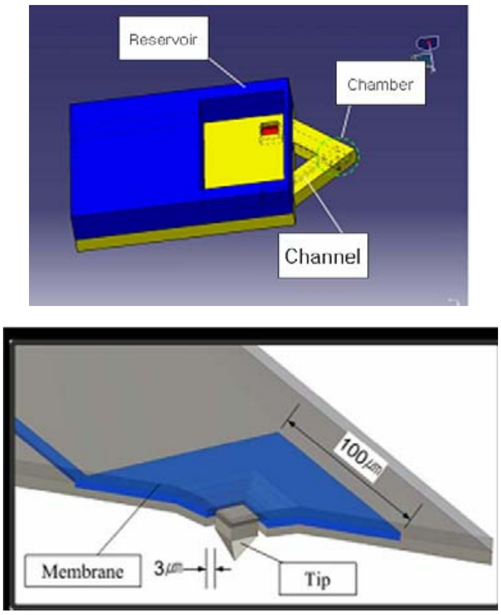

Fig. 1. Schematic of nano fountain pen.

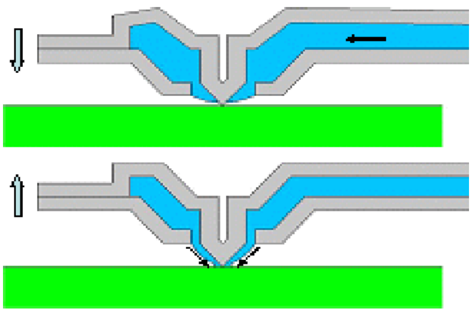

Fig. 2. Schematic of the working mechanism of nano fountain pen.

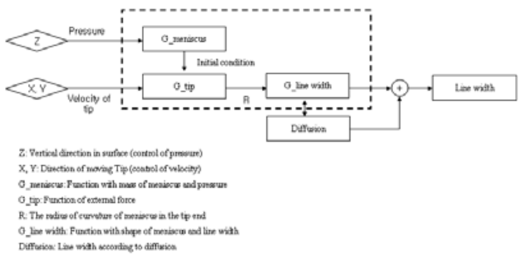

Fig. 3. Block diagram of whole system.

an equilibrium width and does not change its shape. Matching two cases, line width can be adjusted.

So the whole line width is shown by Eq. (1) [8]:

$$L_f = L_{tip} + L_{diffusion} \quad (1)$$

with L_f as the final line width, L_{tip} is the line width that is created by the tip, and $L_{diffusion}$ is the line width that is created by diffusion.

2.2 Modeling of line width by tip

A result of modeling was introduced about the initial condition as shown in Fig. 4. [6, 7] In Fig. 4, two curves that compare the theoretical with simulation are shown. Mass flow is coordinated at Y–axis, and pressure that is applied at the tip is coordinated on the X–axis. In Fig. 4, the initial mass of the meniscus is controlled by pressure.

The meniscus is deformed between the tip and substrate. At this time, the capillary force and surface tension force are dominative force on the meniscus. A dominative equation is shown in (2). This Eq. (2) is introduced in [9]. It supposes that the shape of the tip is spherical. When tip is attached in the substrate to deform meniscus with pressure-this is shown in Fig. 5(a)[8]. So the capillary force makes a meniscus around the tip. Modeling result is shown from (2) to (7) [8] :

$$F_p = k(2\pi Rd)(\frac{\gamma}{r_1}) \quad (2)$$

where γ is the surface tension, r_1 is the radius of rotation at initial state, R is the tip radius, d is the distance between the tip and substrate, k is constant, θ_1 is tangent angle of meniscus, ϕ is angle that is made between center of sphere and meniscus contact point.

After the meniscus is deformed around the tip, the tip comes out the substrate and makes a pattern. Fig. 5b [8] illustrates the change of meniscus shape when the tip is moved. In this case, the capillary force changes as formed in (3). Equation (3), which is introduced at [9], is modified to fit our system. Capillary force can be found by multiplying the surfacing working on γ/r. The quantity of meniscus is very small at this stage, so it is presumed that the capillary force happens on every part of the meniscus. Therefore, multiplying γ/r by the microscopic surface

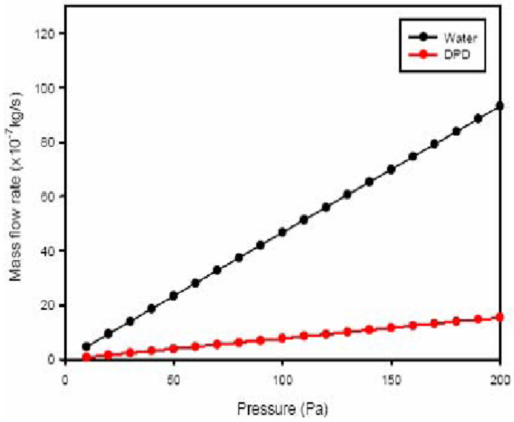

Fig. 4. Initial condition.

which is shown in Fig.5b, deriving it by total meniscus the total area is shown in Fig.5c. So equation (3) can be acquired. In this stage K is found experimentally as the capillary force changes according to the quantity of the meniscus.

$$F_{p\_edit} = k(2\pi Rd)\frac{\gamma}{r_{equilm}} \quad (3)$$

with r_{equilm} as the radius at equilibrium state (Fig. 5b). The radius of rotation is a function of acceleration, because the radius of rotation is changed by the AFM force. In a way, acceleration changes the radius of rotation. So the radius of rotation is $r_1(a)$ and $r_2(a)$ in moving state. If $r_1(a)$ and $r_2(a)$ are used at the same time in the modeling, then the modeling becomes complex, so r_{equilm} is used.

When the tip is moved, the total force occurring in the system consists of external forces which is the force of the X-Y plotter and the capillary force of the meniscus. Fig. 6 [8] illustrates a simplified modeling; the total force balance is (4)

$$F_{afm} - F_{p-edit} = m_{meniscus}a \quad (4)$$

Rearranging (4):

$$r_{equilm} = \frac{2k\pi Rd\gamma}{F_{afm} - ma} \quad (5)$$

Using (1) and (5), we calculated the line width of ink as (6):

$$L_f = 2[(R + r_{equilm})\sin\phi - r_{equilm}\sin\theta_{equilm}] \quad (6)$$

Where

$$\theta_{equilm} = \frac{\theta_2 + \theta_3}{2} \quad (7)$$

where θ_2 and θ_3 are the contact angles of the liquid at the surface. If acceleration exists, line width is made. Even if the acceleration is removed, the line width will remain. The reason is no change of the radius of gyration of the meniscus because it is in the case of uniform motion action of external force.

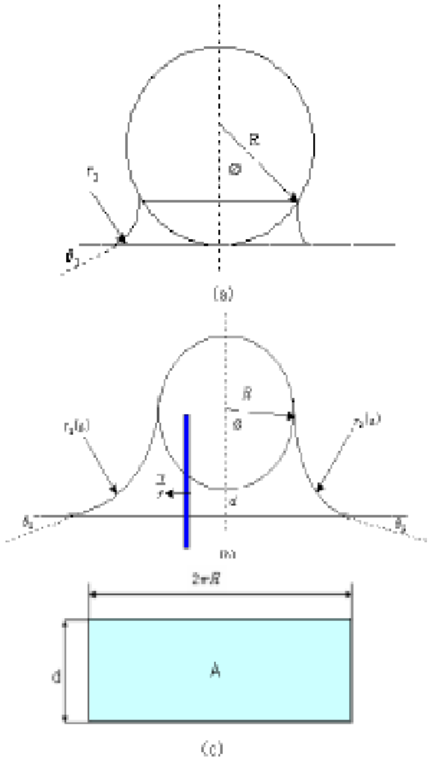

Fig. 5. Body diagram of tip (a) In initial stste, (b) In moving state, (c) surfacing working on γ / r.

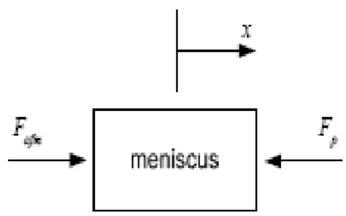

Fig. 6. A simplified modeling.

2.3 Modeling of line width by diffusion

Initially, molecular ink from the reservoir transfers the tip via micro channels under active capillary forces. The rate transport from the tip can vary with a number of parameters, including the distance between the tip and the substrate, the velocity of the tip, the ink composition, surface roughness, energy of substrate, environmental conditions as temperature, pressure, and humidity. Changing the hydrophobicity of the surface substrate causes the energy of the surface to change, which affects the surface diffusion of inks and then makes the shape of the meniscus change [8].

After the mass of initial meniscus is deformed at the substrate, a pattern is made by moving the tip. The diffusive and evaporative phenomena appear simultaneously. Fig. 7 [8] illustrates the change of the meniscus shape. At initial time $t = 0$, the height of the meniscus is k; because water in meniscus is evaporated and meniscus is diffused simultaneously, the height of meniscus will be decreased. Due to $t = t_e$, the height of meniscus is c, and the final width of line width is $2 \times b$. After time t_e the shape of the meniscus is very stable and does not stretch out an extended time. Modeling result is shown in from (8) to (16) [8].

Suppose that after time $t = t_e$, the length of line width is l; the mass of meniscus:

$$V = \frac{\pi}{4} c \times l \times b \quad (8)$$

The initial mass of the meniscus is added by volume of pattern and evaporation of solution. It is shown in (9):

$$m_0 = V\rho + m_{water} \quad (9)$$

where m_0 is the mass of initial meniscus, V is the mass of the pattern, ρ is the density of ink, m_{water} is the mass of evaporation. In equation (9), we calculated the mass of evaporation [9]:

$$m_{water} = \int AFCdt \quad (10)$$

where A is the surface area, F is the rate of evaporation, C is the concentration at critical time. In equation (10), A and F are the fixed values, but C is a function of time and displacement. So to find the function of concentration, Fick's 2nd law is applied.

$$\frac{\partial C}{\partial x} = D\frac{\partial^2 C}{\partial t^2} \quad (11)$$

Boundary conditions:

$$\frac{\partial C}{\partial x}(0,t) = 0 \quad (12)$$

$$\frac{\partial C}{\partial x}(L,t) = 0 \quad (13)$$

(Symmetry condition)
Initial condition:

$$C(x,0) = C_0 \quad (14)$$

The solution of Fick's 2nd law with two initial conditions (12), (13):

$$\text{C(x,t)} = C_0 \times e^{-D(\pi/L)^2 t} \times \cos(\pi x / L) \quad \mathbf{(15)}$$

with D is the diffusion rate of meniscus, L is the final position, C_0 is the initial concentration of ink in reservoir. Line width is calculated by substitution (15) for (10):

In Fig. 7, b means the final line width, c means thickness after diffusion, k means initial thickness of meniscus. Eq. (16) is the final result of diffusion modeling. Initial mass of meniscus (m_0) is induced in Fig. 4 And other parameters are the properties of ink. So line width (x) can be calculated by using equation (16).

$$m_0 = \frac{1}{4}\pi\rho c L x + AF\frac{L^2}{D\pi^2}C_0 \cos(\pi x / L) e^{-D(\pi/L)^2 t} \quad (16)$$

3. Open-loop fuzzy control

Two control algorithms were used at the same time. When the tip is in contact with a substrate, a pressure occurs in membrane. At this time, pressure must be controlled to define the mass of the meniscus. This control algorithm is called "Fuzzy 1" in this paper. Length of pattern and linewidth are input factors in "Fuzzy 1". This process occurs in the 'Z-direction' in AFM. A PZT is an actuator in AFM to act in the Z-direction.

When the initial mass of the meniscus is defined, velocity must be controlled to control line width. This algorithm is called "Fuzzy 2" in this paper. The result of "Fuzzy 1" and line width are input factors. In AFM, x-y plotter moves to pattern, so velocity of x-y plotter is actually controlled. The entire diagram of "Fuzzy 1"and "Fuzzy 2" is shown in Fig. 8.

3.1 Z-direction control (Fuzzy 1)

"Fuzzy 1" controls pressure for vertical direction (Z direction) in AFM to control the initial mass of the meniscus. A quantization, membership function and rule base are defined by result of modeling in section 2. The length of pattern and line width are inputs. The reason is that initial mass of meniscus is decided by line width and length of pattern.

A quantization, rule base and membership function are shown in Table 1, Table 2, and Fig. 9. If the input line width is 130nm, then the quantization step is -2.4. Because quantization step is -3 when line width is 100nm and quantization step is -2 when line width is 150nm, so -2.4 can be calculated by linearity. It is applied at the same tine in length of pattern. Length of pattern comes in 1520μm then quantization step is -1.96. These quantization results are matched at NM-NS in membership function of line width, ZO-NS in membership function of length of pattern in Fig. 9. Min-Max law of defuzzification process is used to decide initial mass of the meniscus.

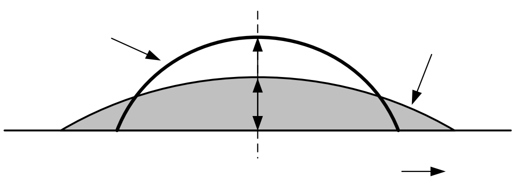

Fig. 7. Equilibrium shape of meniscus.

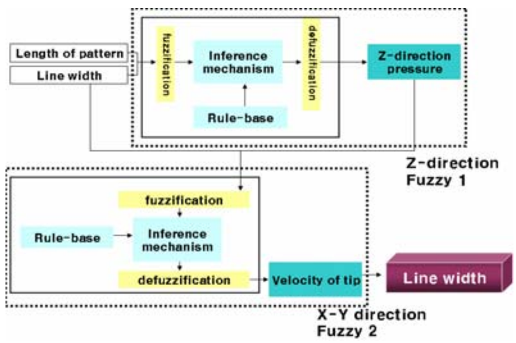

Fig. 8. Algorithm of Open Loop Fuzzy.

Table 1. Quantization step for fuzzy 1.

	w(line width)	L(Length of pattern)
-5	$0 < w < 50nm$	$0 < L < 100\mu m$
-4	$50 \leq w < 100nm$	$100 \leq L < 500\mu m$
-3	$100 \leq w < 150nm$	$500 \leq L < 1000\mu m$
-2	$150 \leq w < 200nm$	$1000 \leq L < 1500\mu m$
-1	$200 \leq w < 250nm$	$1500 \leq L < 2000\mu m$
0	$250 \leq w < 300nm$	$2000 \leq L < 2500\mu m$
1	$300 \leq w < 350nm$	$2500 \leq L < 3000\mu m$
2	$350 \leq w < 400nm$	$3000 \leq L < 3500\mu m$
3	$400 \leq w < 450nm$	$3500 \leq L < 4000\mu m$
4	$450 \leq w < 500nm$	$4000 \leq L < 4500\mu m$
5	$w \geq 500nm$	$L \geq 4500\mu m$

Table 2. Rule base.

W/L	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NM	NM	NS	ZO	ZO	ZO
NS	NM	NM	NS	ZO	ZO	ZO	PS
ZO	NM	NS	ZO	ZO	ZO	PS	PM
PS	NS	ZO	ZO	ZO	PS	PM	PM
PM	ZO	ZO	ZO	PS	PM	PM	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

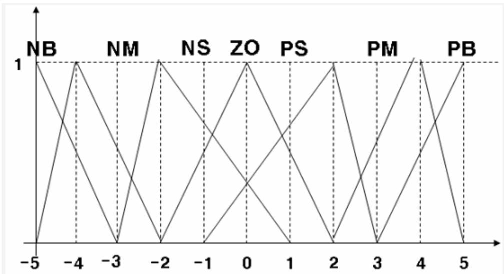

Fig. 9. Membership function.

3.2 X, Y-direction control (Fuzzy 2)

If initial mass of meniscus is controlled in "Fuzzy 1," the tip achieves a pattern as moving of X-Y plotter fixed in AFM. At this time, as the speed of the X-Y plotter is controlled, then line width is controlled. This is called "Fuzzy 2" in this paper. Input variables are initial pressure that is result of "Fuzzy 1" and line width. If initial meniscus and reference line width are fixed, then velocity of pattern is decided by result of modeling. A quantization table, rule base and membership function are shown in Table 3, Table 4, and

Table 3. Quantization step for fuzzy 2.

	w(line width)	P(pressure)
-5	$0 < w < 50nm$	$0 < P < 30Pa$
-4	$50 \leq w < 100nm$	$30 \leq P < 60Pa$
-3	$100 \leq w < 150nm$	$60 \leq P < 90Pa$
-2	$150 \leq w < 200nm$	$90 \leq P < 120Pa$
-1	$200 \leq w < 250nm$	$120 \leq P < 150Pa$
0	$250 \leq w < 300nm$	$150 \leq P < 180Pa$
1	$300 \leq w < 350nm$	$180 \leq P < 210Pa$
2	$350 \leq w < 400nm$	$210 \leq P < 240Pa$
3	$400 \leq w < 450nm$	$240 \leq P < 270Pa$
4	$450 \leq w < 500nm$	$270 \leq P < 300Pa$
5	$w \geq 500nm$	$300Pa \leq P$

Table 4. Rule base.

W/L	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NM	NM	NS	ZO	ZO	ZO
NS	NM	NM	NS	ZO	ZO	ZO	PS
ZO	NM	NS	ZO	ZO	ZO	PS	PM
PS	NS	ZO	ZO	ZO	PS	PM	PM
PM	ZO	ZO	ZO	PS	PM	PM	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

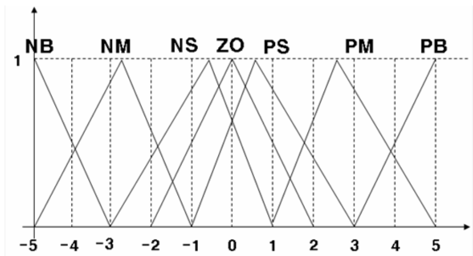

Fig. 10. Membership function.

Fig. 10. If initial pressure is 30pa and reference line width is 175nm, then it comes to NM, NB and NM, NS, ZO. These rule base elements are calculated according to position degree. According to this result, the defuzzification process decids the velocity of pattern by using Min-Max method.

4. Result

4.1 Result of modeling

4.1.1 Modeling of tip velocity and initial meniscus

A relation line width with initial mass is shown in Fig. 11 at fixed velocity. X-axis and Y-axis of graph

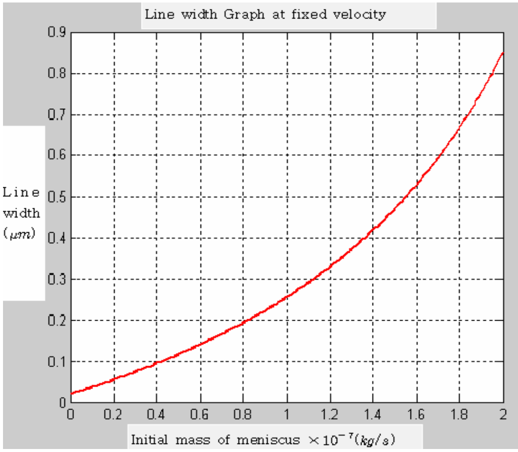

Fig. 11. A relation of line width with initial mass.

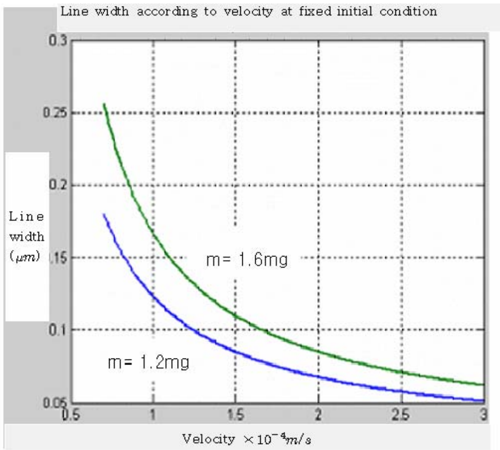

Fig. 12. A relation of line width with velocity.

mean initial mass of meniscus and line width. A similar graph is shown in [8]. This result magnified x scale double more than existing graph [8]. The reason is to see the tendency of line width by initial meniscus quantity detail. If the initial mass of the meniscus is larger, then the line width is wider. So various line widths can be made by varied initial mass of meniscus.

A relation of line width and velocity is shown in Fig. 12 at fixed initial mass of meniscus. Two initial conditions which are 0.0016g and 0.0012g, were used to obtain a result such as Fig. 12. This result is the thing to investigate the change of line width by change of the speed in fixed meniscus amount. When initial condition and pattern speed are 0.0016g and 0.002mm/sec, line width becomes about 90nm. But if initial condition and pattern are 0.0012g and 0.002mm/sec, line width becomes about 65nm. Therefore, it can be confirmed that speed and initial condition can control line width at the same time.

If velocity of the pattern is increased, then line width decreases. So various line widths can be controlled by initial meniscus and velocity.

4.1.2 Modeling of diffusion

The line width becomes wider when ink diffuses during patterning. The result of Eq. (15) is shown in Fig. 13 [8]. At Fig. 13, if the concentration is below than 0, then diffusion stops. To confirm whether diffusion rate influences the line width, modeling was executed. It is shown in Fig. 14. At the result, the diffusion rate affects the time of saturation but does not affect line width. In Fig. 14, three diffusion rates are used, because the purpose is to see that line width change s according to individual special quality of ink; moreover, diffusion rate does not influence line width so we did diffusion rate by 1, 2, 3 (μm^2/sec) for convenience sake.

The ink characteristic affects the diffusive phenomenon. The concentration rate is related to the relative humidity of ink: with higher concentration the line width reaches to equilibrium stability faster. The ink concentration depends on the amounts of molecular material in the ink. When the concentration is changed, then diffusion rate and density are changed at the same time.

Fig. 15 [8] shows three cases about the relationship between the line width and the changes of ink characteristics.

Case 1:
m = 0.0004 (g), C = 0.3, D = 5, $\rho = 0.39$
Case 2:
m = 0.0006 (g), C = 0.5, D = 4, $\rho = 0.45$
Case 3:
m = 0.0008 (g), C = 0.7, D = 3, $\rho = 0.5$

where, C: Concentration, D: Diffusion rate, ρ : Density.

But in this paper, specially, initial mass of meniscus is more important factor to control line width. So if other factors (concentration, diffusion rate, density) are fixed, then result how much diffusion is occurred should be known. We changed the value initial meniscus mass with three cases and initial meniscus is much more about ten times (0.005, 0.006, 0.007g) than Fig. 15; The result is shown in Fig. 16. The diffusion occurs up to 810nm in the case of 0.007g, but diffusion occurs up to 700nm in the case of 0.006g.

The results are shown in Fig. 15 and Fig. 16 almost the same. That is to say, characteristic coefficients of ink have small affects to deform line width. So the initial mass of meniscus is a very important parameter.

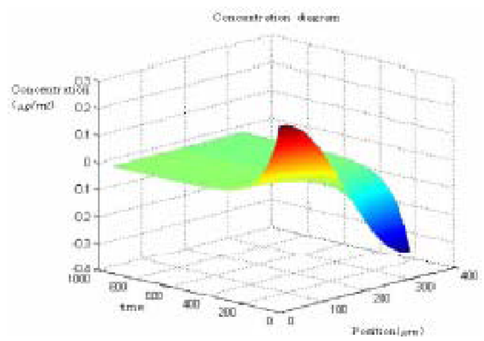

Fig. 13. Concenration diagram.

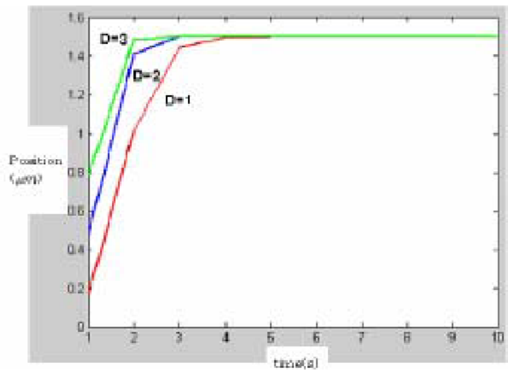

Fig. 14. Relation of line width and diffusion rate.

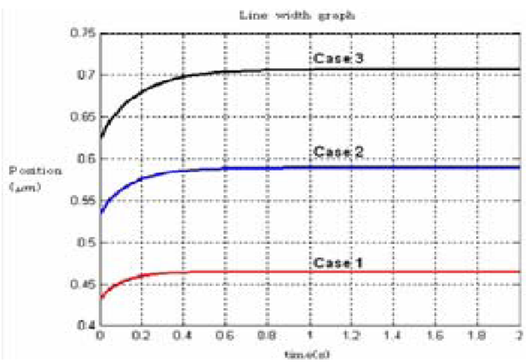

Fig. 15. Line width in three cases.

4.2 Result of control

Fig. 17 is the result of “Fuzzy 1”. When a line width and length of pattern are defined, an optimal initial mass of meniscus is defined, as in Fig. 17. In Fig. 17, the relation between line width and length of pattern with initial mass of meniscus is shown. If the line width is high and length of pattern is high, then initial mass of meniscus is high.

The result of “Fuzzy 1” is the input of “Fuzzy 2”. Fig. 18 shows the result of velocity control. If line width is 270nm at fixed initial condition, the pattern speed becomes about 0.002mm/sec. So if the pattern speed is high, the line width can decrease to tens nms, and if the pattern speed of pattern becomes slow, the line width is up to hundreds nms. Hence, various line widths can be made with changing velocity.

When it is a grid with reference line width, the output traces the reference line width (Fig. 19). In Fig. 19, error happens. A big error happens in the discontinuity neighborhood; it can assumes that this is the limit

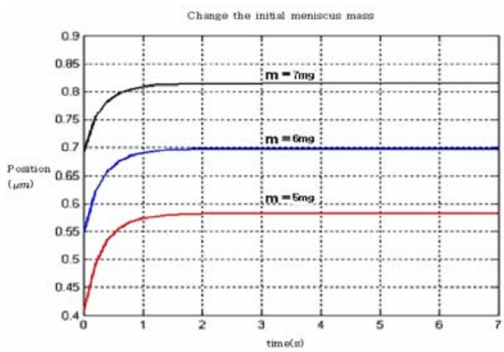

Fig. 16. A relation of line width and initial meniscus mass.

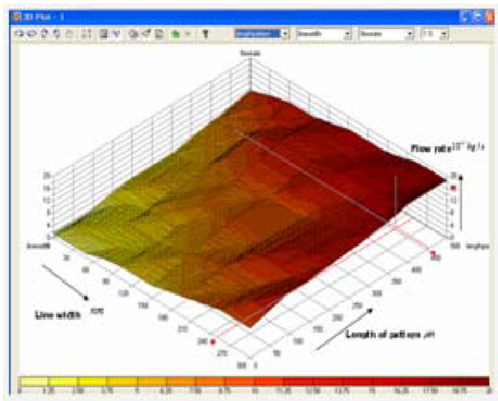

Fig. 17. Control of initial meniscus.

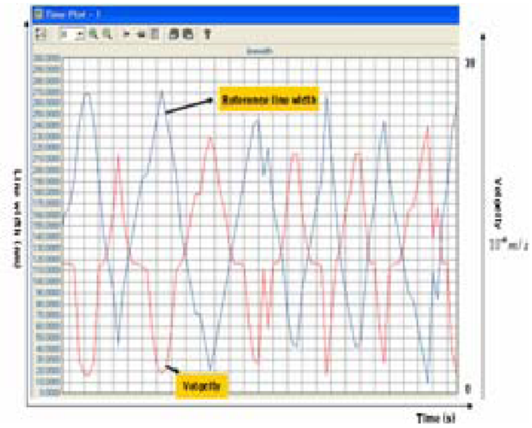

Fig. 18. Control of velocity.

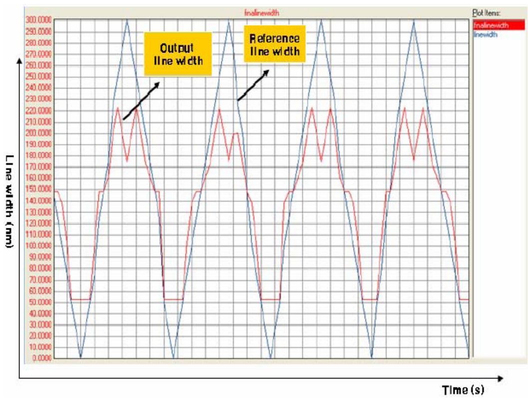

Fig. 19. Control of line width.

of the open loop Fuzzy algorithm. One can not do closed loop control because one can not measure line width of nm unit by real time in AFM equipment. However, region that can see linear is becoming smooth control that error happens in 10%s. This time, the line width is before diffusion.

5. Conclusion

In this paper, the modeling and control of ANFP was implemented. ANFP can overcome disadvantages of FPN and DPN as a results of this paper. When pressure is applied at the tip, it creates various initial mass of meniscus. This various initial meniscus can make various line widths. And line width can be controlled by speed of pattern. In DPN, speed of pattern is about 0.001mm/sec, but in ANFP, the speed of pattern is up to 0.1mm/sec. So ANFP can rapidly make various line widths. In addition a Fuzzy algorithm was used to control line width. The result of modeling was used to make a rule base and membership function. As the shown in the results, the velocity of the tip and initial meniscus can be controlled and it can be applied in a real system.

At the present, the only method that controls diffusion after patterning is the control of the initial meniscus but it is not a fundamental method. Therefore, a system of prevention of diffusion for AFPN must be developed. A sensor that can measure line width at the same time pattern does not exist, and it can make it impossible to do closed loop control. So we will develop a sensor to sense line width real time at AFM.

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