INTRODUCTION

Cell manipulations in the confined space of a microfluidic chip have great advantages in the field of biotechnology because of the low contamination capability, repeatability, and high throughput ability. Especially cell manipulations by microbot in a microfluidic chip have great advantages for the treatment of biological cell instead of micromanipulator due to their non-skill dependent, high throughput and high repeatability. We have continuously developed magnetically driven microbot actuated by permanent magnets and achieved high power (mN order), and high precision (μm order) actuation by oscillating glass substrate [1]. The main superiorities of the microbot driven by permanent magnet to other noncontact microbots such as optical tweezers [2] and Helmholtz coil [3], were its high power output and thus it can be applied to wide range of cell manipulations for multi-scale of biological cells. However, there are several weakness on the microbot driven by permanent magnets in terms of positioning accuracy at high speed, biocompatibility, and precise fabrication. Here, we propose new type of microbot composed of hybrid structure of Ni and Si. Taking advantage of flexibility of Si fabrication, three dimensionally patterned surface is produced on the robot in order to reduce fluid friction. Figure 1 shows the concept of the microbot composed of Ni-Si hybrid structure. Nickel remains same at the actuation part in order to obtain strong magnetic force from the permanent magnet, but Si is surrounding nickel to have bio-compatibility when the robot manipulates biological cells. In addition, regularly arrayed V grooves, which is called “riblet”, are patterned on the microbot and they reduce fluid friction force. As a result, the microbot can achieve high power output from the permanent magnet, precise accuracy at ultra-high speed region as well. It leads to high throughput cell manipulations in a microfluidic chip.

THEORY

The riblet shape, which is regularly arrayed V groove and also known as shark skin, is practically used for airplane and ship to reduce fluid friction force [4]. The basic principle to reduce fluid friction force by riblet is that squeezing liquid by the V groove generates upward fluid force on the riblet surface and it makes the lubricant film thickness increase. As a result, the shear stress from the substrate reduces and the fluid friction force decreases. Here, the fluid pressure analysis is conducted to understand the principle of the riblet surface and lead to optimizing the riblet shape in order to minimize the fluid friction on the microbot.

Figure 2 shows the definition of the variables for the riblet. In order to simplify the calculation, the front surface to velocity direction is classified as Region I, and back surface is classified as Region II. The height \( h(x) \) at arbitrary position \( x \) is expressed as follows:

\[
\begin{align*}
\frac{\partial}{\partial x} = a \cdot \frac{h_2}{h_1} \frac{x}{B} & \\
\frac{x}{B} = x / B
\end{align*}
\]

By derivation of equation (1), we obtain

\[
dx = \frac{B}{h_2 (a-1)} dh
\]

Here, we assume that the fluid pressure at boundaries of the Region I and Region II is 0, that is \( P(0) = P(B) = 0 \). Then, the following is derived

\[
B(x) = \frac{B}{h_2 (a-1)} dh
\]

\[
P(x) = \frac{1}{a} \frac{1}{h_2 (a-1)} dh
\]

\[
dh = \frac{B}{h_2 (a-1)} dx
\]

\[
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\]
from Reynolds equation.

\[
\frac{d}{dx} \left( \frac{h^3}{\eta} \right) = 6U \frac{dh}{dx}
\]  

(2)

where \( \eta \) is viscosity resistance.

For \( I_2(x) = \int dx \), \( I_3 = \int dx \), \( h_a = \int(B) \),

\[
I_2(x) = \frac{B}{h_x(a-1)} \left( \frac{1}{h_x} - \frac{1}{h_1} \right), \quad I_3(x) = \frac{B}{2h_x(a-1)} \left( \frac{1}{h_x^2} - \frac{1}{h_1^2} \right)
\]

And \( h_a = \int(B) = \frac{\int(B)}{\int(B)} = h_x + \frac{1}{h_1} \)

\[
P(x) = 6\eta U \left[ I_2(x) - h_a f_1(x) \right]
\]

\[
= 6\eta U \left[ \frac{B}{h_x(a-1)} \left( \frac{1}{h_x} - \frac{1}{h_1} \right) \right] - \frac{2h_x}{h_1} \left[ \frac{B}{2h_x(a-1)} \left( \frac{1}{h_x^2} - \frac{1}{h_1^2} \right) \right]
\]

To simplify the equations, we set \( h = \frac{h}{h_2} = a - (a-1) \cdot \pi \)

\[
P_1 = \frac{6\eta UB}{h_2} \left[ 1 - \frac{1}{h_2} \right] - \frac{1}{h_2} \cdot \left( 1 - \frac{1}{a} \right)
\]

(3)

For Region II, by same manner as Region I, we can get

\[
P_2 = \frac{6\eta UB}{h_2} \left[ 1 - \frac{1}{h_2} \right] - \frac{1}{h_2} \cdot \left( 1 - \frac{1}{a} \right)
\]

(4)

Figure 3 shows the fluid pressure distribution calculated by equation (3) and (4), when \( B = 250 \mu m, h_1 = 10 \mu m, h_2 = 5 \mu m, U = 5 \text{mm/sec}, \eta = 0.882 \times 10^3 \text{Pa's (water)} \). As shown in Figure 3, upward force is generated on Region I, and downward force is generated on Region II. When integrating the all fluid pressure over the surface area, the total pressure force is always upward. This upward force makes the lubricant film thickness increase and fluid force decrease.

In order to minimize fluid friction on the robot, lubricant film thickness must be maximize. During the robot movement in a microfluidic chip, there are three forces arise in vertical direction: gravity force (\( F_{\text{gravity}} \)), vertical components of magnetic force (\( F_{\text{magnet}} \)), and fluid pressure force on the riblet (\( F_{\text{fluid}} \)). These three forces are balanced during movement if the velocity of the robot does not change and thus the lubricant film thickness is kept same. That is,

\[
F_{\text{gravity}} + F_{\text{magnet}} + F_{\text{fluid}} = 0
\]

(5)

Here, \( F_{\text{gravity}} \) and \( F_{\text{magnet}} \) are easily measured and \( F_{\text{fluid}} \) can be calculated by equation (3) or (4). Therefore, we can find optimum combination of \( h_1 \) and \( B \) to maximize \( h_2 \) under the condition of equation (5).

Figure 4 shows calculation result of \( h_2 \) under the constraints of equation (5). The gravity force (\( F_{\text{gravity}} \)) of the microrobot was 5 \( \mu N \) and the vertical component of magnetic force \( F_{\text{magnet}} \) was 23 \( \mu N \), which was experimentally measured. Based on this calculation result, the film thickness \( h_2 \) is not depend on riblet width \( B \) and it is maximized to 3.5 \( \mu m \) when \( h_1 = 9.0 \mu m \) (riblet depth is 5.5 \( \mu m \)).

**EXPERIMENTAL**

**Fabrication:**

In order to fabricate the optimum riblet shape on the microrobot, anisotropic wet etching and deep reactive ion etching (DRIE) were employed. The fabrication process is shown in Figure 5. SiO2 was sputtered on Si wafer with (100) crystal orientation and patterned by buffered hydrogen fluoride. Then V groove was formed by KOH after the undercut phenomenon of
the SiO₂ mask. Ni support layer was then fabricated and DRIE was conducted to fabricate Si-Ni hybrid structure. After the DRIE, electroplating was employed to form the Ni portion and removed Ni support layer and Cr/Au.

Figure 6 (a) shows SEM image after wet etching. The angle of the V groove was 55 degree due to (100) crystal orientation, and the depth of the V groove was 5.7 μm while the optimum riblet depth was 5.5 μm. Figure 6 (b) shows fabricated Si-Ni hybrid structure of microrobot. The fabrication was conducted precisely as optimum design owing to the Si’s facility of the fabrication. In addition, there is no risk of bio-compatibility since the Si is well known as bio-compatible material.

**Evaluation:**

Figure 7 shows the result of the evaluation experiments for the positioning accuracy of the microrobot against the target circular trajectory (diameter 1.0 mm). In low velocity region, the amount of error of microrobot position from stage trajectory was almost same between the robot with and without riblet while Si-Ni composite MMT with riblet surface obtain certain advantages against Ni microrobot without riblet in high velocity region. Si-Ni composite microrobot with riblet keeps precise poisoning accuracy in high speed region (more than 5 mm/sec) as well. This is because the more velocity increases, the more fluid friction reduces owing to the riblet shape as known as equation (3).

**RESULTS AND DISCUSSION**

Now that the magnetically driven microrobot achieved precise positioning in high speed region as well with mN order output force, high speed cell manipulation in a microfluidic chip can be also achieved. In order to demonstrate the performance of the microrobot for cell manipulation, assembling MDCK multicellular aggregate was conducted. Assembling multicellular aggregate by the microrobot enables to create flexible cell array in high speed. Figure 8 shows the MDCK multicellular aggregate, which is staind in red, blue and green, assembly by dual arm microrobots. The throughput of the assembly can be increase thanks to high power output of MMT since it can treat more than 1000 cells at a time. Also it is easy to transport multicellular aggregate to the set position to achieve flexible array with different type of spheroids.

**CONCLUSIONS**

In this research, we have developed high speed microrobot by fabricating riblet surface on the magnetically actuated microrobot. The riblet surface was proved analytically and experimentally to be effective to make the friction decrease. The evaluation experiments shows the developed microrobot can be actuated in high speed region (more than 5 mm/sec) with stable accuracy while the conventional microrobot deteriorated the accuracy with increasing the drive velocity. The microrobots successfully achieved to assembly MDCK cellular aggregate in a microfluidic chip with arbitrary array.

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