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Processing method utilizing stick-slip phenomenon for forming periodic micro/nano-structure

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ABSTRACT

The stick-slip phenomenon was used to develop a simple, low-cost, and large-area-processable microfabrication method for forming periodic structures, because the stick-slip phenomenon occurs easily and its vibration period can be on the micro/nanometer order. At first, an original device that causes the stick-slip phenomenon between a razor and a polymer film was fabricated. Thus, periodic microstructures on a polymer film could be formed by a simple method in which a film is rolled up only when a razor is pressed into the film surface. Periodic nano-structures could also be formed by adjusting the processing conditions. Thus, a processing method utilizing stick-slip phenomenon for forming periodic micro/nano-structures (termed SS processing) was developed. Collaterally, it was revealed that the period of the periodic structures formed by SS processing decreased as the contact force between a razor and a film decreased and as the constraint force against a razor by a film increased. Moreover, a mathematical expression was proposed for predicting the period of the periodic structures formed by SS processing by introducing an abrasion coefficient into a theoretical formula for the SS phenomenon. Consequently, the calculated result using this expression showed good agreement with the experimental results.

1. Introduction

Materials with micro/nano-structures show functions that are not observed in corresponding ones with macrostructures. For example, Clapham and Hutley (1973) reported that the moth-eye structure (nano-nipple array) reduces surface reflection of eternal light. Therefore, the moth-eye structure improves visibility of displays. In addition, Gao et al. (2007) reported that material surface becomes hydrophobic by the micro-hemisphere and nanosphere structure. Miyake et al. (2010) reported that the nanostripe structure reduces friction and wear. Thus, the need for periodic micro/nano-structures is increasing in many fields.

Microfabrication is the process of forming micro/nanostructures. Laser processing and nanoimprinting are used typically; therefore, various adaptations of these techniques have been proposed. Bieda et al. (2016) fabricated sub-micron surface structures by picosecond direct laser interference patterning. Nagato et al. (2014) developed laser-assisted nanoimprinting method. Toosi et al. (2016) utilized hot embossing to imprint micron/submicron periodic structures. However, in case of laser processing, the number of suitable target materials is limited, and in the case of nanoimprinting, the total cost is high, for example, because of the cost of the mold. On the other hand, periodic micro-structures can be formed by mechanical processing. Yan et al. (2010) cut microstructure by using a diamond ball endmill. However, formation of nano-structures using this process is difficult, and friction increases the difficulty in controlling the process. In particular, if the friction vibration, called the stick-slip (SS) phenomenon (Fig. 1) first reported by Bowden and Leben (1939), is generated, controlling mechanical processing becomes more difficult. Thus, all the current microfabrication methods have both advantages and disadvantages, and in many cases, these are expensive and time-consuming because of the complexity of the process. Therefore, a new microfabrication method is required to solve the above problems.

The SS phenomenon occurs easily and its vibration period can be on the order of micro/nanometers. Therefore, it is possible to use the SS phenomenon for microfabrication. In fact, Yan et al. (2014) fabricated nanodots and Watson et al. (2006) fabricated parallel channels on a polymer surface by the SS phenomenon caused by the movement of a cantilever for a scanning probe microscope (SPM). Li (1996) fabricated a bamboo-like morphology by SS phenomenon during the scratch test. However, these methods are expensive and cannot be used for large-area processing. Therefore, in this study, an original, simple, low-cost, and large-area-processable microfabri-

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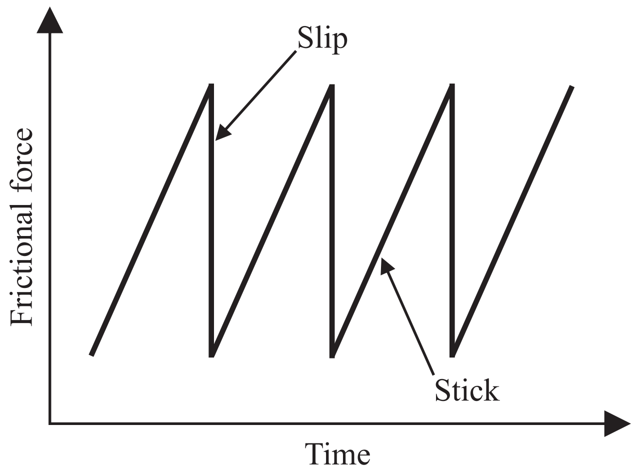

Fig. 1. Typical regular stick-slip. The static friction coefficient between two surfaces is larger than the kinetic friction coefficient, typically. When the frictional force is smaller than the maximum static frictional force, the surfaces stick. On the other hand, when the frictional force is larger than the maximum static frictional force, the surfaces slip.

Table 1
Properties of PET film (FE2000).

Density[g/cm^3]	Young'smodulus[GPa]	Breakingstress[MPa]	Breakingstrain[%]
1.38	3.98	172	229

Table 2
Friction coefficient between PET film (FE2000) and TE-2.

μ_s	μ_k	$\Delta\mu$
0.216	0.158	0.058

μ_s and μ_k are the static friction coefficient and kinetic friction coefficient, respectively. $\Delta\mu$ is the difference between μ_s and μ_k.

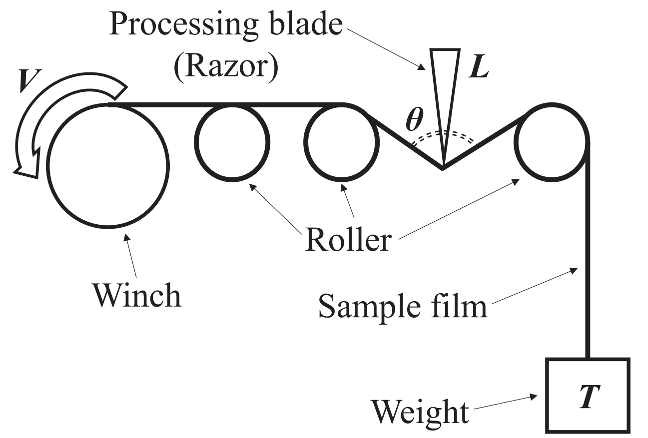

Fig. 2. Schematic diagram of SS processing.

Table 3
SS Processing conditions.

	T[N]	θ [°]	V[mm/min]	L[mm]
Max	10.78	165	10	1
Min	2.94	130		

T, θ, V, and L are the processing load, processing angle, processing speed, and length of the free end of the processing blade, respectively.

cation method is developed to form periodic micro/nano-structures by utilizing the SS phenomenon. In addition, this process is controlled and periodic nano-structures with a period similar to the wavelength of visible light wavelength (380 nm–750 nm) is formed.

2. Experiment

2.1. Sample and processing blade

A polymer film was used as a sample because its hardness and Young's modulus are lower than a processing blade and it is not stretched during the process. A polyethylene terephthalate (PET) film, which is widely used in several applications (touch panel, LCD etc.), was selected. Table 1 shows the properties of the PET film (FE-2000, Futamura Chemical, Japan) that was used in this study. Its thickness was 37 μm and its surface roughness, which was measured by SPM, was approximately 2 nm.

A razor (FAS-10, Feather, Japan) was used as a processing blade, because it has a high hardness and high Young's modulus (202.2 GPa) and has a sharp tip (tip angle of the blade: 15.5°). This razor is made of carbon steel TE-2. Table 2 shows the friction coefficient between the PET film (FE2000) and TE-2.

2.2. SS processing (formation of periodic micro/nano-structures)

The formation of periodic micro/nano-structures by utilizing the SS phenomenon was attempted. For this, an original processing device (SS processing device, Fig. 2) was fabricated.

This device consists of a winch for rolling up a sample film, rollers, and a holder for setting the processing blade. A rotary speed control unit is attached to the winch and the processing speed $\boldsymbol{V}$ (rolling-up speed) can be changed by the control unit. Moreover, the vertical position of the holder can be changed, and the processing angle $\boldsymbol{\theta}$ (bending angle of the film) can be changed by adjusting its position. Several types of holders are prepared, and the length of the free-end of the processing blade $\boldsymbol{L}$ can be changed by selecting the holder. Furthermore, when the end of the film was fixed to the winch and a weight was attached to another end of the film, the film becomes taut. Then, the processing load $\boldsymbol{T}$ can be changed using the weight. The device is started up after setting the above processing conditions (processing speed $\boldsymbol{V}$, processing angle $\boldsymbol{\theta}$, length of free end of the processing blade $\boldsymbol{L}$, processing load $\boldsymbol{T}$). Consequently, the film is rolled up and the SS phenomenon occurs at the contact area of the sample film and the processing blade.

Table 3 shows the range of the SS processing conditions in this study. The processing blade was replaced with a new one before each experiment. In addition, a rectangular film (2.0 cm in width, 20 cm in length) was used for the processing. The long side of the film is the machine direction (MD) direction and the short side is the transverse direction (TD) direction.

2.3. Evaluation of surface morphology of SS processed film

Scanning electron microscopy (SEM: S-4300, Hitachi Hi-Tech Science, Japan) was used to determine whether a periodic micro/nano-structures were formed on the surface of a SS processed film. The period and depth of the structures (termed the structure period and the structure depth) were measured using a scanning probe microscope (SPM: AFM5400L, Hitachi Hi-Tec Science, Japan). In addition, all plot points for the structure period and the structure depth are an average of at least 30 data.