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Detection of transferred materials and of flaws under glued steel sheet using tactile sensor

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ABSTRACT

The evaluation of the stiffness variance (Young's modulus) of a substance transferred on a surface is important in clarifying lubrication and wear phenomena. In this study, a tactile sensor function is added to a stylus of a surface roughness meter, and a simultaneous measurement system that can be used to measure roughness and regionally detect a transferred thin substance is constructed. As a result, it is clarified that the oscillatory frequency of the sensor varies depending on the compound stiffness properties related to Young's modulus of the coating material and substrate. The observation of flaws existing under a glued steel sheet of 40 μm thickness, as well as the measurement of a region of a transferred thin substance, also becomes possible.

1. Introduction

For the improvement of the lubrication condition, the transformation of a film on a lubrication surface is effective [1,2]. In particular, the distribution and stiffness of a transferred film and surface roughness are important information for its improvement. For example, the reduction of friction and wear by a thin film of polytetrafluoroethylene (PTFE) transferred on a metal surface is well known [3]. In recent years, the lubrication effect of a soft metal lubrication film such as Ag on substrate was inspected, and it became clear that the friction in the coating film of thin Ag (0.1–1.0 μm) transferred onto a silicone substrate had minimum value [4,5].

An optical method has generally been used for the observation of transferred and coated materials. However, the evaluation of compound physical properties, such as stiffness or hardness, which is indispensable for the improvement of the lubrication characteristic between the film and substrate, is impossible by an optical method. For the evaluation of the hardness of film transferred on lubrication surface, there are universal and ultrasonic hardness testers, but both tools are destructive and cause indentation, and therefore, continuous observation for making a distribution map is difficult. Consequently, the development of a nondestructive measurement technique, which can be used to obtain these data and the surface roughness of a substance on a substrate continuously, is expected. The first purpose of this study is to construct a simultaneous measurement system using the tactile function for the roughness and stiffness of a transferred thin film.

By the way, the nondestructive inspection of the deterioration of the adhesion condition between a glued thin sheet and a substrate and the progression of flaws due to erosion on the substrate surface glued are important in industry [6]. In addition, quality inspection of the production sequence of such a jointing material also becomes important. The second purpose of this study is to establish a simple and easy nondestructive inspection technique.

To achieve the above purposes, we attempt to employ a tactile sensor function using a phase shift method [7], the oscillatory frequency of which is changed by varying the physical property and the contact condition of the sensor. This tactile sensor function has been applied to the diagnoses of breast cancer and prostate cancer, and some medical test devices, such as tactile sense catheter, micro force sensor and micropipette, were developed [8–12].

In this study, a simultaneous measurement system that can be used to measure roughness and regionally detect substance variance is constructed by adding the tactile sensor function to the stylus of a three-dimensional roughness meter.

2. Measurement system and principle

Fig. 1 shows the schematic of the measurement system including a tactile sensor. In this study, the tactile sensor function was added to a stylus, having a tip radius of 10 μm, of a

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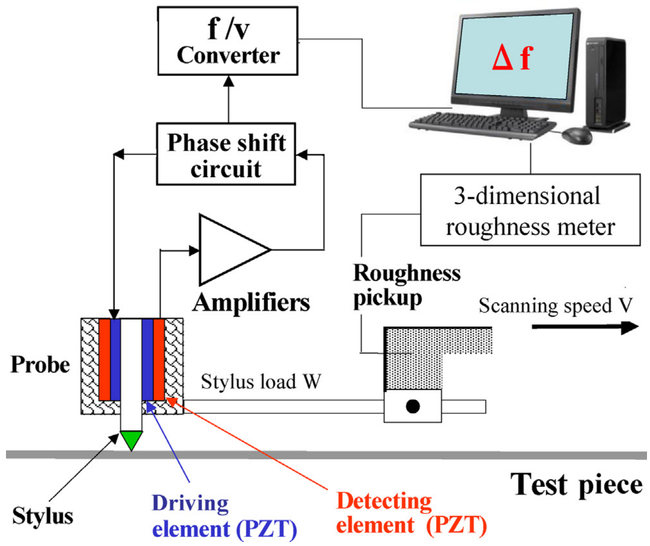

Fig. 1. Measurement system using tactile sensor. Tactile sensor consists with feed back system including phase shift circuit and two PZT.

three-dimensional surface roughness meter, and the simultaneous measurement system for the roughness and the stiffness of a transferred thin film was constructed.

This tactile sensor consists of two piezoelectric elements (PZT). The driver has 1 mm inner diameter and 2 mm outer diameter, and the detector has 2 mm inner diameter and 3 mm outer diameter. Both cylindrical PZT are attached to one end of a stylus of 1 mm diameter, and they are set into a hard urethane foam that can insulate the propagation of vibration but does not attenuate the PZT own vibration. The tactile sensor is placed in a closed electric circuit; the oscillatory frequency is converted to voltage by an f/V converter, and the behavior of the difference in oscillatory frequency (Δf; Hz) between the contact condition and noncontact condition is gathered simultaneously with the data of surface roughness.

Fig. 2 shows the vibration rod of the stylus. When an alternating voltage is applied to the electrodes, the driving element vibrates freely in the direction of its length. The detecting element detects a vibration that is influenced by the rod and driving element. This system has the phase shift circuit shown in Fig. 1 for adjusting the phase contrast between the driver and detector to zero and has a gain variation compensation circuit. Then, this feedback circuit system oscillates at the resonance frequency of the rod and PZT element [7].

If the free end of the stylus comes into contact with the surface of an unknown object, the resonant frequency of the feedback circuit changes depending on the equivalent impedance of the equivalent

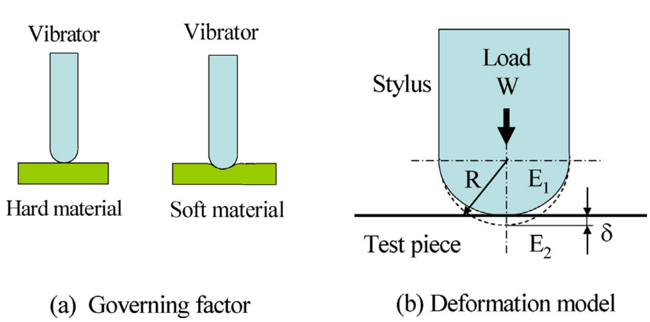

Fig. 2. Governing factor and deformation model. Stiffness related to a frequency shift of the sensor is affected by the material properties, such as the equivalent Young's modulus *E*, stylus load *W* and equivalent radius *R*.

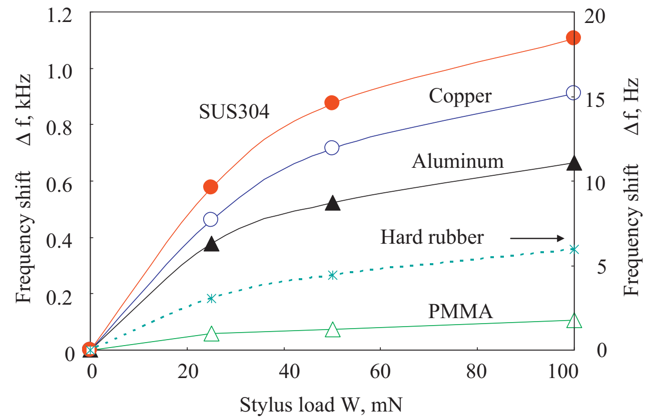

Fig. 3. Relationship between stylus load and frequency shift Δf. Each point is average value of 5 times of measurement but fluctuation in every data is less than 5%. The vertical scale for the rubber is at right side.

circuit of electrical/mechanical vibration system including PZT-based tactile sensor pressed against the surface of unknown object. The change in oscillation frequency between the contact and noncontact conditions can be written as follows for the hard material shown in Fig. 2(a) [7]

$$\Delta f = \frac{k_x}{2\pi^2 Z_0} \quad (1)$$

where Z_0 (N s/m) is the equivalent impedance of the sensor system consisting of the tactile sensor and the feedback circuit and k_x (N/m) is the equivalent stiffness for the equivalent impedance of the object. Therefore, the oscillation frequency increases depending on the stiffness of the hard material. Correspondingly, Δf for the soft material is

$$\Delta f = -\left(\frac{k_0}{2\pi^2 Z_0}\right)\left(\frac{m_x}{m_0}\right) \quad (2)$$

where k_0 and m_0 (kg) are the equivalent stiffness and equivalent mass for the equivalent impedance of the sensor system, respectively, and m_x is the equivalent mass for the equivalent impedance of the object. When the stylus comes into contact with the soft material, the oscillation frequency decreases depending on the equivalent mass of the unknown material [7].

In this study, the frequency shift due to the difference in stiffness described in Eq. (1) is considered. When the stylus comes into contact with the hard material, as shown in Fig. 2(b), this stiffness is affected by the material properties, such as the equivalent Young's modulus of elasticity E (Pa), stylus load W (N) and equivalent radius R (m), as follows [13].

$$k_x = \left(\frac{R^{1/3}}{0.77}\right) W^{1/3} E^{2/3} \quad (3)$$

If a stylus having a considerably small tip radius in comparison with the radius of roughness asperity is employed, the equivalent radius becomes the constant radius of the stylus tip. Then, it becomes possible to identify the difference in the material because the frequency shift Δf is governed only by the material properties such as Young's modulus for the constant stylus load.

Fig. 3 shows the relationship between stylus load W and frequency shift Δf with respect to stainless steel SUS304 (E = 193 GPa), copper (E = 120 GPa), aluminum (E = 69 GPa), polymethyl methacrylate PMMA (E = 3.2 GPa) and rubber (E = 0.1 GPa). All the materials exhibit the same behavior, that is, the frequency shift Δf is increased with increasing stylus load and the increasing ratio decreases with the load. The variation of frequency shift ratio γ_W, which is the ratio of Δf_W in a certain load and Δf_{100} in the case of