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Test method

Evaluation method for heat transfer coefficient of a contact interface across a microscale thin liquid polymer film

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A R T I C L E I N F O

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A B S T R A C T

The research presented here evaluates the heat transfer coefficient of the contact interface of a thin liquid polymer film between a pair of columnar aluminum bodies with an initial temperature difference of approximately 160 K. We measured the unsteady temperature changes inside the columns. The heat transfer test was performed with three types of liquid polymers: squalane, oleic acid, and silicone oil. The heat transfer coefficient of the polymer films as a fitting parameter was obtained by ensuring the numerically computed time evolution of the columns' temperature corresponded with the experimentally measured data. The interfacial heat transfer coefficients of the thin polymer films (mean thickness: 60 μm) for all three polymers used were 1.75 kW/m^2·K, 2.75 kW/m^2·K, and 4.10 kW/m^2·K. The present estimating method for determining interfacial heat transfer coefficients was suitable for a material-polymer film-material contact model. The time evolution of the temperature at the contact surfaces was also effectively evaluated using the numerical simulation.

1. Introduction

Evaluation of the interfacial heat transfer is important for designing components such as cooling systems for friction components of machinery [1], materials processing tools [2,3], and electronic parts [4]. When assembling the heat-generating electronic parts, polymer based thermal interface material, such as thermal grease, is used at the interface of the parts and heatsink component for enhancing thermal transfer [5]. The path of heat removal from a central processor unit (CPU) involves conduction across the interface of the CPU package case surface, through a thermal interface material, into a heatsink, and then convection to the environment [4]. Polymer based lubricants are supplied at the loading interface to control mechanical friction and prevent or reduce surface damages to machinery components. In the state of hydrodynamic lubrication, the sliding interface becomes low friction state without any wear. Triglycerides and fatty acids typically provide good oiliness when acting as a lubricant additive. Fatty acid has a polar group in the molecule component, which carries out adsorption orientation on a solid surface [6,7]. The adsorbed molecules are disconnected from the surface through a thermal activation process that reduces lubricous capability under hydrodynamic lubrication conditions [8,9]. Therefore, cooling the surface of friction parts, while maintaining a suitable oil temperature, is an important operating criterion for preventing friction damage to the parts themselves. The cooling requirement provides the need for establishing an appraisal method of the heat transfer characteristics in a metal–polymer film–metal interface. In the state of boundary lubrication, the oil film on a phreatic surface becomes thinner while the metal-to-metal contacts occur locally [10,11]. Thus, the state producing the frictional force is based on the shearing of the thin oil film and metallic contact points. Under boundary lubrication operating conditions, the temperature of a mechanical system is raised through the generation of frictional heat [12–14].

The research presented here evaluated the heat transfer coefficient of the contact interface with a thin polymer film introduced between a pair of metal columns for which the two initial temperatures are different. The unsteady temperature changes were then measured inside the two columns. The heat transfer coefficient of the polymer films was determined as a fitting parameter by relating the experimental temperature changes of the columns to the numerically computed time evolution of temperature in the columns.

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2. Experimental methodology

2.1. Liquid polymers

Three types of liquid polymers were prepared as the test oils for the experiment. They were squalane, oleic acid, and silicone oil. Squalane is commonly known by another name, 2,6,10,15,19,23-hexamethytetracosane, and is considered a saturated hydrocarbon. It is chemically stable and hardly degrades [15]. Oleic acid is an unsaturated fatty acid, which has good oiliness making it suitable for use as a lubricant additive [16]. Silicone oil (i.e., polysiloxane) has good thermal stability and low environmental toxicity. In the market, there are many kinds of silicone oils with different viscosity. In the present study, a silicone oil with a kinematic viscosity of 50 mm^2/s at 298 K was purchased [17].

2.2. Heat transfer measurement

Measurement of the heat transfer coefficient of the polymer film at the contact interface was performed. The schematic of the experimental testing apparatus is shown in Fig. 1(a). Two aluminum columns with a purity of 99.85%, diameter of 25 mm, and length of 80 mm were prepared to model the heat accumulator and heat sink. The two individual columns form one set with opposing contact surface regions. The common center axis of the pair of columns is in the vertical direction. The arithmetical mean surface roughness, i.e., R_a, of each column's end surface was 0.43 μm. The 1 mm diameter K-type sheath thermocouples were inserted in three positions within each column at 8 mm, 30 mm, and 50 mm from the contact surface end of the columns, respectively. The details of the columns are shown in Fig. 1(b). The thermocouples were inserted in the columns horizontally so that these would theoretically be right-angled to the primary heat flow.

The experimental measuring process was developed as follows. The upper column was heated first in excess of 453 K using a gas burner. When the temperatures were measured using the three thermocouples in the upper column uniformly indicated 453 K, the contact surface of the upper and lower columns were brought in contact with each other. The initial temperature of the lower column was adjusted to 292–393 K. The temperature changes due to heat transfer from the upper column to the lower column were measured in each thermocouple and were recorded by a multichannel digital recorder. The mean contact pressure for the columns was established in the range of 6.7–41.3 kPa. In this research, the contact pressure is defined as the load applied to the lower end of the upper column normalized by the column's end area. The average thickness range of the polymer films was estimated to be 55–65 μm at 293 K based on the adhering weight of polymers on the contact ends of the two columns.

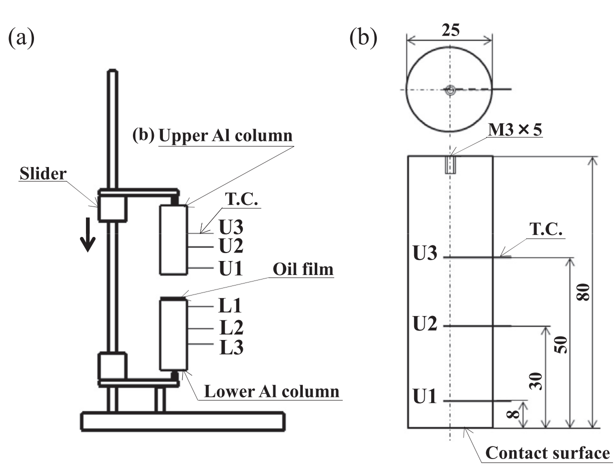

Fig. 1. (a) Schematic image of testing equipment. (b) Geometry of the aluminum columns.

2.3. The heat transfer simulation by numerical calculations

The time evolution of the temperature distribution, as a result of unsteady heat transfer in an aluminum column, is described by the following heat equation:

$$\frac{\partial \theta}{\partial t} = k(\theta) div(grad\theta) \quad (1)$$

where θ is temperature in the column, and $k(\theta)$ is thermal diffusion coefficient. The value of aluminum's $k(\theta)$ as a function of temperature is derived from literatures [18,19]. The heat flux q from the upper column to the lower column can be expressed as follows:

$$q = h(\theta_U - \theta_L) \quad (2)$$

where θ_U is the temperature at the bottom end surface of the upper column, θ_L is the temperature at the upper end surface of the lower column, and h is the heat transfer interface coefficient. The temperature dependency of the coefficient h was not taken into consideration for this calculation. The heat flux q_A emitted into the ambient air from the surface of the aluminum column can be expressed as follows:

$$q_A = h_A(\theta - \theta_A) \quad (3)$$

where θ_A is the temperature of ambient air, and h_A is the convection heat transfer coefficient. In the calculation model, heat loss from the small supports holding each column was disregarded.

The numerical calculations were performed by a finite difference method. The columns were divided into 161 elements in the length direction. Though the thickness of each element (except the column's ends) was 0.5 mm, the thickness of the end elements was 0.25 mm. While it was not possible to experimentally measure the temperature change at the contact surfaces of the columns, it became possible to estimate the temperature change numerically using the finite difference method.

3. Results and discussion

3.1. Convective heat loss of the aluminum column

It is necessary to evaluate the convection heat transfer coefficient at the column's surface since the heat outflow from the heated column surface to the ambient air occurred during the heat transport test. The cooling process of the heated columns due to contact with ambient air at a temperature (θ_A) of 292 K was investigated. The upper column was heated up in excess of 453 K and then the recording of the time evolution of the temperature was started at 453 K as the temperature decreased during the cooling process. To achieve an alignment of both graphs of the measured and numerically calculated time evolution of temperature, the convection heat transfer coefficient of the column was determined to be 14 $W/m^2 \cdot K$. The numerically simulated cooling curve with the coefficient 14 $W/m^2 \cdot K$ is fitted to the experimental curve, as shown in Fig. 2. The numerically simulated cooling curves with the convection heat transfer coefficients 10 and 15 $W/m^2 \cdot K$ are also indicated in Fig. 2. These cooling curves cannot be conformed to the experimental curve at all. Thus the value 14 $W/m^2 \cdot K$ can be adopted as the