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Effects of vibration frequency and amplitude on friction reduction and wear characteristics of silicon

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ABSTRACT

The effects of vibration on friction reduction of silicon, aluminum-coated silicon, and aluminum plate sliding against a silicon nitride ball were assessed under various conditions. It was found that friction coefficient could be decreased significantly to 0.1 for all specimens at specific vibration frequency ranges. Also, vibration in the vertical direction resulted in the highest friction reduction of silicon compared to the longitudinal and tangential directions. As for the wear characteristics, it was found that the least amount of wear occurred on silicon followed by aluminum coating and aluminum plate specimens. Though the amount of wear depended on the vibration frequency, the frequency that led to low friction did not necessarily correspond to low wear.

1. Introduction

It has been known since decades ago that imparting vibration to a mechanical component can lead to reduction in friction. In one of the very early works on this topic, Fridman and Levesque used sonic vibration in 1959 to decrease static friction between two metals in contact [1] and Godfrey showed that vibration can effectively reduce friction between two sliding metals in 1967 [2]. In this research, three fixed balls were made to slide against a flat steel plate which was vibrated at relatively low frequencies up to 1000 Hz. Also, Lenkiewicz investigated the effect of vibration on static and kinetic friction coefficients using steel and cast iron [3]. It was shown that friction could be reduced by 80% using relatively low vibration frequency (20–120 Hz) and relatively high vibration amplitude (5–40 μm). Even though the vibration frequency was relatively low, high vibration amplitude allowed for the significant reduction of friction coefficient. This work also suggested that induced vibration can reduce the stick–slip phenomenon.

Since the reporting of these early works that demonstrated the effectiveness of vibration to reduce both static and dynamic friction of metals, numerous other works followed [4–8]. Skare and Stahl investigated the static and dynamic frictional behavior of stainless steel specimens under the influence of external vibration using various conditions [4]. They proposed the reason for the decrease in friction under vibrating condition as the separation of the surfaces due to vibration and alteration of the surface properties due to repeated contact. Chowdhury and Helali focused on the effects of vibration frequency and amplitude on friction reduction of mild steel sliding against various polymeric materials [5]. The results showed that vibration with frequency and amplitude in the range of ~500 Hz and ~200 μm, respectively, was effective in friction reduction of polymeric materials. Chowdhury and Helali also investigated the effect of humidity in friction reduction using vibration for mild steel [8]. The results showed the slightly higher reduction in friction could be achieved at high humidity condition (RH ~80%) when the vibration frequency was relatively low (~100 Hz). However, for relatively high vibration frequency (~500 Hz) humidity did not affect the friction reduction effect.

Though vibration for friction reduction is commonly induced in the vertical direction, the effects of vibration in the other directions were also investigated. Gutowski and Leus used an ultrasonic generator to investigate the effects of longitudinal and tangential vibrations in the frequency range of 6–42 kHz on the friction between steel and cast iron [6]. The results showed that tangential vibration, which is perpendicular to the sliding direction, could significantly decrease the driving force of the slider. Teidlet et al. used a specimen integrated with a piezoactuator to investigate the effects of vibration directions (x, y, and z) on the friction of various metals [7]. In this test longitudinal (x) direction showed best friction reduction effect. Thus, the effect of vibration direction on the friction reduction effect varied among these studies depending on the operating conditions such as applied load and vibration amplitude.

In addition to the experimental works on the effect of vibration on reduction of friction, numerical modeling of this phenomenon has also been carried out [9–11]. Tworzydol and Becker studied the influence of forced vibration on static friction coefficient by numerical modeling of the compliant contact interface [9]. They showed that frictional force decreased in vibration condition and

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explained that the interface damping weakened the friction reduction effects. This study demonstrated the significance of vibration input in dictating the mechanical behavior of contacting asperities, which ultimately affects the frictional behavior. Hess et al. modeled a continuously sliding Hertzian contact system as a non-linear mass–spring–damper system to study the friction reduction effect using vibration [10]. It was suggested that contact loss due to vibrating motion induce reduction of the frictional force. Recently, molecular dynamics (MD) simulation technique was used to investigate the friction reduction effect in vibration condition. Capozza et al. used MD simulation to investigate the role of tiny vibrations in tribological response of a confined system under shear [11]. As these works have shown, the effectiveness of vibration in reducing friction has been demonstrated for sliding systems ranging from macro- to molecular-scale.

From the application point of view, friction reduction technique using vibration has been applied in mechanical machining and metal forming processes. In mechanical machining such as cutting and grinding, artificially applied mechanical vibration was used to increase the efficiency of the processes [12–14]. For instance, Kim and Loh showed that 2-dimensional vibration assisted cutting can decrease the cutting force and improve the machining quality [13]. Also, in metal forming process such as the rolling, extrusion and drawing processes, ultrasonic vibration can decrease the frictional force [15–17]. Mousavi et al. investigated the effect of ultrasonic vibration applied on the die during the extrusion process and found that it was effective in reducing the extrusion force [16]. As such, the advantage of using vibration to reduce friction between two materials in contact can be effectively exploited in manufacturing processes where energy savings are highly desirable.

As mentioned above, the effectiveness of vibration in reducing friction has been well documented. However, most of the previous works have concentrated on metals and polymers. Only a limited number of studies could be found on the topic of friction reduction of silicon-based materials using vibration. The focus of these works was concerned with increasing the manufacturing process efficiency of these materials [18,19]. Since the frictional behavior under a given vibration condition is known to depend on the stiffness of the contact interface, the effect of vibration on friction is expected to depend on the type of material. In this regard, the motivation of this work was to assess the effectiveness of vibration in reducing the friction of silicon-based materials. Silicon was selected as the target material since it is widely used for fabrication of micro-scale systems [20,21]. Unlike macro-scale systems in which bearings and lubrication provide excellent means to reduce friction, they cannot be employed for micro-scale systems because of limited size and surface tension effect of liquid lubricants [22–25]. Therefore, other techniques have been proposed for micro-scale systems such as thin-film solid lubrication and vapor phase lubrication (VPL) [26–32]. However, it is difficult to deposit solid lubricant coatings on the side walls of micro-scale structures with very small gaps. Also, VPL technique requires continuous supply of vapor phase lubricant which may lead to contamination issues. Hence, other methods, such as vibration, that can lead to reduction in friction of silicon-based materials are needed. In this regard, the aim of this work was to gain fundamental understanding of the frictional behavior of such materials with vibration excitation.

Sliding experiments with vibration were performed using a custom-built device. Silicon was used as the test material to slide against a silicon nitride ball. Also, aluminum specimens were used to compare the friction and wear characteristics with those of silicon. Experiments were performed using various vibration frequencies and amplitudes to assess the effects of these variables on friction reduction behavior. Surface damage incurred by the specimens due to vibration was also analyzed. The following sections describe the details of the experimental work.

2. Experimental details

2.1. Specimen preparation

In order to assess the effects of vibration on reduction of friction, three types of specimens were prepared: silicon, aluminum-coated silicon, and aluminum plate. Silicon specimens were cut from Si (100) wafers to a dimension of $10 \times 10\ mm^2$. In order to compare the frictional behavior of silicon with a metal under vibration conditions, aluminum was selected. Aluminum specimens were prepared as a coating as well as a bulk material. For the coated aluminum specimen, E-beam evaporator (ULVAC) was used to deposit aluminum on a $10 \times 10\ mm^2$ silicon substrate with a thickness of about 100 nm. The bulk aluminum specimens were cut from a pure aluminum plate to a dimension of $10 \times 10\ mm^2$. For a given specimen, up to 10 tests were conducted with sufficient distance between the sliding tracks. Also, since the specimen surface was quite uniform, there was no reason to expect any difference in the frictional behavior with respect to the location of the ball on the specimen. The average surface roughness of silicon, aluminum-coated silicon, and aluminum plate specimens were ~1 nm, ~10 nm, and ~0.3 μm, respectively. The hardness of silicon was ~9.8 GPa and that of the aluminum specimens was about ~167 MPa [33,34].

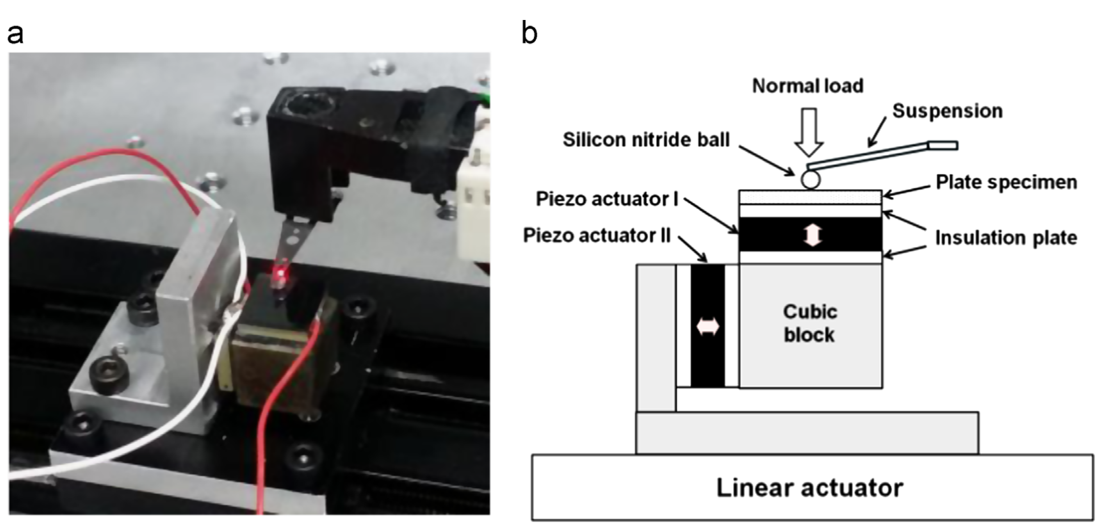

Fig. 1. Experimental set-up for friction measurement with vibration excitation: (a) photograph and (b) schematic image of the set-up.