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Experiment on Frictional Characteristics of Brushes Using Toothbrushes

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A simple test rig that produces reciprocating motion of toothbrushes was manufactured, and the tribological characteristics of brushes were examined experimentally. The experimental parameters were normal load (0.84–5.31 N), sliding speed (10.5–105 mm/s), mated plate specimen materials (stainless steel, polytetrafluoroethylene, and polyethylene terephthalate), surface roughness of the plates (0.03–5.30 μmRa), stiffness of the brush bristles (medium and hard), and lubrication conditions (dry and wet). The effects of the load, speed, materials, roughness, stiffness, and lubrication conditions on the friction and cleaning were shown.

Keywords : Toothbrush, Friction, Tribology, Reciprocation, Experiment

1 INTRODUCTION

Brushes are used in everyday life [1] like in oral care and in several industries such as brush sealing, electrical contacts, and road sweepers. In the field of oral tribology, Zhou and Zheng [2] reviewed the published papers dealing with dental wear, temporomandibular joint (TMJ), and saliva. Lewis and Dwyer-Joyce [3] visualized, simulated, and modeled the teeth cleaning processes. Lewis, et al. [4] examined how abrasive particles in toothpaste interact with the filaments and cause material removal from a stain layer on the surface of a tooth. Dogu, et al. [5] investigated the flow field for a brush seal operating with a certain bristle-rotor clearance. Shin and Lee [6] studied the effects of the wear behavior of copper–graphite brushes that provided sliding electrical contacts in a small brush-type DC motor. Vanegas Useche, et al. [7, 8] studied the dynamics of a freely rotating flicking brush in a road sweeper using a mathematical model. In all these cases, the physical behavior is an interaction between surfaces in relative motion (the tips of the brush bristles and the surface of the mated materials), namely, tribology.

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In this report, a preliminary experiment on friction and cleaning of brushes was conducted representatively by use of toothbrushes. The effects of the normal load, sliding speed, bristle stiffness, specimen material, surface roughness, and lubrication conditions on the friction coefficient and removal performance were examined.

2 RIGS AND METHODS

2.1 Reciprocating tester

Figure 1 shows a schematic of the test rig [9]. The rig mainly consisted of an electric motor (a brushless DC motor; rated output: 40 W) (10 in Fig. 1) and a controller (11), a crank and a shaft (9), a strain-gauge-type load cell sensor (rated load: 0.98 N, natural frequency: 350 Hz) (3) and dynamic strain amplifier (frequency response: 200 kHz) (2), a test toothbrush (5), a test plate (6), and a data logger (1). The test toothbrushes were reciprocated in 10-mm strokes at a constant rotation speed by the electric motor and the crank mechanism.

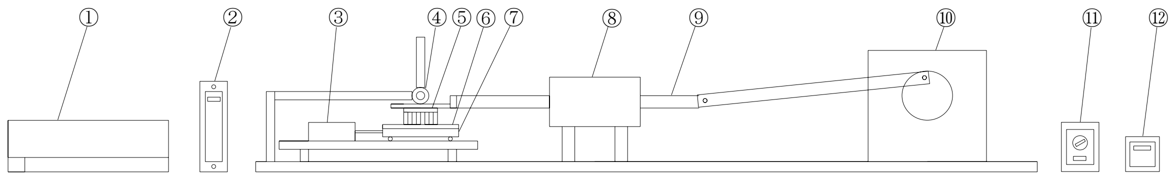

Fig. 1 Reciprocating brush tester

The toothbrushes were rubbed against the test plates, which were set in a basin on the mount (7); the mount was placed freely to move on the base with the balls of rolling-element bearings and connected to the probe of the load cell sensor with a specific screw. One end of the screw connecting the load cell sensor (3) and the mount (7) was manufactured to turn counter-clockwise for easy use.

2.2 Test toothbrushes

Toothbrushes were used as test brushes because of products familiar with the public and easily available on the market [(10)], although there were several types of brushes. Each brush head had 28 tufts with 25 bristles per tuft. The bristles were made of nylon. The tips of the bristles were semi-spherical, and the nominal surface of contacting top of the bristles was flat. The stiffness of the toothbrushes was categorized as medium and hard.

Bristle stiffness was simply measured by the in-house tester shown in Fig. 2. The tester consisted of a hinge (a in Fig. 2), support (b), and weights (c). A 15-mm-long bristle (d) was extracted from a test toothbrush and set at the end of the hinge. As the weight was increased, the buckling load, at which the bristle is bent, was measured. The load of one bristle was approximately 22 mN for the medium-bristle brushes and 56 mN for the hard-bristle brushes.

2.3 Test plates

Test plates 90-mm long, 20-mm wide, and 2-mm thick were prepared. The test plates were made of either stainless steel (SUS304D in the Japan Industrial Standards, JIS), polytetrafluoroethylene (PTFE), or polyethylene terephthalate (PET).

A tooth is mainly made of enamel, pulp, cementum and dentine, but dental restrorative materials are consists of synthetic components such as amalgams, resin based composites, metal ceramics. We also primarily concern about tribology of industrial brushes. Therefore, we selected these materials of the plates.

The surfaces of the test plates were roughened to three roughnesses using No. 60 and No. 240 emery papers. The calculated average roughness Ra of the surfaces was measured by a contact-type surface profile meter along and across the sliding direction 10 times

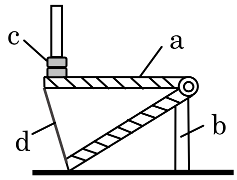

Fig. 2 Tester for measuring bristle stiffness

each. The roughness σ indicates the measured values of Ra: σ = 0.10 ~ 0.14 μmRa (smooth), 0.18 ~ 0.24 μmRa (mid), and 0.27 ~ 0.43 μmRa (rough) for the SUS test plates; σ = 0.03 ~ 0.04 (smooth), 1.06 ~ 1.23 (mid), and 2.80 ~ 3.47 μmRa (rough) for the PET plates; and σ = 0.17 ~ 0.20 μmRa (smooth), 1.38 ~ 1.83 μmRa (mid), and 4.46 ~ 5.30 μmRa (rough) for the PTFE plates.

2.4 Procedure and conditions for friction tests

The experiment was performed in the following order: The normal load W acting on the brushes was set at a specific lower value, and operation began with a lower sliding speed v, defined as the speed at the center of the reciprocating motion of the brush head. Under a constant load W and speed v, the frictional force F between the brush bristles and the test plate was measured with the load-cell sensor (3 in Fig. 1), and the signal was recorded on the data logger (1).

The normal load W acted as dead weight and was set to six values: W = 0.84, 1.74, 2.63, 3.52, 4.42, and 5.31 N. The sliding speed v was representatively defined at the center of the stroke. The speed v was set to four values: v = 10.5, 26.2, 52.4, and 105 mm/s, which are corresponding to the rotational speed n of the electric motor shaft: n = 0.33, 0.83, 1.67, and 3.33 s^{-1}. The lubrication conditions were specified as either dry or wet; in the wet condition, lubrication by mineral water was applied.

The force F varied markedly within a shorter rubbing period, so running-in was conducted to stabilize the initial surface conditions before each test with a new brush was begun. The running-in time was set at five hours for the medium-bristled brushes and one hour for the hard-bristled brushes following a preliminary test. The frictional characteristics were evaluated by the nominal friction coefficient f (= F / W), where F was defined as the force measured at the center of the stroke.

For higher loads and higher speeds the frictional force was very large, so that the experiment was interrupted.

2.5 Procedure and conditions for cleaning tests

The cleaning effect was simply evaluated in terms of the removal ratio of painted ink on the test plates. The surface of the SUS plate was painted with water-based black ink. At specific time intervals during the rubbing test, i.e., at time t = 10, 30, and 60 min within the first hour, and every 60 min after the first hour, the surface of the plate was photographed by a digital camera. The photographs were processed by binarization software that replaced white pixels with zeros and black pixels with ones. The area ratio α of the black and white (zero and unity) pixels was calculated, and the differences between images taken before and after the test were evaluated. In the cleaning test, the normal loads were that W = 2.63 and 3.52 N, and the sliding speeds were that v = 10.5, 52.4, and 105 mm/s.

3 RESULTS AND DISCUSSION

3.1 Friction measurement

Figure 3 shows the frictional force F versus the rotating speed n of the electric motor for the SUS test plate with a roughness σ = 0.12 μm, a medium brush, and the dry condition. The force F was increased for larger normal load, but F became slightly larger for higher speed conditions. Fig. 4 illustrates the friction coefficient f versus the load W at v = 10.5, 52.4, and 105 mm/s. The coefficient f increased apparently as the load W decreased.

Figures 5 and 6 depict the results using brushes with hard bristles under dry condition and the results with medium ones in the water-lubricated condition respectively, using the SUS plate.

At higher loads in Figs. 4 and 5, the friction coefficient f for the medium-bristled brushes was slightly smaller than that for the hard ones under dry condition. Comparing Figs. 4 and 6, one can see that the friction coefficient f under the lubricated condition was somewhat larger than that under the dry condition. In this experiment, water did not function as a lubricant to reduce the friction.

Figures 7 and 8 illustrate the effects of the roughness and test plate materials; PET and PTFE, respectively. In both figures the friction coefficient f was larger for greater roughness. The coefficient f also depended on the materials; f of the SUS plate was largest among these mated materials.

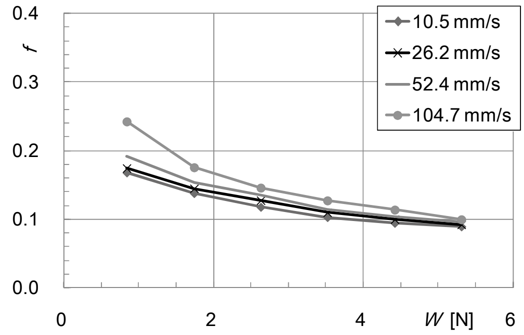

Fig. 4 Effects of load W and speed on friction coefficient f (σ = 0.12 μm, SUS, medium, dry)

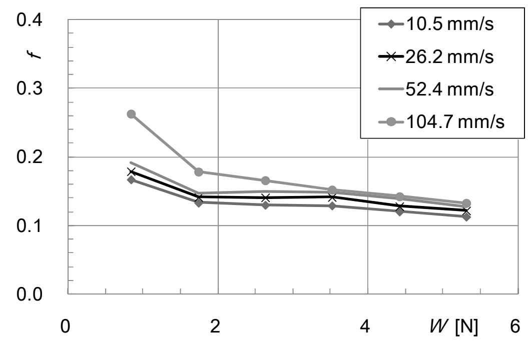

Fig. 5 Effects of load W and speed on friction coefficient f (σ = 0.13 μm, SUS, hard, dry)

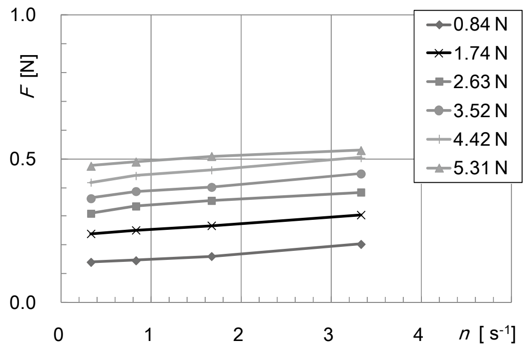

Fig. 3 Friction F vs. reciprocating frequency n (σ = 0.12 μm, SUS, medium, dry)

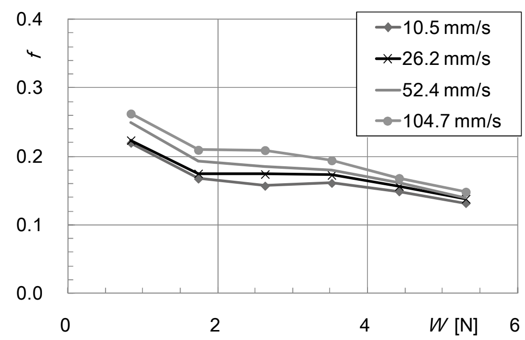

Fig. 6 Effects of load W and speed on friction coefficient f (σ = 0.10 μm, SUS, medium, wet)

3.2 Cleaning measurement

Figures 9, 10, and 11 demonstrate the effects of the normal load, sliding speed, and bristle stiffness, respectively, on the removal area α. As the brushing and rubbing time *t* increased, the area increased, and then gradually saturated. The repeatability was checked in the preliminary test, where it was obtained with a deviation of up to about three points.

In Fig. 9 the area α at a higher load was larger than that at a lower load. In Fig. 10 α was less affected by the velocity, although the cumulative sliding distance and the number of stroke times were increased in proportion to the speed. Moreover, in Fig. 11 the area under medium-bristled toothbrushes was larger than that under hard brushes.

4 CONCLUSION

For evaluating the frictional force and cleaning effect of brushes, a simple tester of toothbrushes was built. The effects of the load and speed on the friction coefficient, as well as the differences in the plate material, plate roughness, bristle stiffness, and lubrication conditions were examined.

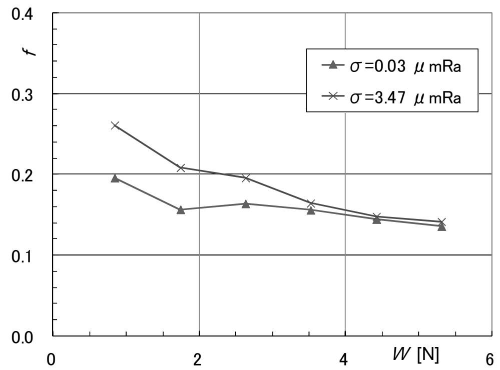

Fig. 7 Effect of roughness on friction coefficient *f* (*v* = 52.4 mm/s, PET, medium, dry)

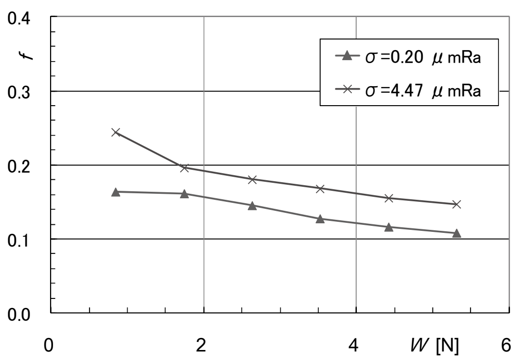

Fig. 8 Effect of roughness on friction coefficient *f* (*v* = 52.4 mm/s, PTFE, medium, dry)

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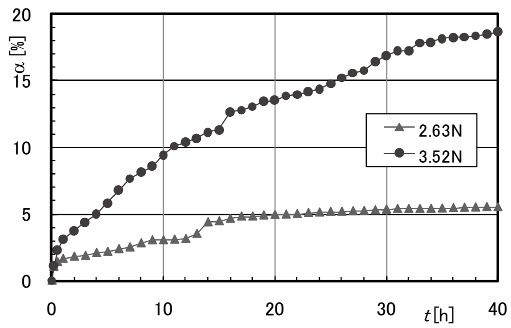

Fig. 9 Effect of load on removal area ratio α for rubbing time *t* (*v* = 52.4 mm/s, SUS, medium)

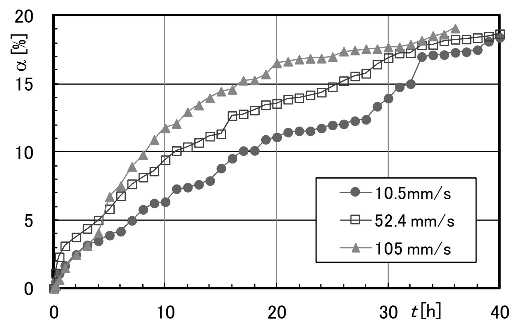

Fig. 10 Effect of speed on removal area ratio α for rubbing time *t* (*W* = 3.52 N, SUS, medium)

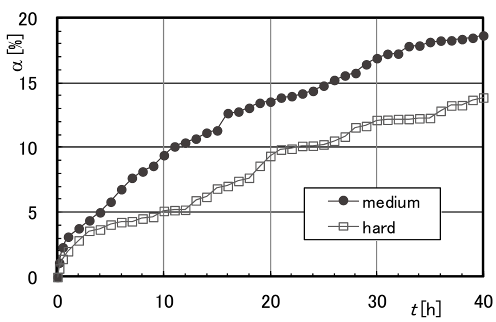

Fig. 11 Effect of bristle stiffness on removal area ratio α for rubbing time *t* (*v* = 52.4 mm/s, *W* = 3.52 N, SUS)

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