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Problematics of friction in a high-speed rubber-wheel wear test system: A case study of irregularly rough steel in water lubricated contact

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ABSTRACT

A custom-made slurry-type high-speed rubber wheel wear testing system was modified for measuring friction. Friction behaviour of irregularly rough steel against CSM-rubber in water-lubricated contact at a velocity range of 1.7–17 m/s was investigated. A noticeable friction maximum was observed near the midpoint of the range extremities, at 6.7–8.3 m/s, and the resulting wear marks on steel specimens also suggested the highest severity of contact at these medium speeds. Higher end of sliding velocity range returned friction to lower levels and less wear was observed. This was interpreted as a product of reduction in frictional heat due to slight improvement in mixed lubrication. In conclusion, the peculiar friction behaviour was interpreted as a system-specific anomaly, implying that similar problematics could be encountered in other rubber wheel wear test systems as well.

1. Introduction

New wear-resistant and friction-related material solutions are commonly tested with standardized procedures, such as the ASTM G99 pin-on-disk [1] or the ASTM G65 rubber wheel sand abrasion test [2]. However, the usefulness of experimental data acquired with standardized tests should be considered limited, since they only enable reliable comparison of materials within certain boundaries of parameters. In order to reliably test and compare materials' performance potential for a specific application, the test procedure has to be selected and, in some instances, modified to correspond with the process conditions as closely as possible. Rubber wheels are commonly used for wear testing in wide range of parameters, both in dry and lubricated conditions. Incorporating friction measurement into a rubber wheel system is a natural evolution of the test setup when more information on various surface interaction phenomena is required. However, rubber has a very peculiar sliding friction behaviour that needs to be considered both in wear testing and when measuring friction in such systems.

This study reports the friction behaviour observed in a wet high-speed sliding wear test setup when testing naturally rough hot rolled steel surfaces against smooth rubber. The applied sliding velocities were uniquely high for a rubber wheel wear test system, ranging from 1.7 m/s to 16.7 m/s. The effects of such velocities on friction in this system were unknown, and thus a friction measurement capability was incorporated into the device and series of friction measurements run to explore the validity of said equipment for reliable wear testing. Even though one of the famous Laws of Friction dictates that "friction force is independent of sliding velocity" [3], pioneering experimental and theoretical works on rubber friction by Roth et al. [4], Grosch [5,6], Barquins [7], Roberts [8], Persson et al. [9–12], Heinrich [13], Klüppel [14] and Le Gal [15,16] report in great detail how sliding friction of rubber is affected by changes in sliding velocity and other system parameters, like load, the amount and type of lubrication medium, as well as the chemical composition of the sliding surfaces. These works cover frictional behaviour of elastomers in a wide range of sliding velocities from well under 0.1 m/s to over 40 m/s with vastly differing methodologies, though it can be said, that sliding of elastomers against rigid and rough surfaces remains an incompletely understood field in tribology. Nevertheless, the findings and the general concepts developed in said works are considered applicable in the context of this research and are cautiously utilized for explaining the friction behaviour observed in the high-speed rubber wheel wear test device.

2. Theoretical background

The tribological behaviour of rubber and elastomers in general is not completely understood, despite the high significance, considering the widespread use of sliding-related rubber products, such as windscreen wipers, in-line skate wheels, guide rollers and vehicle tires. Wear and friction phenomena related to rubber now commonly take into account the dual nature of rubber friction [5,12], which comprises of the conventionally important surface adhesion and equally important viscoelastic deformation. Due to its low elastic modulus, rubber

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deforms notably under moderate pressure, causing high static friction by a mechanism of mechanical interlocking, where rubber completely or partially fills cavities of a surface it is pressed against. On the other hand, sliding motion against macroscopically rough surfaces under some loading conditions causes rubber to undergo viscoelastic deformation loops, where a portion of mechanical energy is converted into heat by the friction of entangled elastomer chains and effectively dissipated into the rubber [11].

Adhesion is another, more direct, source of frictional heat. The relative significance of adhesion in elastomer sliding scenarios depends on the real area of contact between the asperities of both surfaces. This surface area, in turn, is dictated by the roughness characteristics as well as the deformation capacity of said surfaces under a given load. In the case of an elastomer against a hard and rough surface, the low elastic modulus of the elastomer becomes a dominant feature, rendering the elastic properties of the hard surface inconsequential [12]. However, some of the surface area obtained by extensive elastic deformation at standstill is not necessarily retained during fast sliding motion, where the viscoelastic properties may not allow for the rubber to "spring back" and fill profile features of certain size or smaller [11]. Therefore, determining the role and influence of the adhesion component compared to the viscoelastic origin is more complex than merely observing the interaction of roughness, load and surface area.

According to Persson [11], the viscoelastic behaviour of elastomers does not only explain the intricacies of rubber friction, but can also be used for explaining the wear of elastomers in a two-body sliding contact. The main interpretation is, that in order to induce significant material removal from a rubber surface, either very low ambient temperature or very high frequency shear rate is required. Both of these factors produce a similar effect, where the elastomer reaches a glassy state, severely hindering its capacity to accommodate said shear stresses and thus becoming susceptible to fracture initiation and propagation.

Due to the system under investigation in this article being a water-lubricated one, basic theory of lubricated sliding needs to be considered as well. Contacts in the sliding interface in lubricated conditions are conventionally divided into three main regions of the Stribeck curve [3]: boundary lubrication, mixed lubrication or elastohydrodynamic lubrication (EHL) region, and hydrodynamic (HD) lubrication. In conventional oil lubricated test procedures (e.g. ASTM D 5707 [17]) and applications, the minimum value of friction coefficient is observed in the transition region between mixed and HD lubrication, at a specific range where the dynamic viscosity of the lubricating medium allows for a thin supporting film to form under given normal load and sliding velocity between moving surfaces.

It is well known, that sliding pairs of most materials under normal atmospheric conditions, lubricated or not, are not atomically clean interactions between materials [18]. In moist and water-containing environments the outermost layer on metallic surfaces tends to be hydroxide (-OH) group that is attached to thin metal oxide, and is additionally almost inevitably covered by other impurities from the surroundings. Thus, the strength of adhesion in water-lubricated sliding is, at least in the region where surface asperities interact, dependent on the amount and type of boundary lubricants and impurities.

3. Experimental procedure

3.1. Modified high-speed sliding wear apparatus

Friction measurements were conducted with a high-speed sliding wear test device built specifically to emulate process conditions containing water and hard particles. The construction and operating principle presented in Fig. 1 closely resemble that of the ASTM G65 standard cylinder-on-flat type rubber wheel abrasion test, where a test piece is pressed against a rolling rubber-coated drum with predetermined normal force W that is transmitted into the contact by a lever structure. However, contrary to the mentioned standard test, in our test configuration sliding speed as well as normal load were adjustable and water or water-based abrasive slurry could be used instead of dry silica sand. Due to this being a high-speed slurry-type test device, a cover made of hard translucent plastic was used during the test runs. Formation of wear particles could not be confirmed due to the large size of the water container and the unavoidable presence of residual impurities in the wear-testing device.

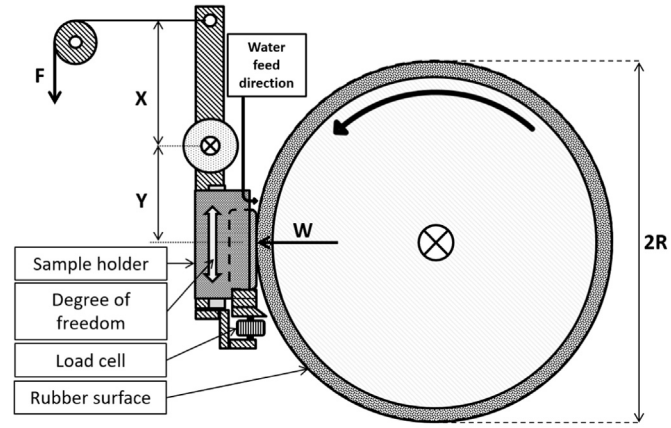

Fig. 1. Friction measurement principle (parameter details in Table 1).

The conditions produced by this testing configuration fall under the category of conventional macrotribology, where contact characteristics are severe and typically result in some degree of wear, and are thus representative of those commonly encountered in rubber wear tests and friction studies. Friction was the point of interest in this study, and thus wear was intentionally minimized by using tap water without abrasive particles as a sliding medium. Fifty litres of room temperature tap water was circulated in a closed loop and fed into the contact interface during the test runs.

The tests were carried out in ambient conditions. The sliding velocity range and other relevant test parameters are presented in Table 1. Test duration and normal load were kept constant, 60 min and 46.9 N, respectively. The two adjusted parameters were the sliding velocity v and the associated sliding distance l. Fixed test duration of 60 min produced sliding distances that correlated linearly with the sliding velocities.

Friction force was measured with HBM u9b can-type load cell incorporated into the sample holder. A Datataker DT80 (Thermo Fisher Scientific Australia Pty Ltd.) datalogger was used for data collection and the measurement frequency was set to 1 Hz, which equals 3600 data points for each 60-min test. Steel samples were in contact with the rubber throughout the whole test cycle. Normal load was applied and data logging initiated at standstill and carried out until complete stop at the end. A cumulative uncertainty factor of ± 3.2% based on relative

Table 1
Test run parameters, See Fig. 1 for clarification.

High-speed sliding wear/friction test equipment	
Sliding velocity, v [m/s] (m/min)[a]	1.7(100), 3.3(200), 5.0(300), 6.7(400), 8.3(500), 12.5(750), 16.7(1000)
Test duration, t [min]	60
Sliding distance, l [km]	6.0, 12, 18, 24, 30, 45, 60 (dictated by sliding velocity)
Load, F [N]	37.5
Lever ratio x/y	1.25
Normal load, W [N]	46.9
Medium	Water, feed ~ 0.26 m^3/h

[a] Velocity converted to m/s from m/min of the test equipment control software.

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