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# Improved ball crater micro-abrasion test based on a ball on three disk configuration

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ABSTRACT

An improved ball crater micro-abrasion test method has been developed that differs from the conventional ball crater method. A ball-on-three-disk (BOTD) configuration provides mechanical stability and three simultaneous measurements of abrasion. An inclined BOTD geometry allows the specimens to be totally immersed in abrasive, which allows the use of dry abrasives as well as slurries and pastes. Use of a rubber ball gives effective three-body abrasion and provides results that are highly correlated with the ASTM G65 method. Use of dry abrasive with a rubber surface, rather than use of slurries and a metal ball, provides cutting action that is closer to actual field conditions, and allows high temperature test. Flooding the substrate with abrasive also avoids the problems encountered in conventional ball crater tests in that it provides spherical scars even for large particle abrasives, and spherical geometry allows direct computation of the volume of wear. Modeling of the BOTD scar geometry indicates that the BOTD contact pressure is similar to the contact pressures used in the ASTM G65 test. The BOTD microabrasion method provided excellent ranking of the abrasion rates of bare steel and two thicknesses of a TiAlN coating.

## 1. Introduction

Although abrasion is a process that involves cutting of a substrate by harder abrasive particles, there is much complexity because of the wide variety of abrasive particles, the different modes of material removal (plastic deformation leading to detachment of work hardened chips or fracture of low toughness materials) and different metal removal processes (plowing, wedge formation and cutting) [1]. Two-body abrasion, such as sandpaper, in which the abrasive particles are attached to a backing material, provides different abrasion rates and wear patterns than three body abrasion, in which the motion of the abrasive particles is not constrained. The hardness of the abrasive and the geometry of the abrasive particles also make substantial contributions to abrasion rates and wear patterns.

For the reasons just cited, many abrasive wear test methods have been developed. An example is the ASTM G65 method (Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus), which involves dropping abrasive from a hopper into the contact zone of a rubber coated metal wheel and the test substrate. Although the ASTM G65 method is the most widely used method for assessing dry, three body abrasion; it is limited in which abrasives can be used by the need to achieve uniform flow of the abrasive through the feed nozzle of the hopper [2]. For example, fine dust and talc-like powders do not flow well and are difficult to use in the ASTM G65 method.

Less used abrasion test methods involve introducing abrasive particles into pin-on-disk and pin-on-drum tests, but these tests are usually limited to two-body abrasion or to abrasive slurries because the geometry and motion of these tests tends to move loose, dry abrasive particles out of the contact track. Another abrasion test, which is often referred to as a ball crater micro-abrasion test, involves using abrasive with a steel ball or wheel to make small craters in a test specimen [3]. Unfortunately, none of these test methods provides the ability to measure dry, three-body abrasion with the full variety of abrasives that are encountered in actual use. For example, a common need is to measure abrasive wear of dust particles trapped between two sliding surfaces, in which one of the surfaces is usually softer than the other. A rubber surface sliding against a hard disk is ideal to simulate this type of situation since the abrasive becomes embedded in the rubber surface, which protects the rubber surface from experiencing abrasive wear and which also more effectively drags the abrasive over the specimen in a way that provides more effective cutting action [4]. The rubber counter surface is also tough, which helps to avoid abrasion of the rubber. Although a rubber counter surface is provided by the ASTM

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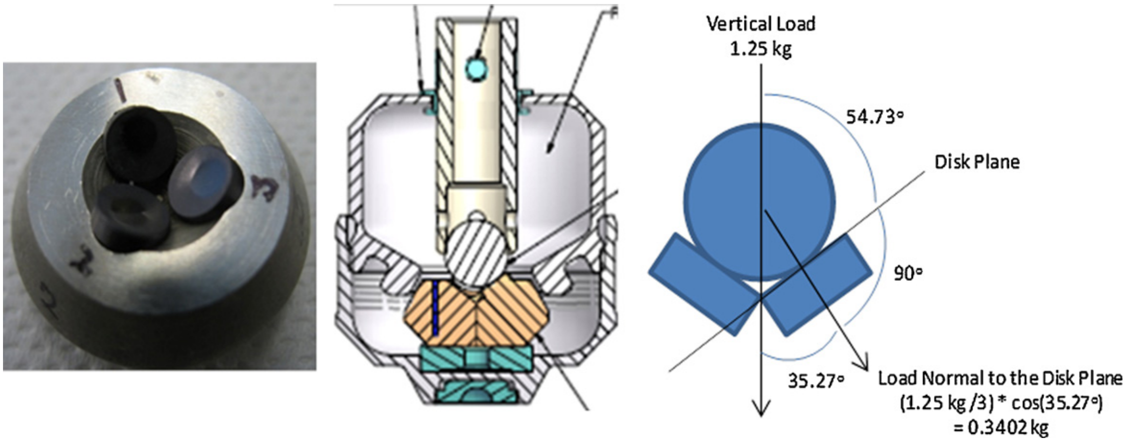

**Fig. 1.** BOTD specimen geometry.

G65 method, this method limits the types of abrasives that can be examined and the conventional ball-cratering micro-abrasion test requires the abrasive particles be in a slurry or paste.

The ball-on-three-disk (BOTD) test geometry has historically been used for evaluating the lubricity of fuels. This test involves sliding a metal or ceramic ball over three disks that are immersed in the fuel to be tested. The extent of wear that is observed on the disks is well correlated with the lubricity of the fuel [5]. Our work was motivated by recognition that replacement of the metal or ceramic ball with a rubber ball would provide an effective test for dry, three body abrasion that should provide similar results to the ASTM G65 method and that would have the advantage that the sample could be flooded with abrasive, or exposed to a dusting of particulate or blowing particulate. The BOTD also allows abrasion tests to be conducted with and without lubrication, and it allows use of slurries, elevated temperatures, controlled environmental conditions, and oscillatory and unidirectional motion.

## 2. Experimental

The geometry of the BOTD ball and specimens is shown in Fig. 1, in which only two of the three specimen disks are shown. We adapted a commercially available Falex BOTD for this study. The Falex design uses a trapped ball and provides for independent loading of the ball on the specimen disks. In the Falex BOTD, the line from the center of the ball to the center of each disk is at an angle of 35.27° from the vertical line along which the load is applied. A vertical load of 1.25 kgf was applied in our tests, which results in a loading by the ball of 0.340 kgf normal to each disk.

The modifications we made to the commercially available BOTD unit made by the Falex Corporation for testing the lubricity of fuels involved: (1) using a 1.27 cm diameter neoprene ball with a 70 Shore Adurometer, (2) flooding the sample chamber with 25 grams of sand of the same type that is used in the ASTM G65 test (AFS50/70), and (3) applying a load of 1.250 kg, which is one half the normal BOTD lubricity test load. We used the normal BOTD lubricity test rotational speed (60 rpm) with unidirectional rotational motion of the ball, which provides sliding motion of the ball on the substrate. The track of the ball in contact with the three pads has a diameter of about 0.73 cm, so 60 rpm produces a sliding speed of 0.023 m/s. A fresh 20 ml sample of sand was used for each test. The rather steep angle of the pads and the rotation of the ball cause significant stirring of the sand. This, coupled with the low contact stress, results in no fracturing or visible changes in the angularity of the sand particles as observed microscopically. The test duration was 3 h. We also measured the thickness of the coatings using two-body abrasion by employing a 1.27 cm alumina ball. The same load and rotational speed were used, but the test duration was 60 min.

We examined three different specimens. One specimen was bare 4140 steel, the second was 4140 coated with 2.3 $\mu$m of TiAlN (titanium aluminum nitride), and the third was 4140 coated with 4.1 $\mu$m of TiAlN. The hardness of TiAlN is 3400 Vickers, and the hardness of the heat treated 4140 is 34 $R_c$ (about 335 HV). This evaluation therefore provides the ability to observe how the measured abrasion wear rates scale with hardness, since abrasion wear rates tend to correlate well with specimen hardness, as well as how abrasive wear rates scale with coating thickness.

Three disks are used in each BOTD trial. The three disks can either be the same material, which provides three replicates of the measured wear rate, or each of the three disks can be a different specimen material, which provides a direct comparison of the wear rates for each specimen for each BOTD trial. Each BOTD trial results in a wear scar on each of the three disks, and the profiles of these scars were measured by a Zeiss Model 1400A profilometer. The scars appear to be spherical, so we obtained a single profile trace through the apex of the scar. Our testing utilized three replicates of a given specimen material for each BOTD trial, and multiple trials were pre-formed to provide enough data for good quality statistical analysis. Parameters that characterize the measured scars, such as the width and depth, were obtained by graphical techniques and by least squares curve fitting using a custom routine in MathCAD 14.

## 3. Theory

The rotating ball on disk configuration, also called the ball crater micro-abrasion method, has most commonly been used to measure the thickness of coatings as shown in Fig. 2 [6]. In this case, abrasive slurry is used and the particle size influences the quality of the observed scar and the accuracy of the thickness measurement.

The coating thickness, $t$, is computed from the scar dimensions $x$ and $y$ identified in Fig. 2 and from the ball's radius, $R$:

$$t = \frac{x \times y}{2 \times R} \tag{1}$$

The rotating ball on disk configuration has also been used to measure the wear rate of coatings, but this is more challenging than measuring the wear rate of monolithic materials because coatings and substrates can have very different wear rates and the ideal test methodology would be to measure wear of the coating without causing breakthrough and comparing this to wear of the substrate for a similar period of time. In reality, wear tests of coatings are almost never done this way because it requires much trial and error