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On the optical microscopic method for the determination of ball-on-flat surface linearly reciprocating sliding wear volume

S. Sharma, S. Sangal, K. Mondal *

Department of Materials Science and Engineering, Indian Institute of Technology, Kanpur 208016, Uttar Pradesh, India

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ABSTRACT

A simple approach for wear volume calculation by optical microscopic technique is proposed for ball-on-flat surface linearly reciprocating sliding wear. The depths at different positions of the worn out section are measured by focusing and defocusing from the flat surface of the sample. Length and width are measured by the movement of focused point along the surface. Image-J software is used to obtain best focused image by maximization of intensity. Measured depths are used to calculate wear volume using a modified geometric equation for the worn out section of the sample consisting of truncated cylinder with central flat bottom and double truncated spheres at two ends. The wear volume measurement is carried out for number of steel samples at different load values at a fixed frequency and it compares well with that determined by laser profilometric analysis.

1. Introduction

Ball-on-flat linearly reciprocating sliding wear is one of the most common laboratory wear testing method to determine the wear behavior of engineering materials. The volume of the material removed is one of the important quantifying parameters for wear property and there are various methods to measure the wear volume. Gravimetric analysis is one of the commonly used methods [1]. But, this method fails when the wear volume is too small. One of the most reliable and accurate methods in the calculation of the wear volume is the three dimensional surface profiling of the wear scar from a large set of multiple surface profiles from a single specimen [2]. Though this method is very accurate, it is extremely rigorous and time consuming [3,4]. There are other modern methods like stylus and electron microscopic techniques existing to measure surface topography [5]. Therefore, there is a need for simpler and quick method for calculating the precise wear parameters [6]. Qu and John [7] have developed a method for the measurement of wear volume on a flat specimen in case of reciprocating pin-on-flat case and physical dimensions of the wear scar are used in the following equations:

$$V_f = L_s\left[R_f^2 \arcsin\left(\frac{W}{2R_f}\right) - \frac{W}{2}(R_f - h_f)\right] + \frac{\pi}{3}h_f^2(3R_f - h_f) \tag{1a}$$

where, V_f, h_f, W, L_s and R_f are the wear volume, depth, width, stroke length and radius of the two spherical ends, respectively. h_f is given as

$$h_f = R_f - \sqrt{R_f^2 - \frac{W^2}{4}} \tag{1b}$$

Qu and John [7] have also developed a method for wear of the flat specimen generated by reciprocating sliders with compound tip curvature, and the following equation was used to calculate its wear volume.

$$V_f = L_s\left[R_f^2 \arcsin\left(\frac{W}{2R_f}\right) - \frac{W}{2}(R_f - h_f)\right] + \pi\frac{(L - L_s)}{3W}\left[h_f^2(3R_f - h_f)\right] \tag{2}$$

where, L and W are the length and width of the scar, respectively. They have shown the wear scar on the flat specimen to be comprising of three segments, the cylindrical middle segment with radius R_f and spheroidal shape compound curvature ends with semi axes R_f and r_f. But, their approach to calculate the wear volume in both the cases might be different with respect to actual volume since these methods have considered the apparent geometric profile of the scar. The actual cross section should include the consideration of the ball or pin getting abraded during the wear and the profile obtained is discussed in the present work. Chattopadhyay et al. [8] have considered the wear of ball contributing in the final wear volume. They have calculated the wear volume with the following equation:

$$V = L[\{R^2 \mathrm{Sin}^{-1}(W/2R) - W/2(R-h)\} - \{R^2 \mathrm{Sin}^{-1}(w'/2R) - w'/2(R-h+h')\}] + \pi[Rh^2 - h^3/3) - \{R(h-h')^2 - (h-h')^3/3\}] \tag{3}$$

where, h, h', R and w' are apparent depth of the wear scar, depth of the wear scar due to ball abrasion, abrading ball radius and scar

* Corresponding author. Tel.: +91 512 259 6156; fax: +91 512 259 7505.
E-mail address: kallol@iitk.ac.in (K. Mondal).

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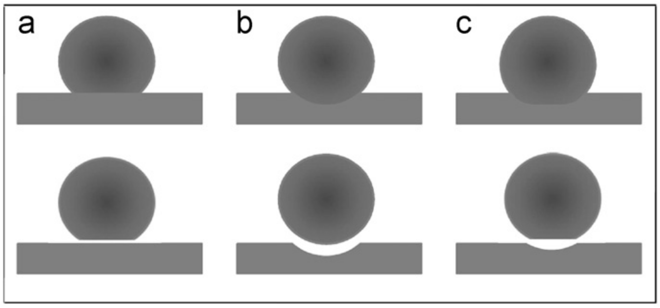

Fig. 1. Possible configurations for different wear situation of the ball and the flat specimen (a) only the ball wears (b) only the flat specimen wears and (c) both ball and flat specimen wear [10].

diameter, respectively. In the present study the wear scar geometry on the ball and the flat specimen is critically analyzed and the wear volume calculation is modified. The analysis of the wear scar geometry is done by optical microscopy to measure the different parameters involved in the calculation. One of the main focuses of the study is to verify and standardize the measurements done by optical microscopy by maximization of intensity [9,10] using Image-J software in order to get accurate results in wear volume calculation.

Two optical microscopic methods are employed to measure the depth at different positions of the worn out groove: (a) focusing and defocusing from the reference plane which is the flat surface on which wear test is done and (b) maximization of focused intensity. The relative wear of the ball and the flat specimen yields different geometric variations as mentioned in ASTM G133-05 [11]. Three different wear conditions are possible in this test. Fig. 1 shows these conditions. Fig. 1(a) shows the condition where the ball only wears and this can happen if the flat specimen is more wear resistant that the ball. In Fig. 1(b) only the flat specimen wears as the ball is of higher hardness compared to the flat specimen. The third and the most general condition is that both the ball and the flat specimen wear as shown in Fig. 1(c) [11]. The actual shape of the worn out groove is also understood from the optical microscopy, Scanning Electron microscopy (SEM) and laser surface profilometric (LSP) analysis. The volume equation of the groove is modified as per the actual shape, and the depths and other dimensions measured by optical microscopic methods are used to calculate the wear volume. The wear volume measured by the presently proposed method comes out to be very close agreement with that measured by LSP analysis. The error in the current method with respect to the LSP data is minimum in comparison to other methods existing in the literature employing the geometric volume equation [6–8]. The present work finally intends to bring a clear and quick understanding of a precise wear volume calculation in a simple manner.

2. Model description

Considering the most general case where both the ball and the flat specimen wear, the linear reciprocating sliding wear tests were carried out with steel balls of hardness ~800 Hv used as a counter-body to test the flat steel specimens. The balls were selected in such a fashion that the hardness of the balls was in the range of 1.5–2 times higher than that of the sample on which wear test was carried out. The elastic limit for the Hertzian contact of the steel ball and steel sample conjugate is calculated from Hertzian equation [12]. In this condition, the third case of wear configuration (Fig. 1c) was attained where the ball and the flat specimen, both wore during the test. A schematic of the wear scar generated by the reciprocating sliding motion of the ball on the flat surface is given in Fig. 2(a–c). Fig. 2(a) shows the scar generated on the flat specimen by a ball and Fig. 2(b) shows the top view of the scar. It consists of three segments. The middle three dimensional segment of the scar is cylindrical (Fig. 2c) and a shape of a truncated sphere is developed at two ends (B in Fig. 2b). Two cases are considered to calculate the final volume of the wear scar.

2.1. Case I: Ball does not wear

Fig. 2 shows the wear scar geometry generated in this case. There are three distinct regions. In Fig. 2(a) the middle segment is region A having a cylindrical geometry and the ends denoted by region B have a geometry similar to the truncated part of a sphere. In the present case, we have considered that the ball is hard enough to resist its own wear. In this case the ball retains its geometry. In Fig. 3(a) the circle represents the ball and the sector PQR represents the section of the ball which corresponds to the cross section of the cylindrical region i.e, region A. The various

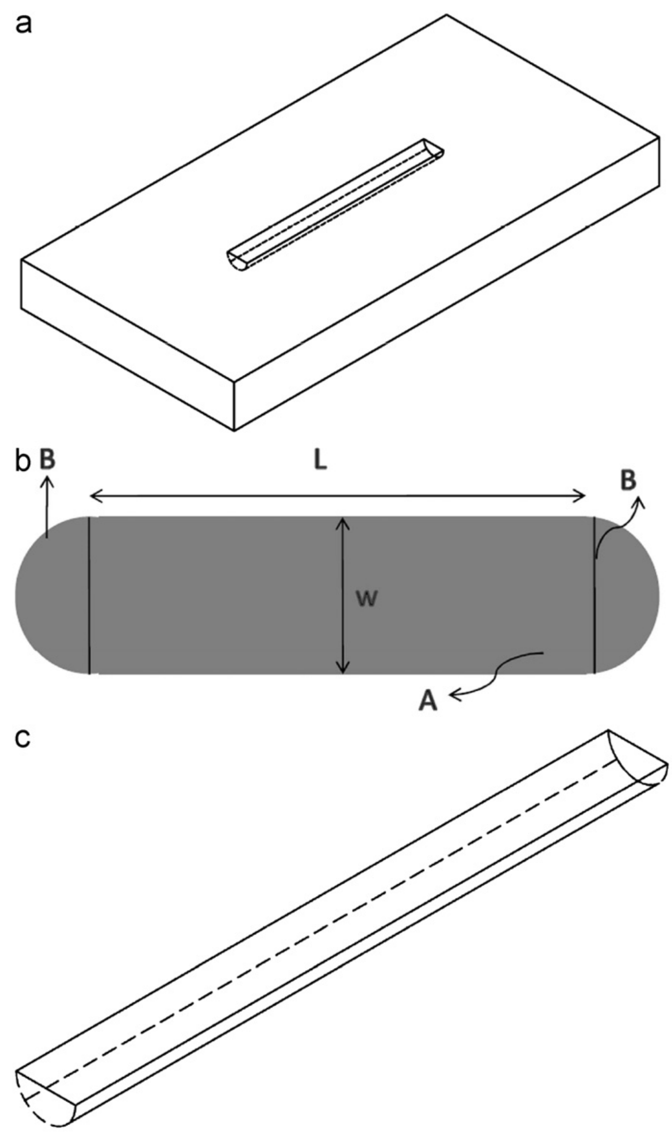

Fig. 2. Schematic representation of (a) the wear scar generated by reciprocating sliding motion of the ball on a flat specimen, (b) top view of the wear scar and (c) 3D view of the middle cylindrical segment.