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Material removal factor (f_{ab}): A critical assessment of its role in theoretical and practical approaches to abrasive wear of ductile materials

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ABSTRACT

Material removal factor, f_{ab}, is defined by ZumGahr as "the ratio of volume of wear debris to the volume of wear groove produced". It appears in the literature within the context of abrasive wear, usually as a possible indication of prevailing mechanisms such as plowing, wedge formation and cutting. Microcracking, an important mechanism in the abrasion of brittle material such as highly hardened steels and ceramics, was not considered in this work. Measurements of cross section areas in scratch tests – groove and pile up – are essential for f_{ab} calculation. This paper presents a short review of the literature in that sense.

It also covers scratch testing of gray cast iron (GCI) and AISI 1070 steel specimens, both with macro hardness close to 200 HV_{30kgf}. Laboratory tests were performed under constant loads selected from 20 to 200 mN, dry interface. Geometric parameters of the scratches were measured with an optical interferometry profilometer and an SEM was used for image analysis. Clear correlations between scratch width (or depth) and applied load were observed, but that was not the case with calculated f_{ab} values. Image analysis confirmed the presence of different abrasion mechanisms at the same scratch shedding light on the difficulties encountered when measuring groove and pile-up areas.

1. Introduction

An important part of the understanding of the mechanisms underlying abrasive processes resulted from the study of unitary events, i.e., testing where observations focused on how an isolated abrasive particle (or an indenter that fulfilled the same task) interacted with the other surface. These scratch tests came to play an important role in the evaluation of the abrasion resistance of surface layers and were standardized in 2003 [1].

Two outstanding examples of early technical literature on two-body (fixed abrasive particles) abrasion were the works of Rabinowicz, Dunn and Russell [2] and Mulhearn and Samuels [3]. Rabinowicz, Dunn and Russell presented a theoretical approach of the abrasive action considering a unitary event where material from the groove was entirely removed as wear debris by an idealized conical abrasive particle; Mulhearn and Samuels introduced the idea of critical attack angle of the abrasive particle – below such angle only plowing would occur. Fig. 1 is a representation of that theoretical model.

With an area correction (see Hutchings [4]) the model can be mathematically expressed by:

$$q = \frac{2 \cdot W}{\pi \cdot H \cdot tan\alpha} \tag{1}$$

where:

q = volume of wear debris produced per unit length of the groove;
W = load carried by the particle;
H = hardness of the material;
α = semi-angle of conical abrasive particle.

Rabinowicz, Dunn and Russel [2] acknowledged the fact that in actual abrasion "*total wear is made up of a number of similar processes*" and they proposed to take that in account by considering ***tan α*** as "*the average tangent of the angle of penetration of all the abrasive particles*". Material displacement to the sides of the groove (pile up) was briefly mentioned in connection with the differences in abrasion resistance between annealed and hardened materials, which surprisingly was "*not in proportion to the increase in hardness*".

Buttery and Archard [5] undertook a series of experiments to explore the relationship between abrasive wear and the industrial grinding process including measurement of forces during grinding tests and scratch tests using different types of indenter. Their approach to the

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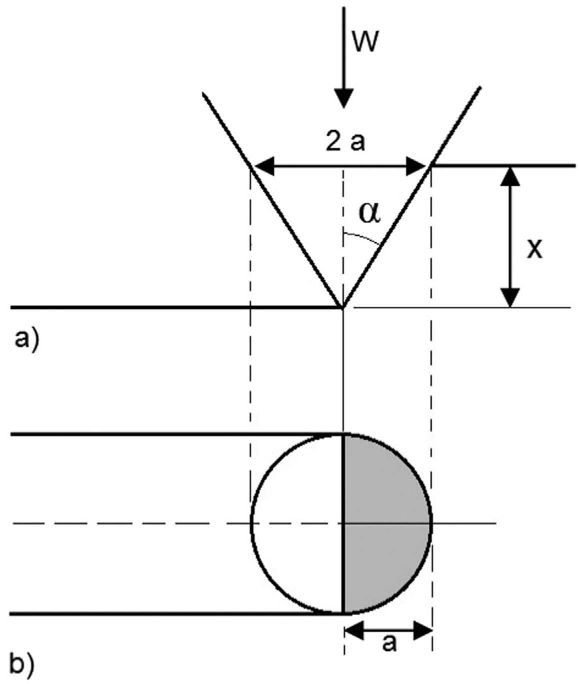

Fig. 1. Geometry of contact between an idealized conical abrasive particle with semi-angle α and a surface: a) in elevation; b) in plan view, adapted from Hutchings [4].

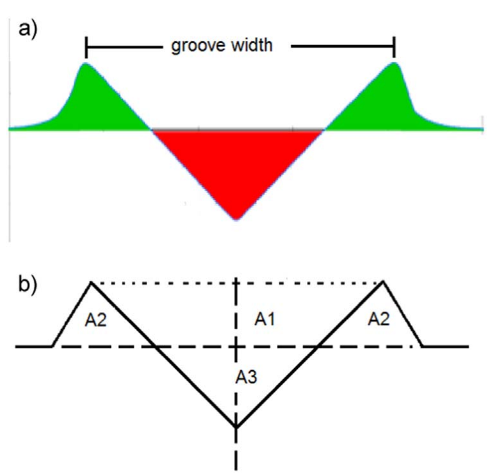

Fig. 2. a) Typical groove showing pile up b) Idealized representation of the groove; adapted from Buttery and Archard [5].

connection between wear theories and the abrasion mechanisms of single particle grooving used the model presented in Fig. 2, including the displacement of material to the sides of the groove (pile up):

The authors proposed to quantify material removal by a parameter "ζ" defined in terms of the areas indicated in Fig. 2 as follows:

$$\zeta = \frac{A_3 - A_2}{A_3} \tag{2}$$

It should be mentioned as an example of the difficulties faced by researchers in the past that Buttery and Archard obtained the areas by weighing profiles cut from graphics generated by a profilometer with an electro-mechanical sensor. In the discussion following the paper, K.L. Johnson brought up an issue, overlooked by most of the succeeding works, leading to a possible source of error. Considering the difference between areas above and below the reference (zero) line as removed material, Johnson argued that:

"…some fraction of this 'lost' material is not actually removed from the solid. (…)The material close to the indenter is compressed plastically and is forced downwards and outwards into the hinterland which expands elastically to accommodate it".

In 1981 Zum Gahr [6] introduced without details a correction factor to the equation expressing theoretical values of removed material volumes. That factor, designated as $\mathbf{f_{ab}}$, was defined as the "ratio of the volume removed by microcutting to the volume of wear groove produced". $\mathbf{f_{ab}}$ values could range from zero (pure microplowing) to 1.0 (pure microcutting). From the point of view of abrasion mechanisms it represented acknowledgement that microcutting and microplowing could occur simultaneously. It should act as a correction factor to the complex theoretical model presented at that time that led to calculated values up to 2.5 times greater than the measured values.

Garrison and Garriga [7] recognized both the difficulty to directly relate abrasion resistance to bulk hardness and the need to consider material that was displaced without being removed. The authors introduced a factor $\boldsymbol{f}$ as a fraction of wear groove corresponding to material "*plowed to either side of the abrasive particle, but not removed*". They proposed an equation where the wear rate was directly proportional to the ratio $(1 - \boldsymbol{f})/ H_s$ where H_s was the hardness of the wear surface and $(1 - \boldsymbol{f})$ was equal to $\mathbf{f_{ab}}$. The paper did not deal with the question of $\boldsymbol{f}$ measurement.

In a subsequent work Zum Gahr and Mewes [8] presented a formal definition of f_{ab} in terms of areas of the cross section of a scratch, making it clear that it was the same as the factor **"ζ"** previously used by Buttery and Archard. The authors pointed to the fact that the parameter – indicating "*the severity of material removal*" – depended on material properties – e.g. hardness, shear strength, Poisson's ratio – and on system characteristics such as wedge angle of indenter, tip radius and attack angle. The experimental part of the work included scratch tests and taper sections through the grooves. Image analysis software was used to evaluate f_{ab} Fig. 3.

In 1986 Kayaba, Hokkirigawa and Kato [9] used the f_{ab} concept – ratio of net groove area to apparent groove area A/A' – under the designation of "*degree of wear*" and associated f_{ab} values to abrasion mechanisms as shown in Fig. 4.

Fig. 4 shows that f_{ab} values depended on the degree of penetration, defined by the authors as the ratio of indentation depth to indentation radius. No details were given on the area measurement procedures.

The book "Microstructure and Wear of Materials" [10] by Zum Gahr detailed the theoretical model previously outlined [6]. A set of complex

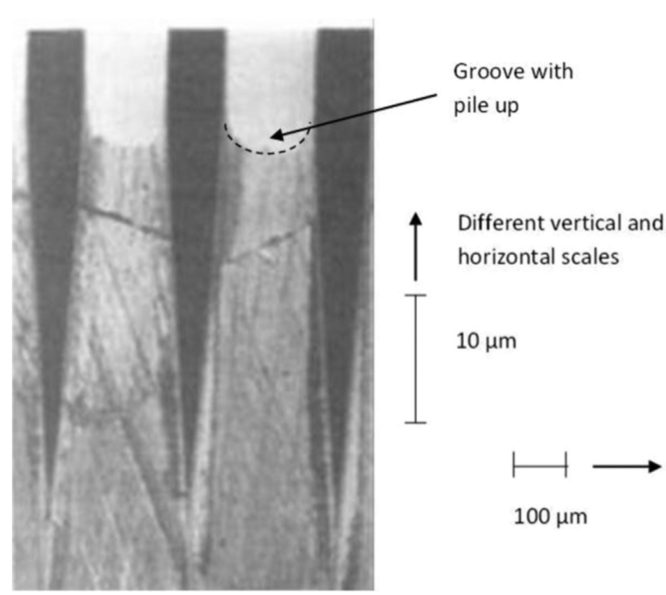

Fig. 3. Taper Section (3 deg) through wear grooves (diamond indenter), on polished surface of β brass, adapted from Zum Gahr and Mewes [8].