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Adapting the energetic erosion theory to hardened steels

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Abstract. This paper presents the ways and means of transformation of the existing energetic theory into a modified form, applicable for hardened steels by predicting their erosion rate in order to obtain a close correlation between the calculated values and test data. Differently from the initial form of the theory, employing static hardness for the estimation of particle penetration depth into the target surface, the modified theory utilizes dynamic hardness. More specified is the determination of the particle shape factor since besides its geometry the effect of crushing strength and angle of incidence are taken into account. In comparison with the values used before, for particles of extra high crushing strength as manufactured corundum impacting against hardened steel target, the shape factor may obtain values three times higher than normally expected.

Key words: erosion, wear, hardened steel, dynamic hardness.

1. INTRODUCTION

A thorough comparative analysis of the existing erosion theories performed by Ellermaa [1] revealed that the closest agreement between the predicted values and test data is attained with the use of Beckmann's energetic erosion theory. In its initial form this theory was presented in [2] and the final theory was published later [3]. According to this theory, removal of a fragment of the material from the target surface, subjected to accumulation of plastic deformation, will occur not until the total amount of energy consumed for shear straining reaches its critical level. The significance of shear straining is effectively demonstrated on the micrographs taken at the University of Cambridge from test pieces of low-carbon steels [4]. However, of prime importance in fighting against erosion is the selection of materials of high hardness, among them hardened steels [5]. In this work we investigate how to extend the applicability of the erosion theory to hardened steels.

2. MODIFICATION OF BECKMANN'S THEORY

For applying this theory, the following assumptions are made: 1) the eroding particles are assumed to be homogeneous and elastically deformable spheres of radius R and density ρ_2; 2) at the instant prior to the incidence, the eroding particle was moving at a constant velocity v along a rectilinear trajectory whereas the velocity vector made with the target surface an angle α; rotation energy of the particles is zero; 3) particle hardness H_2 exceeds that of the target hardness H_1 not less than 1.6 times.

Proceeding from [3], the wear rate I_v of the target material can be found by the following expression

$$I_v = \frac{3}{4\pi\rho_2}\frac{\tau_0}{e_s}(J_{\mathrm{I}} + J_{\mathrm{II}}), \tag{1}$$

where

$$J_I = \left(\frac{5}{3}+\pi\right)\sqrt{2}\left(\frac{h_p}{R}\right)^{0.5}\frac{2\rho_2}{3H_1}v^2\cos^2\alpha = 6.81\left(\frac{h_p}{R}\right)^{0.5}\frac{2\rho_2}{3H_1}v^2\cos^2\alpha, \tag{2}$$

and

$$J_{\mathrm{II}} = 0.85\left(\frac{h_p}{R}\right)^2. \tag{3}$$

Here J_{I} stands for the share of wear caused by the tangential component of the velocity while J_{II} shows the same for the normal component, h_{p} is the depth of indentation produced by the eroding particle, and τ_0/e_s is a dimensionless ratio where the numerator means shearing stress in the target material to be calculated as

$$\tau_0 = \frac{1}{3}L\rho_1\ln\left(\frac{T_{\mathrm{m}}}{T}\right). \tag{4}$$

Here L is the material latent heat of melting, T_{m} is melting temperature of the material (K), T is the ambient temperature, and e_s is the density of the specific shear energy.

According to Beckmann, the ratio of τ_0/e_s is a characteristic of erosive wear resistance of the material, which is also applicable to several other kinds of wear such as abrasive and adhesive wear as well as for drop impact erosion. The accumulated statistical data are graphically represented in Fig. 1, covering pure metals, carbon and alloy steels, and white cast iron [3].

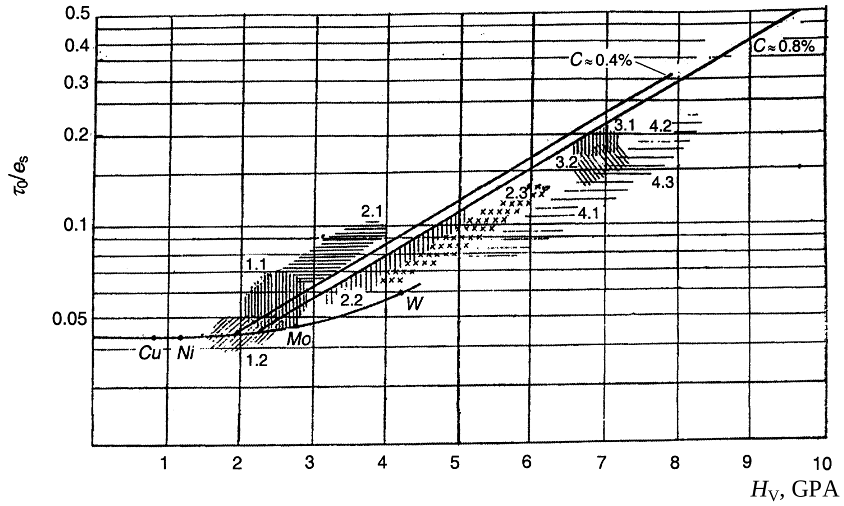


Fig. 1. Variation of τ_0/e_s as a function of initial hardness H_V of the target material: 1.1 – low-alloy structural steels; 1.2 – austenitic manganese steels; 2.1 – pearlitic carbon steels; 2.2 – steels alloyed with Mn, Si, and Cr; 2.3 – alloyed cast steels; 3.1 – hardened tool steels; 3.2 – hardened chromium steels; 4 – carbide-based structures; 4.1 – C > 1.5% special steels alloyed with Mo, W, and V; 4.2 – ledeburitic special steels alloyed with W, Mo, and V; 4.3 – high-alloy white cast irons containing various carbides.

To determine the depth of indentation, a variable of primary importance, Beckmann employed the following equation:

$$h_p = R\sqrt{\frac{2\rho_2}{3H_1}\left[v^2\sin^2\alpha - \frac{4E'}{5\pi\rho_2}\left(\frac{H_1}{E'}\right)^5\right]}, \tag{5}$$

where E' is the reduced modulus of elasticity

$$E' = [(1-\mu_1^2)/E_1 + (1-\mu_2^2)/E_2]^{-1}, \tag{6}$$

E_1 and E_2 are Young's moduli of the target material and abrasive particle, respectively, and μ_1 and μ_2 are Poisson's ratios for the same materials.

To allow for the actual conditions of erosion process, the result calculated by Eq. (1) must be multiplied by the two empirical correction factors designated as k_R and k_φ. The first of them takes into account the angularity of particles, that is, the deviation of the particle shape from an ideal sphere, the second factor being responsible for the effect of particle concentration φ attacking the target on erosion rate. This effect (also known as phase density) turns out to be remarkable if $\varphi > 10$ g/cm^2 s whereas particles rebounding from the target surface will have a screening effect restraining the motion of primary particles. Further, at $\varphi >$ 200 g/cm^2 s, the value of k_φ decreases to 0.4 [6]. For the range of φ from 10 to

200 g/cm^2 s, the values of k_φ can be determined with sufficient accuracy from the formula

$$k_\varphi = 2\varphi^{-0.3}. \quad (7)$$

In cases when $\varphi < 10$ g/cm^2 s, $k_\varphi = 1$ should be used.

Beckmann's treatment of the particle shape factor k_R is originated from the respective investigation by Tadolder [7], where the values of this factor range as shown in Table 1.

The values of k_R have been obtained mainly with a goal to distinguish the particles by shape and were checked by Tadolder on commercially pure metals, which are mostly soft and ductile.

However, data presented in [7] imply that k_R depends on the angle of impact α. Furthermore, Uuemõis in [8] elucidated that crushing strength of the particles combined with impact velocity will also have a substantial effect on k_R. The values of k_R obtained for manufactured corundum particles against low-carbon steel targets at $v = 50$ m/s amounted to 6.7 at $\alpha = 90°$ and to 4.0 at $\alpha = 30°$ [8]. Comparison tests, in which targets of Arne steel (820 HV) were subjected to erosion by corundum and rounded quartz particles at $\alpha = 90°$, yielded $k_R = 6.6$ as well. Despite the fact that crushing strength of quartz particles is much lower than that of corundum, the values of k_R as suggested by Beckmann for $\alpha = 90°$ have been found to remain valid also for hardened steels.

Attempts to attribute to k_R a constant value leads to considerable differences between the calculated and experimental results for impact angles less than 60° (Fig. 2). To compensate this error, an additional correction factor $k_\alpha = \sin^n \alpha$ should be introduced just for making values of k_R more exact. For quartz sand particles $n = 0.4$ and for corundum $n = 0.8$. These values can be used at impact velocities up to 120 m/s. Further in the range of higher velocities n decreases continuously and at velocities over 200 m/s may even fall below zero; that is, with a decrease of α the value of k_R tends to rise instead of falling [7]. Apparently further systematic studies, involving a variety of target materials, impact angles, and velocities are necessary to determine k_R more precisely.

A limitation of the Beckmann's theory in its initial form is that expressions given for the determination of indentation depth in the target surface are based on the static hardness H_1 of the material. However, the fact that at low impact

Table 1. Particle shape factors k_R of different materials

Material	k_R
Spherical white iron shot	1.0–1.1
Rounded quartz	1.05–1.3
Angular quartz	1.3–1.6
Corundum	1.6–1.9
Glass grit	1.9–2.1
White iron grit	2.3–2.7

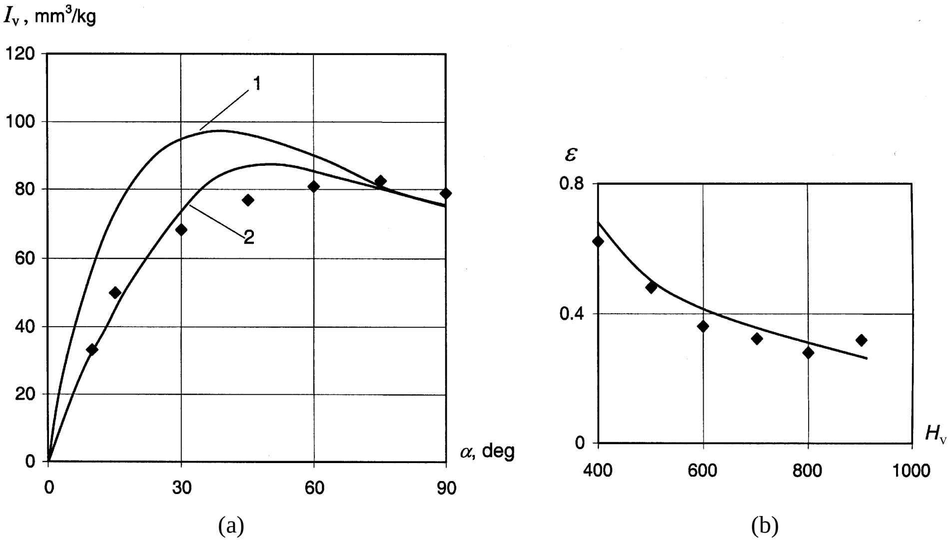


Fig. 2. Comparison of theoretical values of the wear rate I_v and relative wear resistance ε of the 0.8% C tool steel U8A with experimental data: (a) dependence of the wear rate I_v on the impact angle α; 850 HV, particle-stream erosion, $v = 120$ m/s, quartz sand particles of d = 0.3–0.6 mm, k_R = 1.4, k_M = 0.78, $k_\alpha = 1$ (curve 1) and $k_\alpha = \sin^{0.4}\alpha$ (curve 2); the experimental points have been obtained on test rig VK-1 with a vacuum chamber; (b) dependence of relative wear resistance ε on target steel hardness H_V; $\alpha = 90°$, tested at $v = 120$ m/s on centrifugal accelerator with corundum (d = 0.4–1.0 mm) in comparison with standard 0.2% C steel of 130 HV.

velocities the dynamic hardness is remarkably higher than the static one was known long before [9]. For impact velocities, frequently occurring in the erosion process, this was corroborated in [10,11]. It was ascertained that the most expedient characteristic for the assessment of dynamic hardness of the material is the specific energy of crater formation e_0, which is independent of the impact velocity. Taking this into account, Eq. (5) can be written as

$$h_p = vR\sin\alpha\,(2\rho_2/3e_0)^{0.5}, \tag{8}$$

which yields results of notably higher accuracy.

As calculated with the above theory, erosion predictions appear to be independent of the impacting particle size. Actually, with particles sized below 120 μm the wear rate exhibits an abrupt decrease [12,13]. In [1], an additional correction factor $k_d = d/120$ for particle sizes $d = 0$–120 μm was introduced.

In cases when hard facings or hardened steels are involved, the abrasive to material hardness ratio must be taken into account [5]. For this purpose one more correction, the so-called material factor k_M, was defined in [1]. According to the author, $k_M = 1$ when $H_2 \geq 1.6\, H_1$, while for the range of $H_1 < H_2 < 1.6\, H_1$ the value of this factor should be calculated as

$$k_M = (H_2 - H_1)/0.6\, H_1. \tag{9}$$

3. COMPARISON OF PREDICTED VALUES WITH EXPERIMENTAL DATA

For practical use of Eq. (8), the numerical value of dynamic hardness e_0 is expected to be known. Until today no such data, concerning hardened steels, were available. To fill this gap in the theory, the authors suggested a method and procedure of testing [14] using the following relationship between static and dynamic hardnesses:

$$e_0 = 1 + H_{\mathrm{V}},\ \mathrm{J/mm^3}, \tag{10}$$

where H_{V} is Vickers hardness of the steel in GPa.

Proceeding from Eqs. (1), (2), and (3) using data from Fig. 1, the wear rate for various impact angles was computed. For this purpose the value of h_{p} was determined by Eq. (8) and static hardness H_1 in Eq. (2) was substituted by the dynamic hardness e_0. The results were compared with experimental data obtained earlier with quartz sand, and apart from this an additional comparison test with corundum was made. In all the above cases the testing conditions corresponded to $k_\varphi = k_d = 1$. Most reliable are the results obtained with the VK-1 test rig [12], which ensures a minimum dispersion of results with a deviation of no more than $\pm 1.5\%$ from the nominal value.

Within the scope of the present work, a 0.8% carbon tool steel was tested for erosion rate in the VK-1 rig. The value of τ_0/e_{s} for this steel can be taken from Fig. 1 and the results are shown in Fig. 2a. Figure 2b depicts the variation of relative wear resistance ε of the same steel tempered to various hardnesses as compared with that of the reference steel (0.2% C, 130 HV).

For the case of normal impact $(\alpha = 90°)$ the relative wear resistance can be expressed as

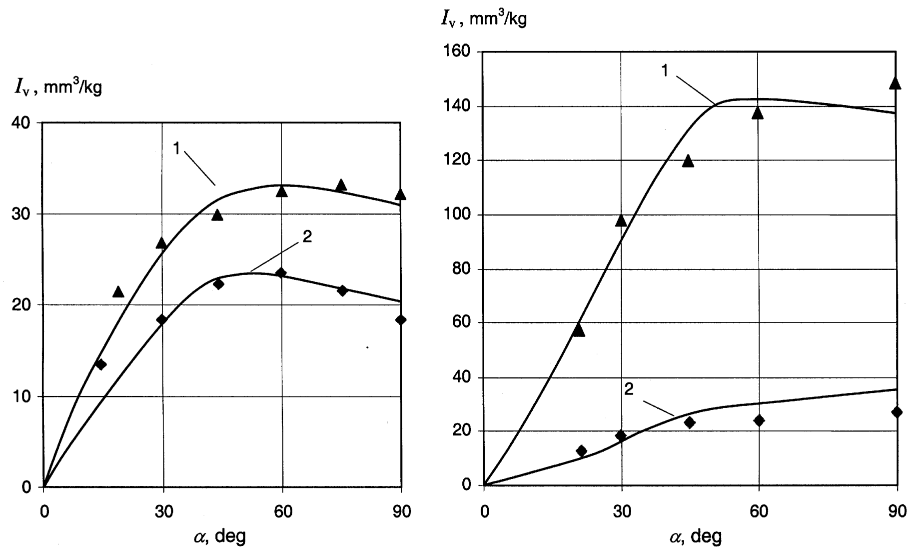
$$\varepsilon = \frac{I_{\mathrm{e}}}{I_v} = \frac{e_0 \tau_{0\mathrm{e}} \varepsilon_{\mathrm{s}}}{e_{0\mathrm{e}} \tau_0 \varepsilon_{\mathrm{se}} k_{\mathrm{M}}}, \tag{11}$$

where I_{e}, e_0, τ_0, k_{M}, and ε_{s} are variables related to the material under study, I_v, $e_{0\mathrm{e}}$, $\tau_{0\mathrm{e}}$, and $\varepsilon_{\mathrm{se}}$ are respective variables for the reference material.

The experimental points in Fig. 2 are based on data given in [5].

Comparison of experimental results obtained on the centrifugal accelerator is presented in Fig. 3.

This comparison suggests that the modified energetic erosion theory is applicable for the prediction of the wear rate of hardened steels at impact velocities ranging from 40 to 120 m/s. At higher velocities, remarkable fragmentation of mineral particles starts leading to changes in the wear process. To cover the range of higher velocities, the above theory apparently needs further verification and probably some modification.



(a) (b)

Fig. 3. Dependence of the wear rate I_v on impact angle α: (a) curve 1: steel U8A, 850 HV, particle-stream erosion, quartz sand particles d = 0.3–0.6 mm, $k_R = 1.4$, $k_M = 0.78$, $k_\alpha = \sin^{0.4}\alpha$; curve 2: steel 0.2% C, 434 HV, particle-stream erosion, quartz sand particles d = 0.4–0.6 mm, $k_R = 1.3$, $k_M = 1$, $k_\alpha = \sin^{0.4}\alpha$ [1]; v = 80 m/s; (b) steel Arne, 820 HV (group 3.1 in Fig. 1), stream erosion by white manufactured corundum particles d = 0.3–0.6 mm, $k_R = 6.6$, $k_M = 1$, $k_\alpha = \sin^{0.8}\alpha$, v = 80 m/s (curve 1) and v = 40 m/s (curve 2); each experimental point represents arithmetic average of three test results.

4. CONCLUSIONS

1. The use of dynamic hardness instead of the static one in computing the wear rate of hardened steel with the expressions of the energetic erosion theory enhances the accuracy of wear rate predictions and provides a close correlation of computed results with experimental data.

2. In addition to the empirical correction factors used before, another correction factor, k_α, compensating the dependence of the particle shape factor k_R on the impact angle α, has been suggested.

3. Future investigations in this field shall be directed towards the adaption of the energetic erosion theory for higher impact velocities and towards its application to hard facings.

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Energeetilise erosiooniteooria kohandamine karastatud terastele

Ilmar Kleis ja Toomas Remi

Käesolev töö käsitleb energeetilise erosiooniteooria modifitseerimist kujule, mis võimaldaks selle abil saadud karastatud teraste erosiooniintensiivsuse arvutustulemusi katseandmeile maksimaalselt lähendada. Erinevalt teooria algkujust, mille kohaselt osakeste pinda tungimise sügavus määratakse materjali staatilise kõvadusega, tehakse seda dünaamilist kõvadust kasutades. Täpsustatakse osakeste kujuteguri määramist, näidates, et lisaks geomeetriale on tähtsal kohal ka osakeste purunemistugevus ja kohtumisnurk. Võrreldes varem kasutatud väärtustega, võib eriti purunemiskindlate osakeste (elektrokorund) kujutegur karastatud teraste erosioonil kasvada üle kolme korra.