Chapter

Remarks on Wear Transitions Related to Hardness and Size of Abrasive Particles

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Abstract

Abrasive wear is highly dependent on the characteristics and properties of abrasive particles. Their hardness and size can define the severity of abrasion in terms of wear rates. Typically, critical values have been empirically determined to define the transition between mild and severe wear. This review aims to update some of the issues related to these critical values and their relations to abrasive wear. After presenting the current state-of-art, the following items are discussed: a) the scratchability of materials; b) the particle fragmentation associated with size effects; and c) description of abrasion severity.

Keywords: abrasive wear, hardness, particle size effect, fragmentation, wear severity

1. Introduction

Probably the most recognized property associated with abrasitvity, i.e., "the ability of a material or substance to cause abrasive wear" [1], is hardness. An unambiguous proof of this relation is the possibility to define hardness by employing the wear that a particle can promote on a surface, as postulated former by Tonn [2].

The relation between hardness and wear depends on the level of severity imposed by the tribological system. In this sense, the mild and severe regimes of abrasion [3] can be associated with the abrasive particle/worn material hardness ratio [4]. For a better understanding, here, this tribological pair will be called 'indenter/worn material' because some examples will be associated with the scratching process. For this reason, the hardness ratio will be referred to as *Hi/Hw*.

For rescuing the historical information, one could ask when the effect of the *Hi/Hw* ratio on the abrasive wear was first experimentally determined. For that reason, five manuscripts were consulted to check the cited references on the topic. A summary of these experimental investigations can be shown in **Table 1**.

Based on data presented in **Table 1**, one can note that the investigations performed by Nathan and Jones [6] and Richardson [7] were most cited, but the former one can be considered that conducted by Wahl in 1951 [12].

For exemplifying the effect of the *Hi/Hw* ratio on friction, it is fashionable to mention the findings of Tabor [15]. He conducted an unusual experiment using a scratch device for investigating the existence of a critical value of the *Hi/Hw* ratio. The experiment consisted of a metal with a sharp point at this end (indenter role)

Manuscript/Year	Aim	Experimental results cited for *Hi/Hw* ratio
Moore, 1978 [5]	Review	Nathan & Jones, 1966 [6]; Richardson, 1968 [7]
Torrance, 1981 [8]	Modeling	Richardson, 1968 [7]
Misra/Finnie, 1982 [9]	Review	Wahl, 1954 [10]
Tylczak, 1992 [11]	Review	Wahl, 1951 [12]; Nathan & Jones, 1966 [6]
Magnee, 1993 [13]	Modeling	Kruschov, 1958 [14]

Table 1.
References cited on the experimental values of the Hi/Hw ratio.

scratching a sheet with variable hardness along its length, obtained by suitable heat treatment. The measurement of tangential force was able to define the mode of contact during the scratching, i.e., if the sharp point was able to scratch the metallic surface or not.

The indenter hardness indicated in **Figure 1** allows concluding that it will scratch the sheet's surface only if $Hi/Hw \geq 1.2$. Here this value is referred to as critical hardness ratio $(Hi/Hw)_{CRIT}$. Magnee [13], in his model formulation, called it a lethal abrasion coefficient.

The relation between the $(Hi/Hw)_{CRIT}$ and the abrasion regime - mild or severe wear - only makes sense if the wear mechanisms and observed damages on bodies' surfaces are well related. This task was done by Pintaude et al. [4], and it is summarized in **Figure 2**. Besides the findings described in [4], the detailed description of wear mechanisms could be found in Piazzetta et al. [16], who performed a Cherchar abrasivity test, sliding on nine rocks.

Considering the previous overview published [17], this review intends to incorporate experimental results to understand the concept of critical hardness ratio. The manuscript will be divided into three sections: i) the scratchability of materials, ii) the fragmentation of abrasive particles and size effects, and iii) the description of abrasion severity.

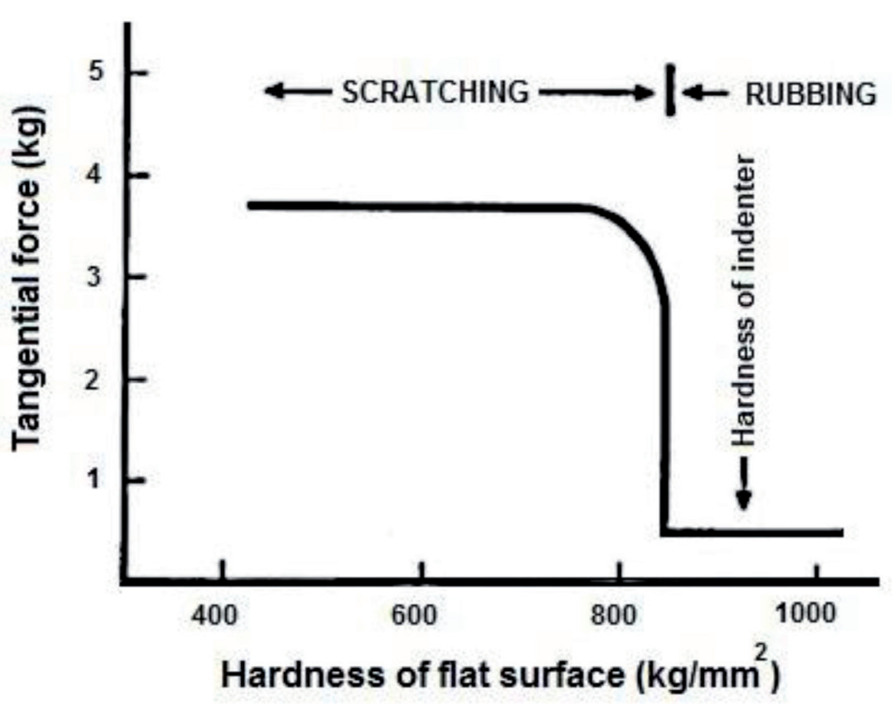

Figure 1.
Friction force determined between a metal point and a metal sheet of varying hardness [15].

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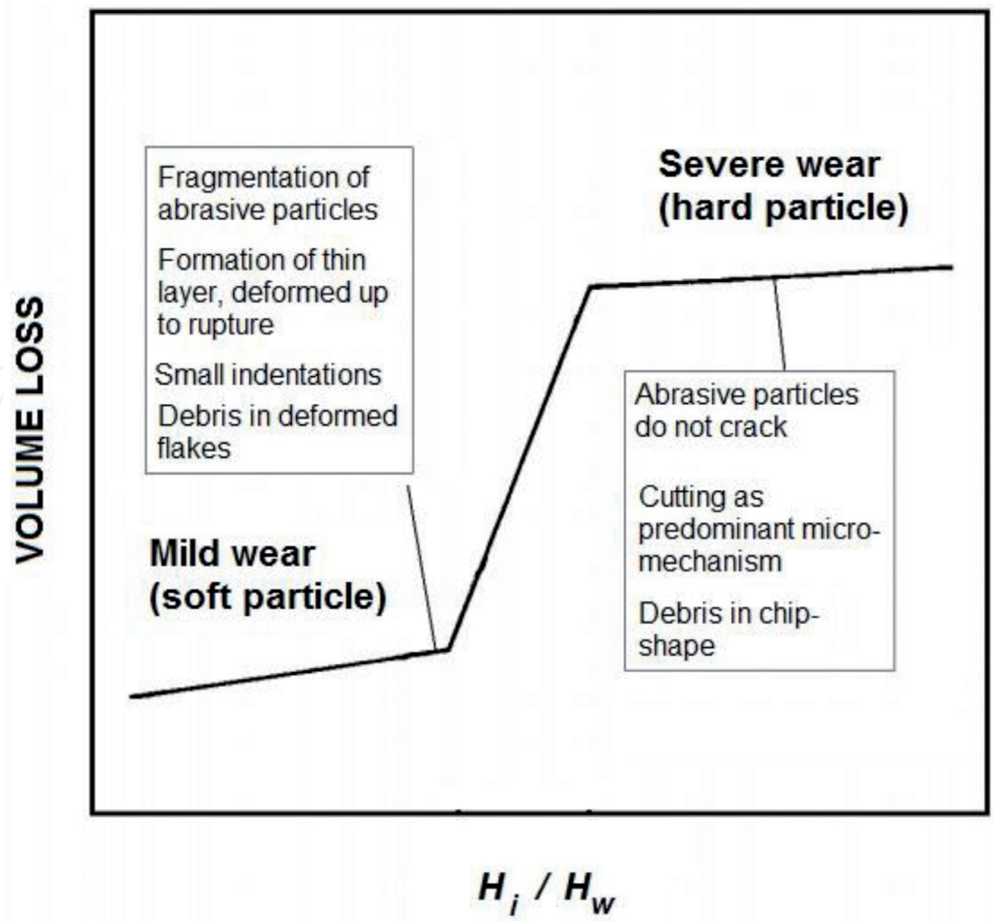

Figure 2.
Summary of wear mechanisms and surface damages on surfaces associated with each wear regime of abrasion, separated by the hardness ratio Hi/Hw, *following [4].*

2. Scratchability of materials: looking for an indicator of hardness differential

In his historical overview of indentation hardness, Walley [18] described the Mohs scale of hardness as the first to define hardness. Other researchers also published the idea of mutual scratchability. For instance, Shires [19] reported that the development of the sclerometry technique began in 1886 for defining scratch hardness. Regarding the Mohs scale, Petrescu [20] pointed out that a question arises if the standard minerals represent an arbitrary selection of increasing hardness substances or obeying a mathematical rule. Based on a series of experimental and independent data, this author concluded that a hypothetical mathematical relationship would need better experimental support. The possibility of a mathematical law would be very relevant to defining a critical value of hardness ratio for defining mild–severe wear transition, as observed by Tabor [15]. For this purpose, some investigations will be discussed based on the indentation hardness of Mohs minerals.

Masuda et al. [21] determined the Meyer hardness for nine minerals of the Mohs scale. The hardness ratio for each pair of minerals up to corundum (mineral number 9) can be calculated, besides data presented elsewhere [14], which was s determined by Broz et al. [22]. This summary is presented in **Figure 3**.

The similarity of values between the two investigations observed in **Figure 3** could be discussed in their crystallographic orientations. However, Masuda et al. [21] were unable to describe the crystallographic orientation of 7 tested minerals. Based on this fact, the similarity of values can be considered surprisingly high, except for pairs 2 and 4.

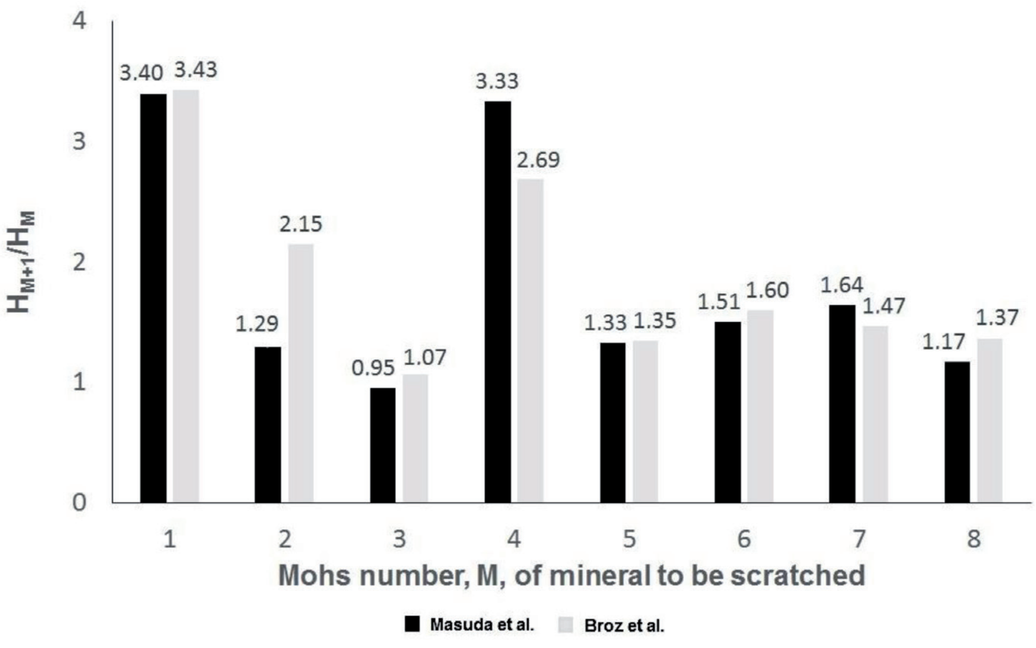

Figure 3.
Hardness ratios for Mohs mineral pairs as measured by Masuda et al. [21] and Broz et al. [22]. Both references used depth-sensing techniques.

Pintaude [17] concluded that any constant value could be defined as the hardness differential required to produce scratches. Therefore, using minerals of the Mohs scale to find a critical value during scratch should be definitively abandoned. Also, using a scratch device to investigate the abrasive wear transition becomes impossible using only common indenters, such as diamond and hardmetal. These hard materials put the scratch process only in severe wear mode. Then, the question is: how do we manufacture relatively soft indenters?

Indentation experiments using varied metallic materials can be easily found [23–25], but soft and sharp non-metallic indenters are much rarer in the literature. In this fashion, the experiments conducted by Engelder and Scholz [26] and their results deserve special attention. These researchers prepared scratch tips with 0.3 mm of curvature made of apatite, orthoclase, quartz, topaz, and corundum. Controlling the normal load, they measured the tangential force during the scratching on different polished surfaces of quartz, microcline, and fused silica. Unfortunately, they did not report the indentation hardness of all minerals but described them in the Mohs scale. We can consider Vickers hardness's data reported by Broz et al. [22] for topaz, quartz, and orthoclase, and considering the value of 7.3 GPa for fused silica presented in [27]. The relative hardness of scratch tips to fused silica is included in **Figure 4** for clarification. (2.4; 1.7; and 0.9).

The variation of friction coefficient with the normal load obtained by Engelder and Scholz [26] is very intriguing. These authors noted a transition from the deformation to the fracture mode of scratch as the load was increased. Under low loads, friction behavior tends to be similar, independent of the relative hardness of the pair. On the other hand, when the fracture is a predominant mechanism, the relative hardness is essential, being the friction coefficient more significant for high values of relative hardness, which was expected.

Two speculations can be made from the above-described results. First, the scratch capacity of tested fused silica is only associated with the fracture behavior, a point of view supported by Akono et al. [28]. For these authors, scratching is a fracture process for all materials. Second, when the fracture acts in favor of the scratching process, some minerals can behave like metals, as described by Tabor [15].

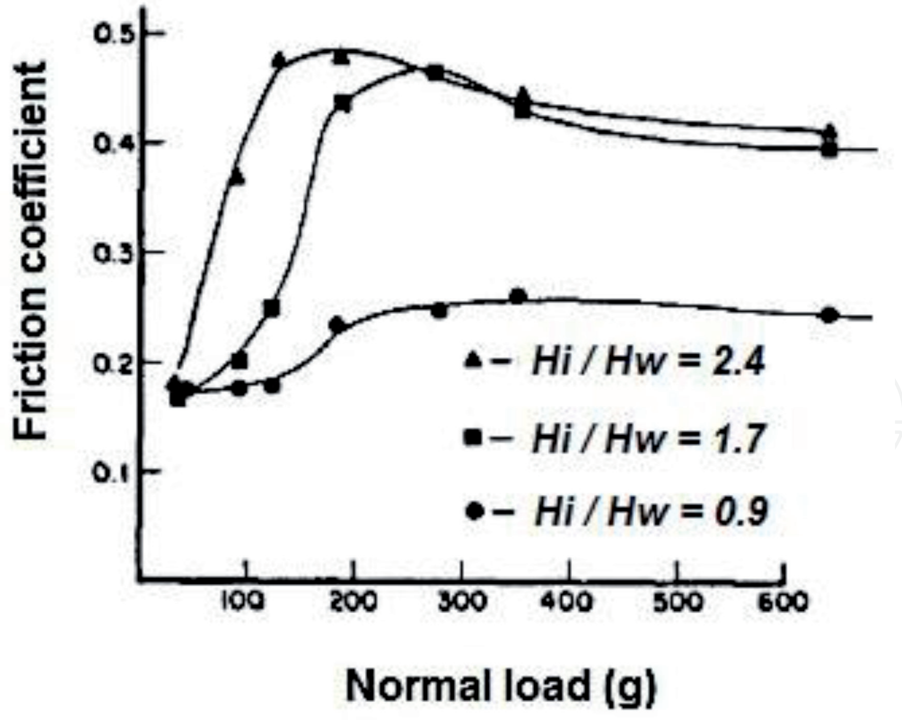

Figure 4.
Friction coefficient as a function of normal load during sliding on fused silica by three minerals [26].

It is worthwhile in **Figure 4** the similar behavior between topaz and quartz scratching fused silica, i.e., for *Hi/Hw* of 1.7 and 2.4, the friction behavior was the same. In contrast, when a hardness ratio is smaller than 1, the friction value is much smaller than those obtained with other pairs. It opens the possibility to extend the range of tested materials by [26] to verify a transition on scratchability.

3. Particle fragmentation and size effects

An experimental observation during mild abrasion, related by Pintaude et al. [29], is the fragmentation of abrasive particles. The cracking of particles is a combination of fracture toughness and the level of stress imposed by the contact. A consequence is the particle size reduction during the wear process. Smaller particles cause less wear, being the particle size effect a well-known phenomenon in abrasive wear [30–40]. Therefore, the fragmentation of particles and size effects are characteristics of events during mild abrasion.

A question arises from this issue: if the wear rate changes for smaller particles, would there be a suitable hardness to express the worn surface? The answer is not simple once the size effect is present in the indentation event, called the indentation size effect (ISE) [41–47]. For example, Pintaude et al. [48] showed that the indentation size observed in steel could change the $(Hi/Hw)_{CRIT}$ value.

Pintaude [49] proposed a route (**Figure 5**) to define an adequate hardness measurement for the wearing event, defined by determining the abraded surface's *Rz* parameter. The results described in [49] were associated with the active force made by a single abrasive particle during the abrasion process. Applying the methodology described in **Figure 5**, maximum force values are obtained (**Table 2**), which correspond to the forces applied by abrasive particles. This equivalency is checked by looking at the resulted values from the model formulated by Bulsara et al. [50], which matched with those reported in **Table 2**.

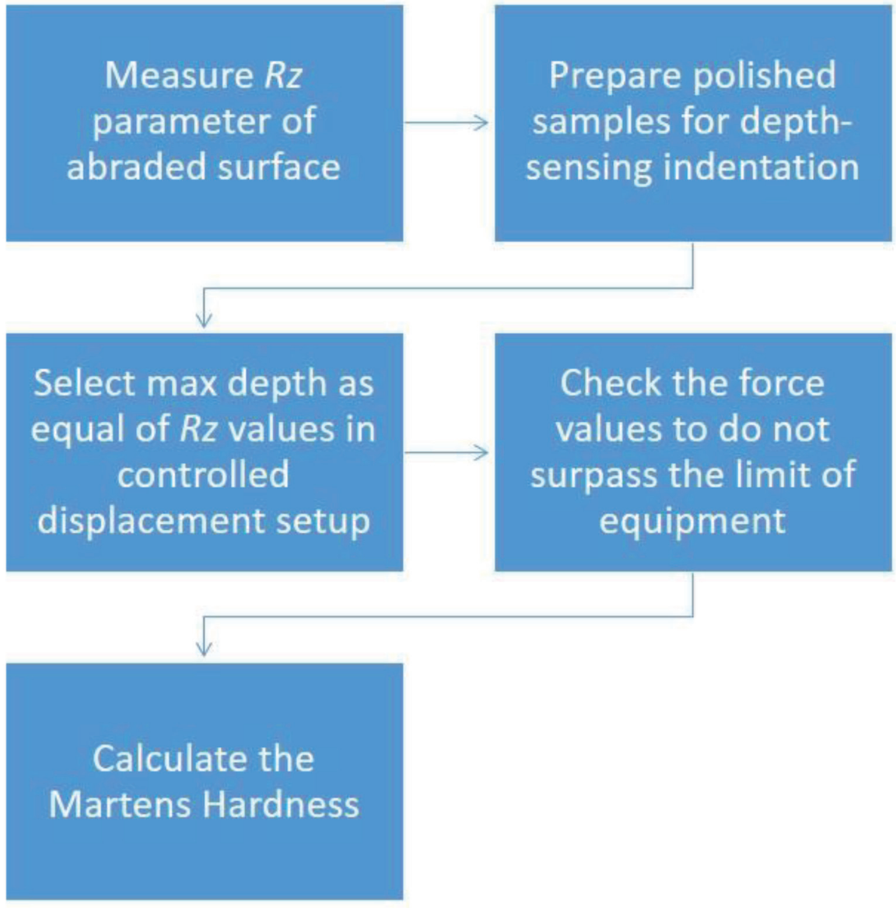

Figure 5.
Flowchart for determining a suitable hardness based on the characteristic left by an abrasion event.

Material	*Rz* produced by 0.06-mm particle	Rz produced by 0.2-mm particle	Max force (N) resulted
52100 steel	1.4 ± 0.2	2.9 ± 0.5	0.743 ± 0.006
HCCI	0.34 ± 0.03	1.7 ± 0.5	0.25 ± 0.02

Table 2.
Rz *parameter (μm) of abraded surfaces, after tests using glass coated paper and the resulting forces (N) from the displacement control indentation (following* ***Figure 5****).*

The Rz parameter can be roughly associated with the depth of penetration caused by an individual particle. This depth results from the combination between the applied normal load and the abrasive size [51].

A suitable coincidence between tested materials (high-chromium cast iron (HCCI) and the wiredrawing 52100 steel) presented in **Table 2** is that both have the same micro-hardness value, considering only their metallic matrices. Thus, the superior wear resistance of HCCI can be explained by a good action of its second hard phase [4]. When a glass paper with 0.2 mm particle size abraded these materials, the wear resistance of HCCI was approximately 30 times larger than that observed for 52100 steel. The hardness of HCCI promoted a reduction of 70% in the *Rz* parameter, considering particles of 0.2 mm. A much more dramatic decrease is noted in tests performed with abrasives of 0.06 mm, approximately four times. One can conclude that penetration depth was much more reduced in tests performed with smaller particle sizes.

The wear transition in abrasion is directly related to the capacity of particles to scratch the surfaces. For the same *Hi/Hw* ratio, scratch capacity is altered by the particle size or applied load if any of these variables are diminished. Consequently, abrasive wear is subject to the size effect, and the best scale of hardness to express the wear behavior is that in its equivalent scale, evaluating by wear depth or wear width.

The initial question at the beginning of this section can also be discussed in the light of Graça et al. [52] findings. These researchers promoted nanoabrasive wear of Ni, Ni-85%Co, and Co using a diamond tip mounted in an atomic force microscope in nanoscale. The wear behavior was better related to their nanohardness and not to their conventional microhardness. On another extreme scale, the findings reported by Bryggman et al. [53] may be included here. Performing field tests measuring the wear of excavator bucket teeth, these authors concluded that the bulk hardness (HV300) was the best indicator of wear resistance.

Considering now the scratching test, the necessity to investigate a relationship between wear and hardness, both affected by size effects, the findings of Kareer et al. [54] bring a new concept. This investigation demonstrated a lateral size effect (LSE), which remains open to the use of hardness as an indicator of wear performance. These researchers performed scratch tests with the Berkovich indenter aligned either edge forward or face forward to the scratch direction. The scratch hardness was highly dependent on the tip orientation, resulting in a size effect much higher than that observed for the indentation hardness. This phenomenon should be more explored in the future for adjusting the scale for relating hardness and wear.

The discussion made in this section can be completed by analyzing the severity levels caused by abrasion in terms of hardness or size variations observed in abrasive particles.

4. Description of abrasion severity

The wear coefficient (K) concept can be associated with system variables not explicit in Archard's equation (applied load, sliding distance, and hardness of worn material). Zum-Gahr [55] described for dry systems possible ranges of K values for two- (10^{-1}–10^{-4}) and three-body abrasion (10^{-2}–10^{-5}). Indeed, the hardness and size of abrasive particles significantly affect these values, independent of the system configuration.

The first values of K to be considered in this discussion is reported by Pintaude et al. [4]. For the hardest tested material studied by these researchers (706 HV), under mild condition - $(Hi/Hw)_{CRIT} < 1.2$ – the wear coefficient found was 4.5×10^{-5}. Severe wear begging at approximately K = 1.5×10^{-2}.

A vast variation in particle size was studied by Sasada et al. [56]. These authors measured the wear caused by SiC particles range from 3 up to 150 μm under three-body configuration, constantly testing similar body and counter-body material. They described three wear regimes as a function of SiC particle size, as shown in **Figure 6** for commercially pure iron as wear bodies.

Looking at **Figure 6**, a wear coefficient of 1.5×10^{-2} was determined for minor sizes. It is the same value reported for severe wear following the results of ref. [4]. On the opposite, Sasada et al. [56] claimed that the wear mechanism is adhesive wear because the particle sizes ($< d_t$) are smaller than the debris dimensions. In those cases, particles could not impede the metallic transfer, resulting in an adhesion mechanism. When this mechanism became operational, minimum wear was reached, meaning a K ~ 2.5×10^{-5}, equivalent to a mild regime.

Therefore, both the hardness and size of abrasive particles can change the wear regime. However, when the investigation of Sasada et al. [56] was published, wear results determined under microscale abrasion test were very incipient [57]. Typical sizes used in microscale fall within the small range of values used in [56], then the comparison between their wear coefficient values seems to be a helpful exercise.

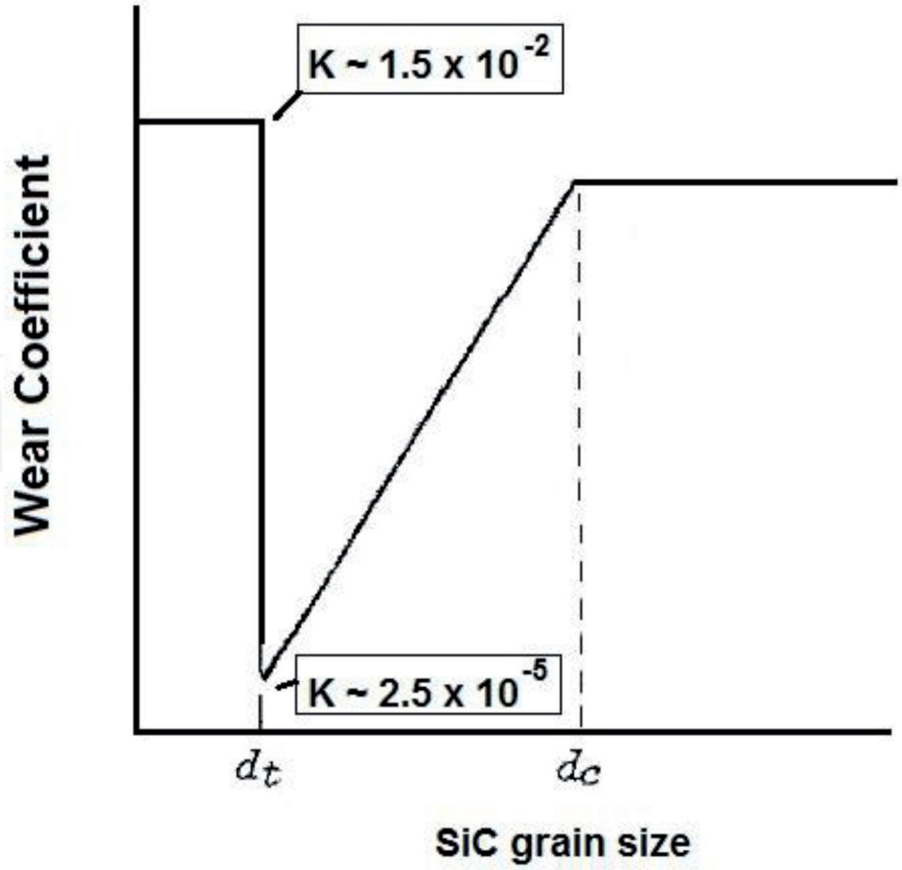

Figure 6.
Variation of wear coefficient as a function of SiC grain size, based on reference [56].

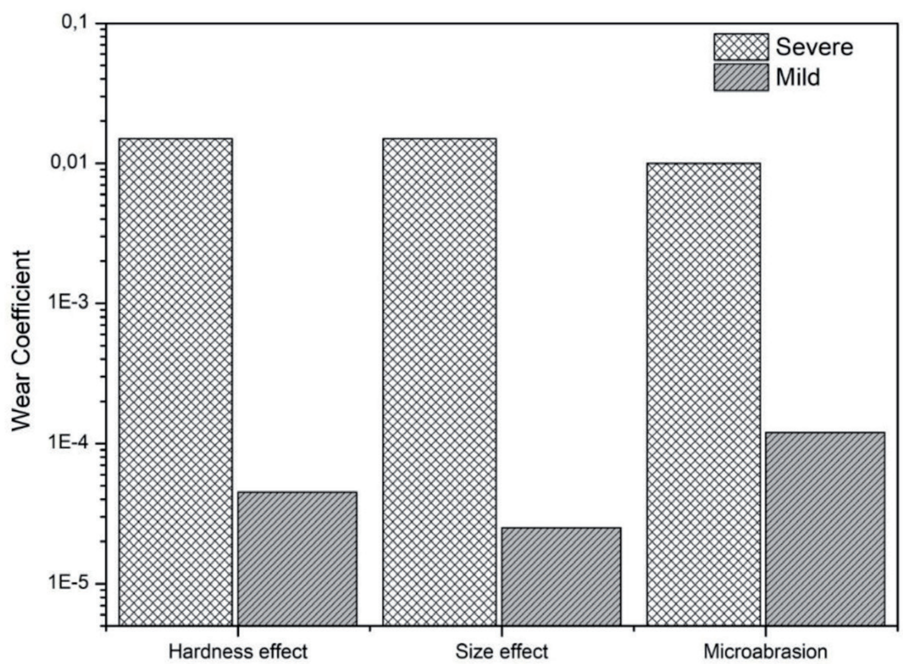

Figure 7.
Summary of wear coefficient limits, considering the effects of particle hardness [4], particle size [56], and microscale abrasion test [58, 59].

Here two investigations [58, 59] conducted under microscale abrasion deserve attention. They are interesting because the abrasive particles and micro-constituents of worn material had very different hardness.

Badisch and Mitterer [58] used three abrasive materials (SiC, alumina, and zirconia), 4–5 μm average size, using 0.3 N load. Testing three steels, they found two levels of wear, which can express by K = 10^{-2} for the high-wear, and K = $3x10^{-3}$ for low-level. Colaço [59] used alumina or silica particles against six hardfacing alloys under 0.8 N load. Values of $2.5x10^{-3}$ and $1.2x10^{-4}$ of wear coefficient can be reported taking the extremum values determined in his investigation. The order of magnitude using alumina is similar to that determined by [58]. Therefore, it is possible to consider limit values obtained with SiC (high-level of severity) and silica (low-level of severity).

Summarizing all described results, **Figure 7** shows the effects caused by particle hardness, particle size, and those verified using microscale abrasion test on the wear coefficients. The range of values determined using microabrasion is not entirely understood yet, taking the restricted and minor sizes used in this system.

The dynamics of a relatively soft and small abrasive should be better understood under the microscale abrasion test. It seems to be the challenge opened by Esteves et al. [60], who studied many combinations between load conditions, concentrations of the abrasive slurry, and hardness ratios of the sample and ball. A future model should consider the number of active particles and the effective force on each grain.

5. Conclusions

In this review, some aspects regarding the critical hardness ratio used to define the mild–severe wear transition in abrasion were presented. Based on the approaches described during the article, the following conclusions can be forward:

1. Scratchability of materials can be helpful to investigate the transition of soft-to-hard abrasion. In this sense, an extension of the results produced by Engelder and Scholz [26] is very promising;

2. The critical hardness ratio is a value influenced by size effects. For choosing a suitable scale of hardness, a route has been proposed, based on the features left by the abrasion process; and

3. Although the particle size effect can change the abrasion severity, wear coefficient values obtained under the microscale abrasion test deserve better comprehension.

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Nomenclature

Hi	indenter hardness
$(Hi/Hw)_{CRIT}$	critical hardness ratio
Hw	worn material hardness
HCCI	high-chromium cast iron
ISE	indentation size effect
K	wear coefficient
LSE	lateral size effect
Rz	average maximum height of the profile

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