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REVIEW

Metallurgical aspects of steels designed to resist abrasion, and impact-abrasion wear

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ABSTRACT
Many abrasion resistant steels rely on a martensitic microstructure to ensure hardness, which in general correlates with better wear performance. However, in practice the steel may be subjected to a complex combination of conditions where hardness alone may not be sufficient to ensure tribological performance. This review is a critical assessment of the mechanical and metallurgical parameters that control wear resistance of steel in impact-abrasion conditions, although relevant work dealing with abrasion has also been included. It is found, for example, that fracture toughness and work-hardening behaviour have a role in enhancing the wear resistance of hard steels.

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Introduction

Wear and tear are familiar to most people in their everyday lives. A study as long ago as 1803 dealt with wear of gold coins to understand whether the softness of the coins determines their susceptibility to friction during economic transactions [1]. In 1833, a simple experiment established that hard metals have less friction and hence wear [2]. In the same study, it was stated that steel has a remarkable capacity to harden, and hence should 'render it preferable to outperform every other substance yet discovered in reducing the friction of delicate instruments'. It was well-recognised even in those days that wear involves contact between at least two substances, so the behaviour of steel rubbing against ice would be different from when it abrades against brass. In other words, wear is not an intrinsic material property, and the environment in which it occurs must also play a role [3,4]. Based on the damage mechanism, wear can be classified broadly into (1) adhesive; (2) abrasive; and (3) other forms which include erosion, fretting, fatigue and corrosion [5].

Abrasion is common in the mining, lifting and excavation industries where it contributes to about 60% of total wear losses [6,7]. In these industries, steels are used extensively to resist wear because of their availability, ease of manufacture and phase transformations that can be exploited to control mechanical properties and microstructure. Given that the applications expose the steel to impact by abrading particles, the wear process is better described as impact-abrasion, which is the main topic of this review.

Abrasion and impact-abrasion

Abrasion involves the removal of material from a solid object when loaded against hard particles which have equal or greater hardness [8]. These particles may originate externally or from debris created by fracture of asperities. Examples of systems subjected to abrasive wear include chutes, hydraulic systems with dirt, extruders and rock crushers [9].

Based on the type of contact with hard particles, the wear process can be categorised into two-body or three-body abrasion. In the former case, the hard particles remain rigid while in three-body abrasion they move during the wear process. Polishing a metallic sample on paper impregnated with hard particles (sand paper) is an example of the two-body mechanism, while polishing the metal using a hard particle suspension on polishing cloth is an example of three-body abrasion.

It was found that the wear rates are an order of magnitude less in three-body as opposed to two-body abrasion, because the abrasive particles spend about 90% of the time rolling on the contact surface without causing much damage and only 10% time in abrading the surface [10].

Shear stresses at the surface for sliding and rolling contact must naturally differ, as shown in Figure 1. Two-body abrasion is similar to sliding contact, whereas three-body abrasion involves a certain amount of rolling contact as well [11]. Therefore, significantly different wear mechanisms apply in these two modes of wear.

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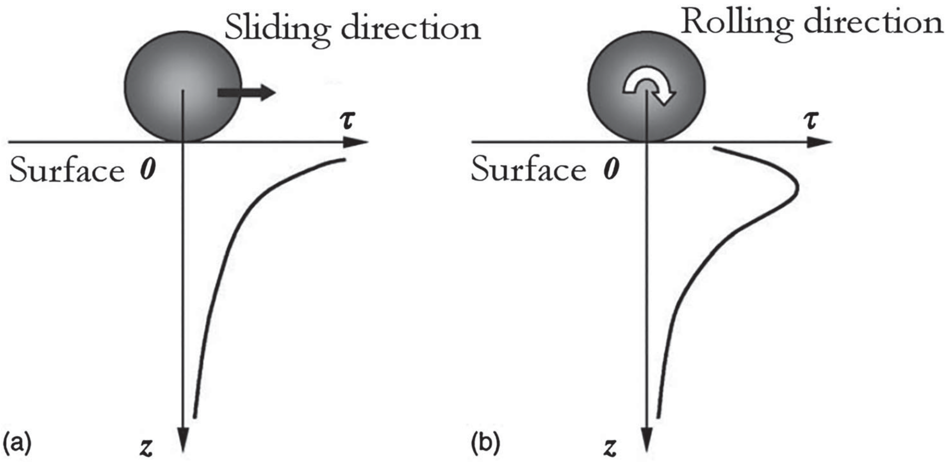


Figure 1. Schematic of the shear stress (τ) as a function of depth below the free surface, (a) for sliding, (b) for rolling particles [15], reproduced with permission of Elsevier.

Impact by abrasives occurs in addition to abrasion in lifting and excavation activities common in the mining industries, for example during the loading/unloading buckets, conveyors, crushers and dump-truck liners [12]. Wear and material loss due to repetitive collision with abrasives are called impact-abrasion. Under repeated impact, macroscopic spalling and fine-scale surface loss mechanisms occur and the damage can interact with abrasion wear [13]. Impact energy as small as 1 J can enhance wear loss in cast irons [14].

A great deal of research has been done on abrasion of metals including steels, important work on experiments, modelling and field tests can be found here [2–5,7,11,17–29]. However, it has recently been identified that impact-abrasion is a real problem in equipment used in mining, lifting and excavation industries, and it needs to be addressed. The work so far has been devoted mainly on developing and designing of test methods, testing of steels under such conditions, and ranking the steels based on their mechanical properties, mainly hardness [12,30–34]. There is some work on understanding the role of various metallurgical and microstructural aspects influencing the impact-abrasion wear of steel [12,13,35–40]. Before, assessing the published literature on impact-abrasion, it is important to compare and contrast the damage mechanism involved in abrasion, and impact-abrasion.

Material removal in abrasion mainly through ploughing, cutting, and wedge formation depending on loading, and abrasive properties [11,41–43]. Cutting leads to removal of material, while wedge formation and ploughing lead to displacement of material due to plastic deformation. Wear in the later case occurs through a mechanism of delamination [44]. In impact-abrasion, in contrast, abrasive particles impact wear component at different angles from 0 to 90° and also at varying velocities. Near 0°, the damage is abrasive, involving cutting, wedge formation and ploughing as mentioned above. At other angles of impact, the material is displaced or removed from the site of the impact depending on the impact energy, and also impact craters are developed. When the impact occurs approximately normal to the surface, the displaced material from the crater is distributed as a lip around the crater, although some material may also be ejected from the sample depending on the energy of the impact. Therefore, impact-abrasion includes chipping and fragmentation besides abrasion damage modes [13].

Figure 2 shows major difference below the abrading surface of abrasion, and impact-abrasion. Cross-sectional microstructure of abrading surface under impact-abrasion produced a severely deformed subsurface. The surface of abrasion wear do not show mixing or craters as in case of impact-abrasion. Heavily deformed material with the presence of embedded abrasive particles can be noticed in 2(b) [45].

In some applications, abrasion wear resistance may be improved by increasing hardness but to address impact-abrasion, other mechanical properties need to be improved. For example, material tested under only abrasion conditions usually has a strong correlation with hardness, i.e. decrease in wear loss with the increase in bulk hardness of the material [32,46]. However, with impact-abrasion wear the loss data exhibit scatter [47,48] as shown in Figure 3, and it is possible that the loss increases with hardness [48].

Mechanical property-wear relationships

Hardness

Considerable research, as well as field tests, indicate that both abrasion and impact-abrasion wear-rates correlate linearly with hardness [12,48–50]. Indeed, commercial steels mostly are developed assuming that wear resistance increases with bulk hardness, Figure 4. However, this may not be the full explanation and it would

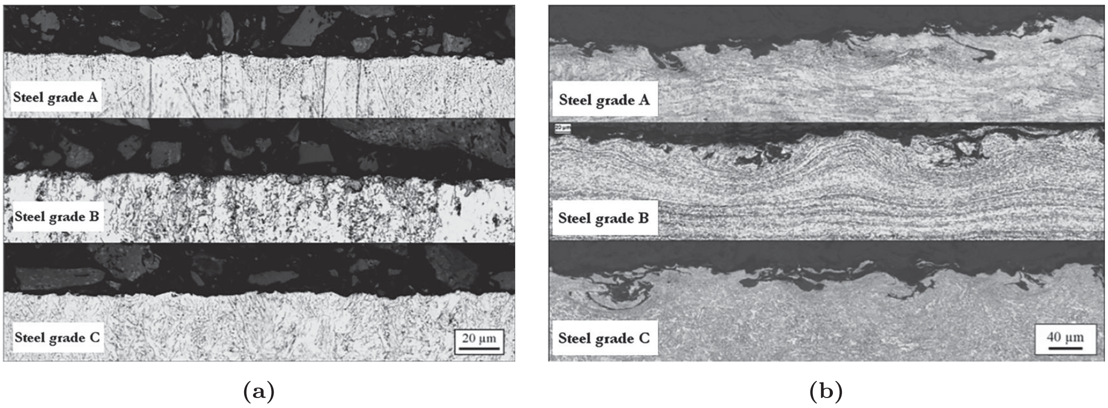


Figure 2. Microstructure of worn subsurface of the steel grades investigated in (a) two-body abrasion, and (b) impact-abrasion. Steel A containing 0.03 wt-% C with 190 VHN, steel B containing 0.17 wt-% C with 320 VHN, and steel C containing 0.19 wt-% C with 390 VHN [45]. Produced with permission of Elsevier.

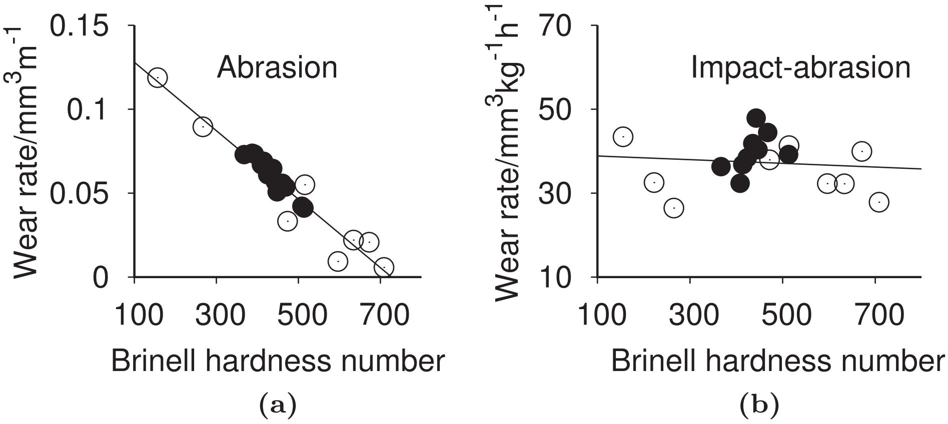


Figure 3. Wear rate as a function of Brinell hardness in (a) three-body abrasion wear test with silica particle of size 200–300 mm, and (b) impact-abrasion in Impeller-in-drum laboratory wear test with high silica quartz particles of size 19–25 mm. Linear relationship between hardness wear rate can be noticed in abrasion, while there is no such correlation in impact-abrasion [16]. Filled circles represent commercial wear resistance steel, while open circles represent generic steels like AISI 1040. Reproduced with permission of Elsevier.

be interesting to examine the roles of other mechanical properties, microstructure and the steel composition in determining wear resistance. These relationships may lead to a better insight into the mechanisms involved, and hence the possibility of better steel design [51].

An exaggerated example illustrates the possible role of factors other than hardness – field test data for wear resistance steel tools used in ceramic industry show huge scatter when plotted against hardness, Figure 5 [52]. Similarly, during wet abrasion, Figure 6 [53,54] the dependence of wear on hardness is certainly not linear.

Further, based on laboratory abrasion experiments, Moore [55] proposed that the wear resistance and hardness change with square root of the carbon content in martensitic steels. However, Rosenburg's [56] results (Figure 7) of wear loss of various martensitic steels in sand blast test do not confirm to the equation proposed by Moore. The rate of decrease in wear loss up to 0.4 wt-% of C is very prominent. Further increase in carbon does not shown significant decrease in wear loss.

The wear loss data do not show a linear relationship may be due to possible impact loads in the application of the tools. Further, wear rate changes considerably with change in surface hardness. An increase in wear resistance takes place only if a sufficient depth of hardening to resist cracking [57]. The ratio of surface hardness (H_s) of the wear material to the hardness of the abrasive (H_a) is a rate controlling parameter in abrasive wear. According to Tabor, surface is scratched by an abrasive only when $H_a \geq 1.2 * H_s$ [58].

The change in wear rate due to the ratio results from a change in the nature of the contact mechanics. At H_s/H_a ratios between 0.6 and 0.8, the fracture mode is dominated by micro-ploughing or cutting due to plastic deformation, while at higher $H_s\ /H_a$ ratios, the material is removed by fragmentation [59]. However, the increase in surface hardness will increase wear resistance only if the material retains its toughness in the deformed layer [60].

The wear of hard steel subjected to a complex wear environment which involves impact or gouging, correlates badly with hardness [16,49,62]. Rendón et al.

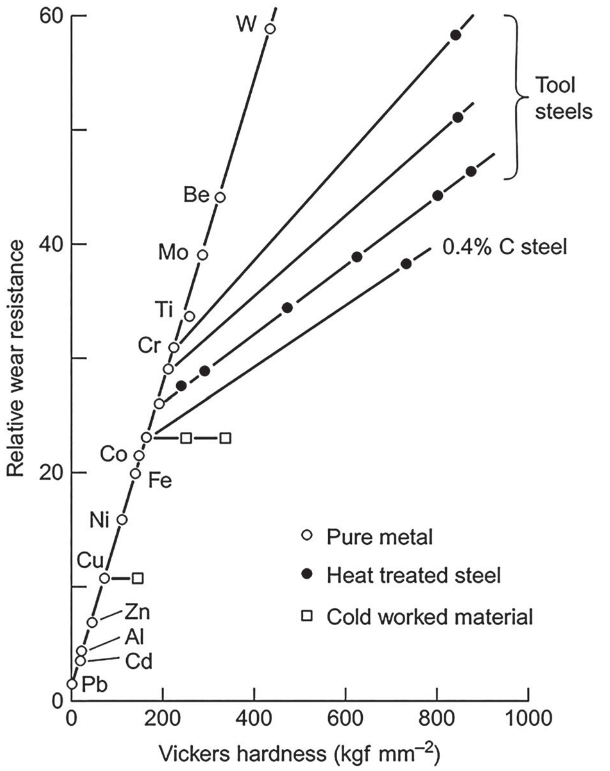


Figure 4. Illustration of abrasive wear resistance of different materials measured in the pin abrasion test as a function of their bulk hardness [49,61], reproduced with permission of Elsevier.

tested commercially available steels under purely abrasion and impact-abrasion conditions. Pure abrasion results were found to have strong dependence on hardness, while wear loss in the latter case depended on hardness as well as toughness.

For instance, Miyoshi et al. [28] studies on wear loss with hardness in sand abrasion test that the wear loss decreases with increase in hardness but at decreasing rate. The decrease is small once the hardness exceeds 500 VHN which corresponds to about 0.3 wt-% C.

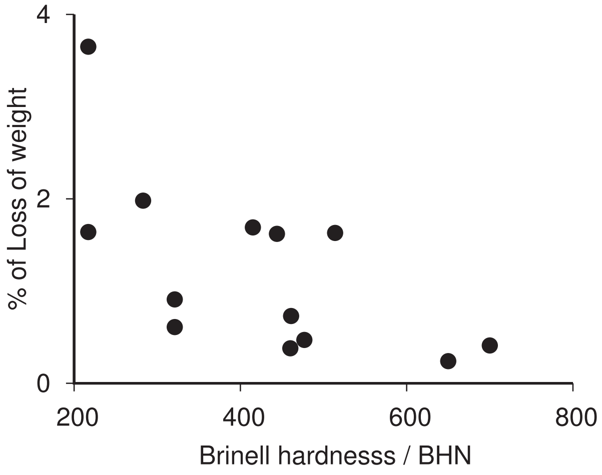


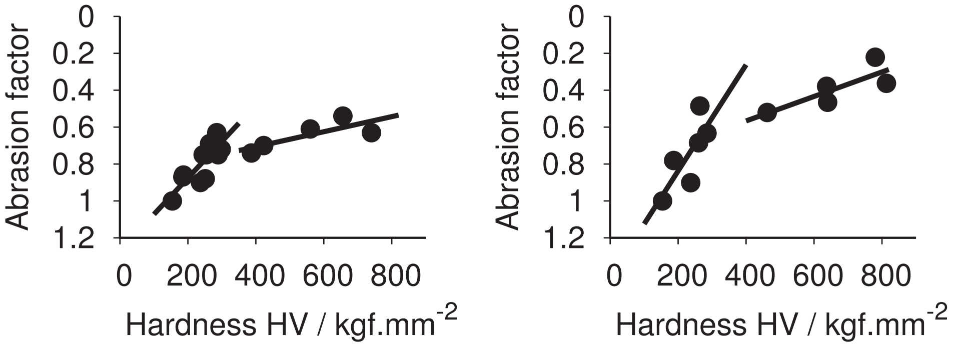
Figure 5. Data for field performance of wear resistance steel tools in ceramic industry. Data from [52].

Therefore it is evident that the hardness alone cannot increase wear resistance of steels for high impact-abrasion resistance applications which require high hardness components. Wear particles are removed by plastic deformation followed by fracture from the impact/abrading surface and hence other mechanical properties must plays a vital role in determining wear resistance of steels of high hardness.

> It is apparent from the totality of results that harder steels in general wear less, but there are diminishing returns once the hardness exceeds about 500 HV. Why is this?

Work hardening

In some interesting experiments, Richardson [29] deformed the surfaces of a variety of materials by shot peening, by wear in stony soil and by burnishing with a tool. His data are analysed here by plotting the *increment* in surface hardness due to the variety of deformations, against the initial hardness (Figure 8). It is evident in hindsight that steels that begin hard, harden less



(a) (b)

Figure 6. (a) Effect of hardness on abrasion factor in a pot with abrasive and water test, and (b) in test with water jet flow with abrasives. Data from [53,54].

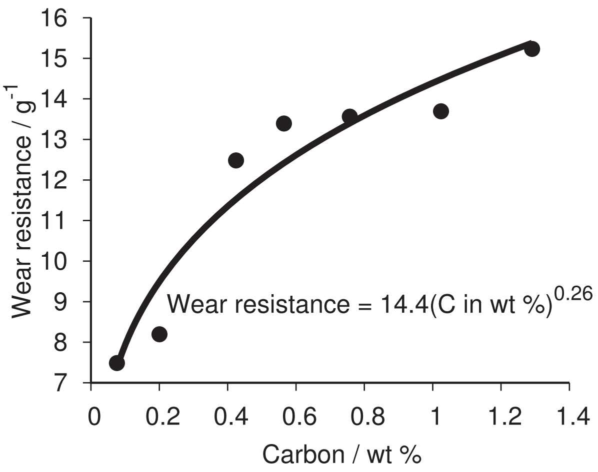


Figure 7. Effect of carbon on wear loss under sand blast test. Data from [56].

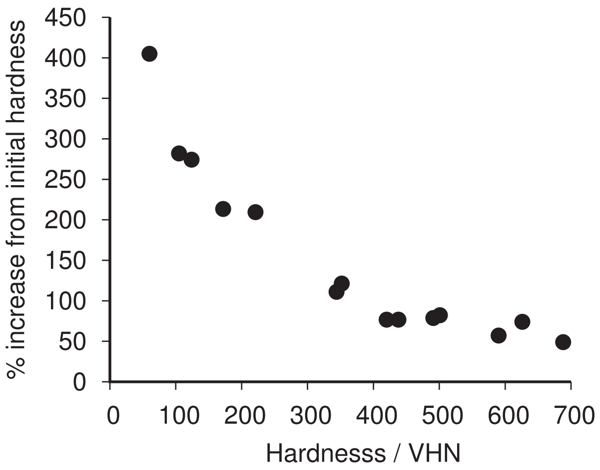


Figure 8. Maximum percentage increase in hardness against initial hardness. Data from [29].

during surface deformation, explaining why the wear rate seems to become insensitive to hardness beyond a certain point. This is consistent with independent studies, for example a recent study on high-stress abrasion, which showed that the surface hardness of steels with an initial hardness of 500–700 HV increased to a much lesser degree than when soft, zone-refined steel was deformed [60].

It is known that a strain-hardened layer increases the ability of the steel to resist further wear. It has also been reported that that wear resistance correlates better with abraded surface hardness than with the bulk hardness, especially in quenched, and tempered steels [29,63,64].

> The ability of a steel to work harden is important in enhancing the wear resistance, because it is the surface hardness that determines the interaction between the abrasive and the steel.

Table 1. Effect of cold work on abrasion. Nickel was tested under a normal load of 39.2 N on 60 grit abrasive, Data from [65]

Condition	Hardness / MPa	Wear rate / $\mathrm{m^3 m^{-1}}$	Hardness after test / MPa
Annealed	870	8.07×10^{-10}	2350
Fully cold worked	2370	8.66×10^{-10}	2370

Figure 4 may appear to show contradictory results to those discussed above. It seems that in spite of the increase in hardness due to cold working, there is no improvement in abrasive wear resistance. However, this is because the plastic strains involved in the cold-working are much smaller than those associated with abrasion [57]. Similar observations are reported for pure nickel where cold work does not have much of an influence on the wear rate (Table 1).

It is known that retained austenite does play a role in work hardening rate and it will be discussed in later section.

Fracture toughness

Fracture at various length scales is an integral part of most wear mechanisms, beginning with asperities to larger debris formation. It is obvious then that fracture toughness must, in some circumstances, play a role. As pointed out earlier, in very brittle materials such as ceramics, fracture toughness is particularly prominent in determining the wear rate [66–69].

Based on experiments on ceramics and tool steels, a generalised relation between wear resistance, hardness and fracture toughness is given in Figure 9, although it is assumed that the fracture toughness increases monotonically as the hardness decreases. The wear resistance is low either at low or high toughness, with a maximum in-between. It at first increases with fracture toughness in spite of decreasing hardness, presumably because detachment by fragmentation is reduced. Cutting or ploughing dominate at combinations where the toughness is high but the material is soft, again leading to poor wear resistance [70]. Increasing the applied load will of course lead to more rapid abrasion [71]. These trends are consistent with actual data, as illustrated in Figure 10.

Hornbogen modified Archard's model to explain the dependence of abrasive wear resistance on toughness [73]. His model postulates three regimes: I – ductile range where wear takes place by plastic deformation or subcritical crack growth as in high fracture toughness metals in their annealed conditions, II – transition range in which wear rate starts to increase when the critical strain, ϵ_c, of material becomes smaller than the applied plastic deformation ϵ_d, and III – brittle range where the ϵ_d is much larger than ϵ_c.

The wear volume per unit sliding distance ($\dot{V}$), varies with hardness in regimes I & III, but in regime II,

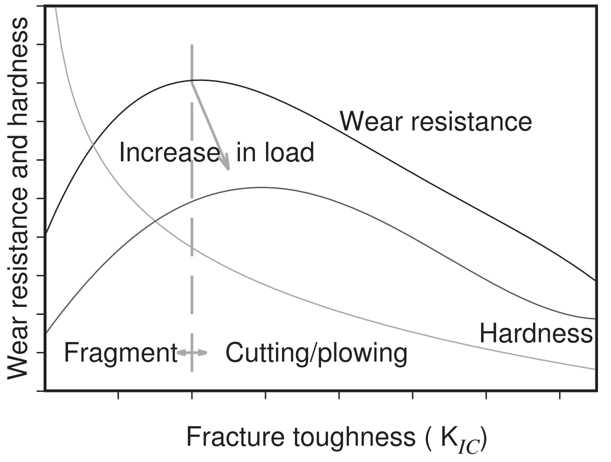


Figure 9. Relation between wear resistance, bulk hardness and fracture toughness of the wear resistance materials [57].

toughness plays a crucial role:

$$\dot{V} \propto \frac{W^{3/2} n^2 E \sigma_y}{H^{3/2} K_{IC}^2} \qquad (1)$$

where E is the Young's modulus, n is the exponent of work hardening, σ_y is yield strength, K_{IC} is the plane strain fracture toughness, W is the applied load, and H is the hardness of the abrading material.

The model assumes that crack growth determines the wear behaviour in transition range II where fracture toughness play a key role. A sharp contact between an abrasive particle and the substrate would result in an elastic-plastic indentation. Fracture then does not occur until the indentation reaches a critical length. Microcracking occurs above the critical length which increases with fracture toughness [67]. In conventional steels, toughness decreases as hardness increases. It is evident from Figure 10(a) in impact wear that the wear resistance of the pure metals increases with material hardness but it does not apply in the case of hardened steel and in Figure 10(b) increase in hardness beyond certain value decreases wear resistance.

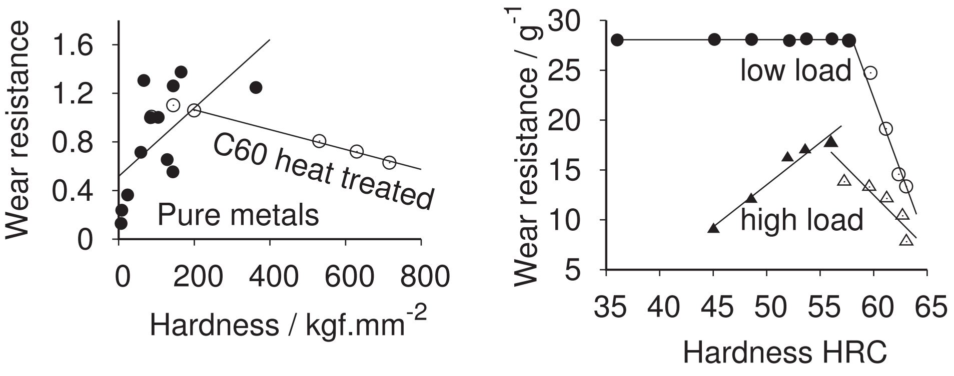
The model can explain the observations qualitatively in Figure 10. However, all mechanical properties of different material and wear data of the material are required to evaluate the model quantitatively. Further, the model was developed based on Archard's equation which was based on asperity contacts/junctions and hence further investigation is required to study if the model is valid beyond asperity length scale (order of micrometres), and also under impact loads.

> In circumstances where a steel is not too brittle, nor too tough, the wear rate varies inversely with the square of the fracture toughness.

Ductility

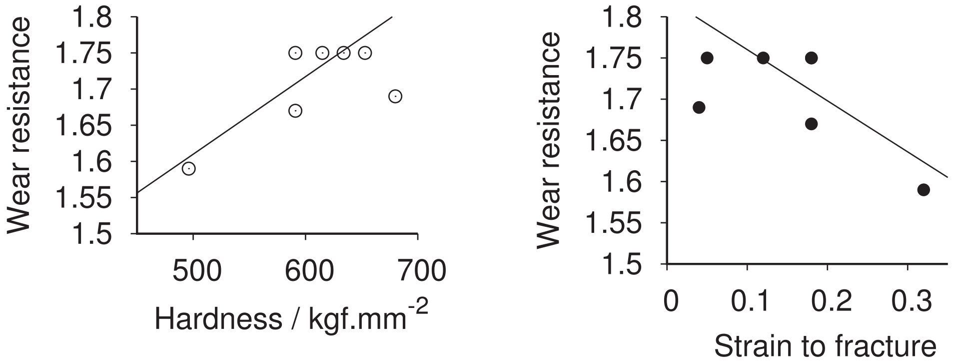
Moore et al. have shown theoretically that plastic deformation accounts for the major part of the energy absorbed in the abrasive wear of a ductile material [74]. They argued reasonably that the work of creating new surfaces during debris creation is very small and about 10^{-4} times the plastic work contribution. The definition of 'ductile' in this context must therefore mean that the steel is well above its ductile-brittle transition temperature. Another calculation based on conservation of energy reaches a similar conclusion, that some 95% of the energy during abrasive wear is consumed in structural changes and deformation at the surface [75]. Structural changes include phase transformation, for example that of retained austenite [76,77]. Uetz et al. also argued that plastic deformation consumes major amount of input energy [72].

Indeed, the correlation of wear resistance with hardness can, for a ductile material, be interpreted in terms of ductility alone, as shown in Figure 11 [78]. Rendon et al. [45] also found that the wear resistance of



(a) (b)

Figure 10. Wear resistance of (a) pure metals and of steel containing 0.6 wt-% C (C60) as a function of material hardness under impact-abrasion conditions at an impingement angle of 90°, (b) steel with its hardness under two variants of impact energy. Wear resistance in Figure 10(a) is in relation to Fe. Data from [49,72].



(a) (b)

Figure 11. Two-body wear resistance of D2 steel with its (a) hardness, and (b) strain to fracture [78]. Wear resistance is not strong function of either hardness or strain to fracture. Reproduced with permission of Elsevier.

commercial steels tested in abrasion is related to both hardness and strain to fracture.

It is difficult to identify the independent effects of hardness and ductility with the sort of correlations presented in the literature. A neural network model of the experimental data would almost certainly be more revealing.

Microstructural constituents

Conventional wear resistance steels are mainly medium carbon (about 0.2 –0.4 wt-%) martensitic in either quenched and tempered or auto-tempered condition [79]. Microstructure is one of the key factors in abrasion, and impact wear resistance of alloys as it affects how load influences the wear rate, and changes in subsurface microstructure influences wear behaviour [36,80–82], but it is difficult to assign an effect of structure that is independent of mechanical properties [83]. For instance, role of retained austenite on wear resistance is inconclusive as some reports claim improved wear resistance due to work-hardening [37,84–91], while others show harmful or no effect of retained austenite on wear resistance depending on loading conditions [34,89,92,93].

Its role is important to study because the conventional steels can contain about 10–15 % retained austenite. Further, high austenite containing Hadfield steel crusher liners show short service life when exposed to impact wear in the field of ore crushing [94].

The improvement in abrasion wear resistance is related to both the hardening effect of the retained austenite and/or the strain induced transformation of austenite into martensite. Such transformation also leads to compressive stresses at the surface which enhances the local ductility and hence permit the wear surface to achieve higher hardness [85,90].

In shot peening studies on Hadfield Mn steels, it was shown that surface hardness increased greatly due to formation of refined microstructure at subsurface [95]. In the same study it was found that three-body wear resistance of the steel after shot peening increased when subjected to soft abrasives, but failed to show any improvement when exposed to hard abrasives in two-abrasion wear due to severe plastic deformation caused during the test. It was also reported that in impact wear, material loss increases under heavy impact energy where wear is caused mainly by plastic deformation as the local ductility improvement due to transformation is small [89].

Increase in hardness not only depends on amount of austenite transformed but also work-hardening mechanism. For example, when tested under impact wear a medium manganese steel showed different hardness values, 467 and 579 HV, despite similar amount of martensite produced by two impact loads 1.5 and 3.5 J, respectively [96]. Lower impact energy causes formation of dislocations cells and fine twins, while at higher energy the density of dislocations increases steeply causing to form islands and wider twins as shown in Figure 12. The high dislocation density increases resistance to plastic deformation, while twin structure cuts the matrix and increases the strength [96,97]. Therefore, the role of retained austenite in impact-abrasion can be very complex depending on wear component and loading conditions.

However, retained austenite films are special in this context, they are known to have complex interactions with abrasives, by enhancing toughness *during deformation*, and by absorbing load prior to any transformation into martensite [77].

Carbide-free bainite and high toughness martensitic steels have relatively recently become prominent in wear investigations [98–105]. The abrasive wear resistance is very high in carbide-free bainitic steels when compared to conventional quench and tempered steels, largely due to the relatively stable retained austenite and the absence of any carbides [77,98,106,107].

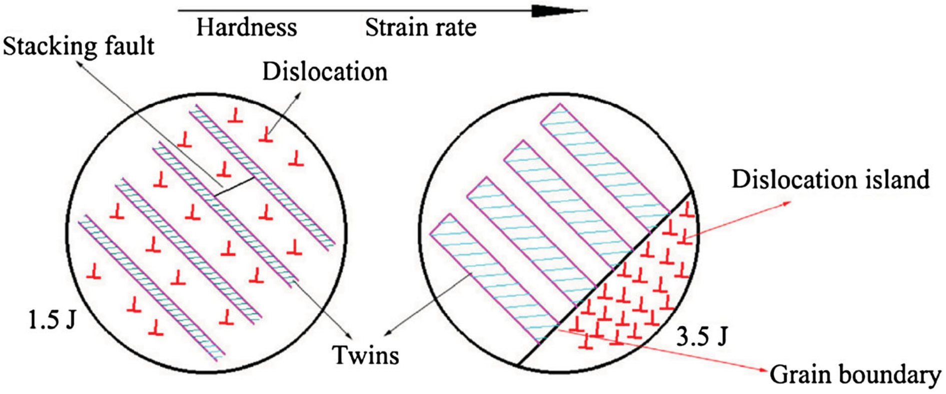


Figure 12. Schematic illustration of formation of twins and dislocation at different impact energies in impact wear [96], reproduced under the terms of the Creative Commons Attribution 4.0 International License.

The wear loss is controlled by microcutting and ploughing in these steels [106]. While in conventional steels containing carbides, it was observed that the carbides can increase hardness but enhance wear rate by causing disruption of plastic flow during particle impact. The inhomogeneous nature of the plastic flow results in very high strain gradients which can lead to void formation near to and cracking of the carbides [108]. It was also showed that large carbides can also act as abrasive and increase wear rate during abrasion [109]. Therefore, it is possible to increase the wear resistance of the commercially available steels by refining its microstructure and increasing the austenite in the film form.

Results of recent studies on wear resistance of dual phase and multiphase steels seems promising, mainly at laboratory stage [94,110]. It was showed that wear resistance of the steel increases with its ductility in these steels [110]. A review articles cites a report that developed a medium carbon two-phase microstructure steel (2 wt-% Mn and 4 wt-% Cr) for truck liner which exposes to both abrasion and impact damage [111]. These steels can be mass produced in conventional mills in hot rolled conditions. However, field testing of the steels is yet to be evaluated.

Carbide-free bainite steels may be feature wear resistance steels. However, the challenge is commercial viability of mass production of this steel.

Precipitation

Commercial wear resistance steels are produced by quenching followed by tempering. Tempering results in formation of iron carbides and/or other metallic carbides depending upon the tempering temperature and alloy composition. Usually they are tempered below 300°C to avoid temper embrittlement. Role of precipitation of iron carbides in steels on wear resistance depends on the particle size, morphology, and their hardness. Hard and randomly distributed fine carbides resist microcutting more efficiently than the large and low hardness precipitates [112].

For example, in Figure 4, precipitation strengthened alloys show no increase in wear resistance with hardness. Abrasion resistance increases if there is an increase in strength at high strains. It is possible in fine precipitation in steel on tempering at low temperature but this is not the case in at high temperature tempering [61,113]. Abrasive wear resistance of steels with carbon ranging from 0.04 to 1.23 wt-% in quenched and tempered (between 300 and 600°C) did not increase substantially. However, the wear resistance increased tremendously when tempered between 20 to 200°C [113,114].

Deng et al. [115] work on 0.32 wt-% C steel in quenched, and then tempered at different temperatures showed that wear resistance increase if the drop in hardness is compensated by improved toughness properties at low temperature tempering below 190°C. However, wear resistance dropped when both hardness and impact energy are decreased [115,116].

It was observed that the carbides in steel can increase hardness but enhance wear rate by causing disruption of plastic flow during particle impact. The inhomogeneous nature of the plastic flow results in very high strain gradients which can lead to void formation near to and cracking of the carbides [108]. It was showed that large carbides can also act as abrasive and increase wear rate during abrasion [109].

Precipitation has limited role in increasing wear resistance of commercial steels containing 0.25 to 0.4 wt-% C.

Grain size

Fine grain size of metals increase hardness at low strains but after sufficient strain the mechanical properties and energy stored during plastic deformation become similar to that of large grain material [117]. Work on brass showed that the strain levels reached at abrading surfaces are extremely high compared with those reached under conventional cold working processes [118]. Therefore, change in grain size may not improve wear resistance [119].

Experimental results of Kashcheev showed no increase in wear resistance with change in grain size [120]. He proposed that non-strengthened boundaries, and dislocations walls, as in cold worked metals, with a higher degree disorientation are not effective against abrasive wear.

However, Sundstrom et al. [12] claimed that decrease in grain size increased the wear resistance. However, when data looked carefully it seems it may be coincidence as the steels compared were of different composition and also change in grain size did not correlate to change in their hardness [12,121]. Therefore, there is no strong evidence to show that grain size effects abrasion or impact-abrasion wear resistance.

Nevertheless, grain size of prior austenite in steel has indirect effect on wear resistance. Change of prior austenite grain size from 50 to 200 μm changes hardness of quenched martensite from 390 to 280 HV in medium carbon steel [122]. Deformed hot-rolled structure exhibit severely pancaked unrecrystallised austenite grains, which contain deformation bands with increased number of defects such as sub-grain boundaries, and dislocations cells. These defects ensure a fine martensite structure, consisting of packets, blocks and laths, which are conducive to good toughness since the tendency to crack under load decreases with lath size [123,124]. It was experimentally proved that decrease in prior austenite grain size decreases the packet size and the block length of transformed and hence strength-ductility combination and toughness were significantly increased by refining packet/block size [124–127].

> Fracture toughness of commercial wear resistance steels can be improved by severe thermomechanical treatment to refine prior austenite grain size and hence increasing their performance under impact-abrasion damage.

Effect of alloying elements

Commercially available steels for wear resistance are listed in Table 2 and in [128], marketed based on their bulk hardness and carbon equivalent (an indication of weldability). These steels are either in the quenched or quenched and tempered martensitic condition with hardness in the range 300 to 550 BHN and carbon from 0.15 to 0.4 wt.%. These steels are alloyed with Mn, Mo and Cr for hardenability, Si for solid solution strengthening, and microalloying elements like Nb, V, and Ti added for austenite grain refinement during hot rolling. Their impact energy is about 20–40 J at −40°C and this is relevant for low-temperature applications.

Medium carbon steels, containing about 0.3 –0.4 wt-% are most commonly used for wear resistance applications possibly due to its weldability and ease of processing in steel plants. It is important that steels produced by thermomechanical processes without any complementary heat treatment make them more cost effective compared with quenched and tempered steels or high carbon carbide-free bainitic steels which require long heat treatment schedules [12]. However, there are no steels specifically designed commercial steels for impact-abrasion wear applications.

The narrow carbon range not only helps to have martensite start temperature about 300°C to develop a heavily dislocated lath martensite matrix with retained austenite interlath films as the second phase [111], but also possible to produce in conventional hot rolling mills. It was also suggested that microstructure with martensite and finer precipitates enhances wear resistance in steels due to quenched martensite and fine precipitates [150].

In steels, carbon is most effective in increasing hardness and hence abrasion resistance. Not surprisingly, the wear resistance of pearlitic steels increases with its carbon content [141,142]. The rate of increase of wear resistance is low in hypereutectoid steels where networks of carbides can embrittle the steels. Similarly, the wear resistance of quenched martensitic, and quenched and tempered steels also increases with increase in carbon content. The hardness of bainitic steels increases linearly with carbon by about 190 VHN per wt-% [143].

Other alloying elements, like Mn, Cr, Mo, B, etc., are added to steel to enhance hardenability so that fully a martensitic structure can be obtained on quenching from the austenite phase field to room temperature. In general the wear resistance steels are produced in thick sections and hence the addition of alloying elements are required to increase the hardenability. Though Si is a strong solid solution strengthening element, its addition is restricted to 0.5 wt-% to avoid red scale formation during hot rolling [144]. Microalloying elements, Ti, Nb, and V are added to control the austenite grain size during hot rolling.

Ojala *et al.* studied 15 commercially available abrasion steels with 400 BHN to understand the role of chemical composition on wear properties. The steels were in the quenched condition with similar amount of carbon, carbon equivalent and alloying additions. Samples were tested using a crushing pin-on-disk wear test.

Table 2. List of various commercially available abrasion wear resistance steels. Composition and CEV are given in wt-%.

Grade	CEV	C	Si	Mn	P	S	Al	Cr	Mo	B	Ni	BHN / kgf.mm^{-2}	YS / MPa	TS / MPa	EL /%	Charpay impact energy / J	Ref.
MAS500 AR	–	0.3	0.7	1.7	0.025	0.015	–	1	0.5	0.005	0.7	500	1250	1450	8	20 at −30°C	[129]
MAS450 AR	–	0.26	0.7	1.7	0.025	0.015	–	1	0.5	0.005	–	450	1200	1450	8	20 at −40°C	[129]
MAS400 AR	–	0.25	0.7	1.7	0.025	0.015	–	1.5	0.5	0.005	0.7	400	1000	1250	10	20 at −40°C	[129]
DUROSTAT 400	0.5	0.13	0.35	1.4	0.02	0.005	0.03	0.5	0.1	0.002		400	1000	1250	10		[130]
DuROSTAT 400	0.55	0.27	0.35	1.2	0.02	0.005	0.03	0.4		0.003		500	1200	1500	8		[130]
AR400		0.2	0.7	1.7	0.03	0.015	0.06	1.5	0.5	0.004	0.4	400	1000	1250	10		[131]
AR450		0.26	0.7	1.7	0.03	0.015	0.06	1	0.5	0.004	0.7	450	1200	1450	8		[131]
AR500		0.3	0.7	1.7	0.03	0.015	0.06	1	0.5	0.004	0.7	500	1250	1600	8		[131]
BISPLATE320	0.4	0.15	0.2	1.1	0.01	0.003		0.2	0.2	0.001		340	970	1070	18	60 at 20°C	[132]
BISPLATE400	0.4	0.16	0.2	1.1	0.01	0.003		0.2	0.2	0.001		400	1070	1320	14	55 at 20°C	[132]
BISPLATE500	0.61	0.29	0.3	0.3	0.015	0.003		1	25	0.001		500	1400	1640	10	35 at 20°C	[132]
BISPLATEHHA	0.61	0.32	0.35	0.4	0.025	0.005		1.2	0.3	0.002		500	1400	1640	14	20 at −20°C	[132]
DILLIDUR325 L												325					[133]
DILLIDUR400 V												400					[133]
DILLIDUR450 V												450					[133]
HARDOX450	0.47	0.21	0.7	1.6	0.025	0.01		0.5	0.25	0.004	0.25	450				40 at −40°C	[134]
HARDOX500	0.49	0.27	0.7	1.6	0.025	0.01		1	0.25	0.004	0.25	500				30 at −40°C	[134]
XAR300		0.2										300					[135]
XARHT		0.25										350					[135]
XAR400		0.15										400				40 at −40°C	[135]
XAR400W		0.25										410					[135]
XAR450		0.19										450					[135]
XAR500		0.25										500					[135]
XAR550		0.3										550					[135]
XAR600		0.35										> 550					[135]
QUARD400	0.36	0.16	0.6	1.4	0.025	0.01		0.5	0.25	0.005	0.1	400	1160	1300	10	40 at −40°C	[136]
QUARD450	0.41	0.2	0.6	1.4	0.025	0.001		0.2	0.25	0.005	0.1	450	1250	1400	10	35 at −40°C	[136]
QUARD500	0.57	0.3	0.8	1.6	0.025	0.01		1	0.5	0.005	1	500	1500	1700	8	30 at −40°C	[136]
Abrazo																	[137]
RQT																	[138]
SAILMA 450 HI		0.25	0.4	1.5	0.055	0.055	0.01						300	560	20	27 at 0°C	[139]
ABREX400	0.35	0.21	0.7	2	0.025	0.01		1.2	0.6	0.005	1	360					[140]
ABREX450	0.4	0.23	1.2	2	0.025	0.01		1.5	0.6	0.005	1	410					[140]
ABREX500	0.45	0.35	1.2	2	0.015	0.01		1.5	0.6	0.005	1	450					[140]
ABREX600	0.54	0.45	0.7	2	0.015	0.01		1.2	0.6	0.005	1	550					[140]
ABREX500LT	0.45	0.35	1.2	2	0.015	0.01		1.5	0.6	0.005	1	450				21 at −40°C	[140]
EVERHARD-C500LE	0.55	0.29	0.55	1.6	0.02	0.01		0.8	0.35	0.004		500	1203	1681	17	21 at −40°C	[138]

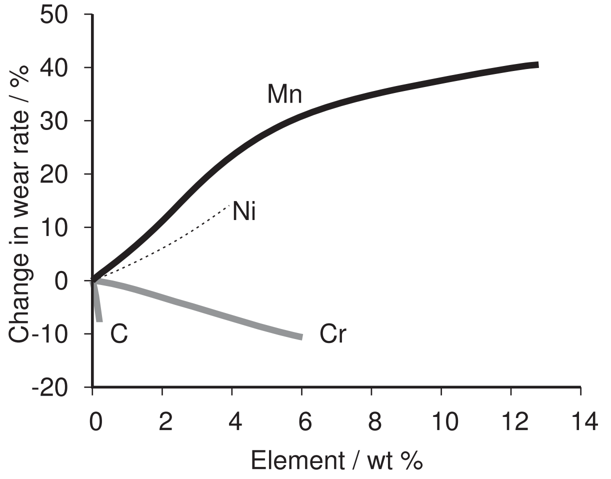


Figure 13. Effect of alloying elements on the wear rate of 1 wt-% C steel. Reproduced from [18].

It was found that steel containing high amount of boron and combined Ni and Mo contents performed better than other samples. The wear loss difference is minimum 20% to the next best sample. However, B is added in very small concentrations that are difficult to control during steel making. Ni increases ductility and toughness while Mo promotes secondary hardening during tempering [79].

Besides microalloying elements, rare earth metals addition can be added to refine the austenite grain size. Fu et al. reported that addition of rare earth metals improved impact energy and also the material performance against wear for a particular application. It was also found that the elements acted as deoxidisers and desulphurisers which results in clean steels [145]. However, rare earth metals are expensive to use on a large scale and are sparsely distributed in the world.

Bhakat et al. studied three-body abrasion resistance of steels containing different amounts of C, B, and Cr for agricultural tools and found that steel containing 0.3 wt-% C with either 0.4 wt-% Cr or 25 ppm B in quenched condition performed better than other combinations due to combination of martensite and fine carbides in the steels [146,147]. Effect of C, Cr, Ni and Mn on change in abrasion wear of line pipes by sand is shown in Figure 13. It seems that Cr is most effective element to increase wear resistance after carbon. Further, from Table 3 it is evident that addition of at least 2 to 5 wt-% Cr enhances wear resistance. Cr increases hardenability, along with carbon form a variety of carbides and it can replace part of Fe to form composite cementite to form complex carbides which play a significant role in increasing wear resistance of steel [148,149].

Previous work on developing very high wear resistance steel suggest that high strength medium carbon steels (0.3 to 0.4 wt-% C) that are alloyed with up to 2 wt-% Mn, 2 to 4 wt-% Cr and 0.5 wt-% Mo in quenched and tempered condition have high wear resistance in high stress abrasion. The steel also has high fracture toughness compared to commercially available steels and hence it is expected that this material should perform better when exposed to impact damage besides abrasion [13,111,116]. For example AISI 4340 steel with 52 HRC and fracture toughness of 49 MPa$\sqrt{m}$ showed sliding wear resistance of 3.7×10^{-6} mm^{-6} mm^{-3}, compared to 7.9×10^{-6} mm^{-6} mm^{-3} with 48 HRC and fracture toughness of 129 MPa$\sqrt{m}$ in case of the newly developed steel [116].

Table 3. Effect of Cr on sand abrasion of 0.3% C steel. Tempered martensite with 500 VHN, Data from [28]

Amount of Cr / wt-%	Wear loss / arbitrary units
0.57	0.904
2.00	0.888
5.13	0.856
13.19	0.822

Way forward

(1) It is evident that fracture toughness plays a role in high intensity impact-abrasion wear. However, careful quantification of the extent of improvement due to increased fracture toughness is still needed. Due to work of Mathew et al. [151], it is possible to produce steel that has very high toughness, 72 ± 1.5 MPa$\sqrt{m}$, and yet is hard, 561 ± 23 HV. The steel can be heated to a fully austenitic state in order to destroy the elegant thermomechanically processed microstructure that is responsible for its high toughness. After quenching, the martensite will therefore not be as refined, and hence should have a lower toughness but identical hardness. This will allow the role of fracture toughness, for example in Equation (1), to be evaluated based on wear results and mechanical properties of the steels.

(2) Similarly, role of retained austenite in carbide-free bainitic or quenched martensite steels in increasing wear resistance need to be quantified when all other parameters are remain similar. For instance, retained austenite in the steels [105,152] can be eliminated by tempering and hence its wear properties with and without retained austenite can be obtained.

(3) There is a huge amount of laboratory and field test data of wear of various steels available against many operating parameters. A neural network model of the data would assign relative importance of the parameters and steel properties which can assist in developing high wear resistance steels.

(4) From the survey of various laboratory and commercial steels steels, medium carbon steels (0.3 to 0.4 wt-% C) that are alloyed with up to 2 wt-% Mn, 2 to 4 wt-% Cr and 0.5 wt-% Mo in quenched after thermomechanical treatment and then tempered at below 200°C can achieve a

combination of high hardness and fracture toughness [18,28,111,113,115,116,123,151]. The steels can be mass produced economically and may be an alternative to many commercially available wear resistance steels to both abrasion as well as impact-abrasion damage.

Conclusions

Several factors influence wear resistance of steel under impact-abrasion conditions, including hardness which is a primary parameter. Nevertheless, the other factors such as toughness, work-hardening capacity and ductility play a role although clear evidence is needed. From the critical review of the published work, the following conclusions can be reached:

- Wear resistance of steels of hardness above 500 VHN of steels is limited by work-hardening capacity, and fracture toughness. Increasing the base hardness perhaps reduces the ability to dissipate impact energy, and the depth of deformation also decreases. An ability to spread deformation to a greater depth can increase the wear resistance at a given hardness.
- As the hardness of the base steel increases, or loading conditions change, the wear damage mechanism changes from ductile to brittle. Therefore, toughness should play a role by delaying microscopic fracture events. The fracture toughness of the steel can be increased by refining martensite and retaining some amount of austenite to enhance fracture toughness.
- There is hardly any published literature to quantify either the role of fracture toughness or work hardening rate on the wear resistance of steels when all other parameters including composition, hardness and microstructure are kept at similar level.
- It is possible that increasing hardness reduces the ability to dissipate impact energy, and the depth of deformation also decreases. An ability to spread deformation to a greater depth may increase the wear resistance at a given hardness. Retained austenite may be useful in this context. Carbide-free bainitic steels have proved to be successful due to their high work hardening rate.
- Alloying additions such as Cr, B, Mo, Ni and Cu contribute to the combination of hardness and toughness if added in right quantity. It is possible that appropriate adjustments to these or other solutes should result in commercially viable wear resistance steel.

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Disclosure statement

No potential conflict of interest was reported by the author.

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