Role of fracture toughness in impact-abrasion wear

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ABSTRACT

Two new low alloyed steels were developed with different fracture toughness values but at similar level of hardness with same composition and microstructural phase. The steels were subjected to impact-abrasion wear test. This work examines specifically the additional role of toughness during impact-abrasion wear, using a newly developed high toughness steel. Microstructural characterisation of the damaged samples revealed that better toughness helps resist both impact and abrasion damage.

1. Introduction

Impact-abrasion includes the effects of both the collision of abrasive particles with the solid surface, and scratching motions; other factors such as particle size, shape, environment and rate of impact and abrasion, together make this a complex problem [1,2]. The phenomenon itself is of considerable importance in the wear-resistant steels used in earth-moving equipment such as excavators and loaders, and machines used in mining operation. Abrasion per se correlates strongly with hardness, although it is well-established that hardness alone does not always explain the wear behaviour [3–11]. For instance, abrasive wear resistance of commercially available steels showed no correlation with their hardness [4]. Loss of material in a phenomenon such as impact abrasion is likely to have some dependence on the failure mechanism [12].

For instance, during abrasive wear, removal of material from the surface occurs when the strain there reaches a critical value. This local fracture-strain may be achieved by a single or multiple abrasive strikes at the surface. Material not removed in this way may nevertheless deform as a result of the abrasion and impact event [13]. It therefore is reasonable to expect that steels with a large fracture stress and work hardening rate should have high wear resistance. For example, it is established that in the rails, the work hardening capacity plays a key role in determining the wear rate of pearlitic steels which perform better than harder martensitic alloys [7]. Hadfield steel is good at resisting wear due to its high work hardening capacity, but when used for ore crushing, it suffers severely from impact-abrasive wear [14]. This is because wear of this kind can be dominated by microscopic cracking resulting from the combination of plasticity and impact, emphasizing the need to consider toughness as a parameter in controlling material removal. This is obvious in brittle materials such as ceramics [15–18].

The purpose of the work presented here was to examine specifically the role of toughness of a newly developed steel on impact abrasion.

2. Material and experimental details

A new low alloyed steel (Table 1) with a unique combination of properties in the hot-rolled condition, has been designed, mass produced, and tested. Usually, for a given strengthening mechanism, increase in strength comes at the cost of reduced toughness. Increasing toughness and strength in combination is therefore non-trivial and requires the introduction of specific additional toughening mechanisms. Refinement of the microstructure is the one general mechanism which is known to improve both strength and toughness. Microalloying with vanadium was identified a method for achieving refinement of the austenite grain size during processing (and therefore to reduce the maximum size of the martensite plates) [19]. Ni at low amount of Mn was added to increase toughness, and Cr and Mo were added to increase hardenability [20,21]. Si was added to avoid formation of carbide formation during cooling [22].

The steel has a hardness of 561 ± 23 HV and a tensile strength of 2.0 ± 0.01 GPa, still maintaining a fracture toughness of 72 ± 1.5 MPa·m1/2. The steel was thermomechanically processed to obtain severely pan-caked austenite and then naturally cooled in ambient conditions to room temperature to generate a martensitic microstructure. The steel has high hardenability and hence it can transform into martensite at cooling rates as low as 1 K·s⁻¹. The final thickness of the hot-rolled plates was 6 mm.

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There are a number of applications envisaged for the alloy, but of particular interest is its use in conditions where it would sustain damage from a combination of impact and abrasion. For this reason, some of the steel was heat treated such that its hardness was maintained, but the toughness was not. To do this, the steel was reaustenitised to destroy the hot-rolled microstructure followed by quenching to room temperature, in which case the hardness was measured to be 666 ± 23 HV. The steel was also tempered at 190°C for 2 h to reduce the hardness to 585 ± 5 HV in order to match that of the as-rolled steel. The hot-rolled steel was also tempered for 2 h to additionally study its wear resistance in the tempered condition. Wear results of all the four variants (hot-rolled, hot-rolled and tempered, quenched, and quench and tempered) are discussed, but the detailed characterisation is limited to the hot rolled and quenched steels. Nevertheless, the additional variants enhance the comparison of the wear rate and its dependence on hardness, as will be seen later on.

Impact-abrasion tests were carried out using an impeller-tumbler testing machine available at Tampere University, Finland. Details of the machine have been discussed elsewhere [23]. Known alternatively as a continuous impact-abrasion test [24], it has been used to test wear resistant steels destined for the mining industry [24–26]. The associated conditions are not as severe as in grinding and crushing, but are greater than those generated in the dry sand rubber wheel test. The machine consists of an impeller shaft carrying samples in a rotating drum containing abrasives. Multiple samples can be mounted at different angles relative to the sample holder tangent. The abrasive can be ore, or typically granite particles in the size range of 8–20 mm [27,28]. The size range is consistent with the simulation of wear in mining equipment [29]. The amount of abrasive can be varied, but it is usually in the range of 400–900 g [25,28].

The entire assembly is enclosed within the drum and the impeller shaft allowed to rotate in the same sense. The test sample has the dimensions 75 × 25 mm. The shaft with samples attached is rotated at 700 ± 5 rpm, while the drum is rotated in the same direction at 30 rpm. There is a simultaneous application of impact from different angles and abrasion from sliding of the particles against the sample surface. The abrasive fractures during the test so that the conditions can change with time. To avoid this, the abrasives are changed after every 15 min of testing. The procedure is repeated for a total testing time of 1 h or more, with the weight loss measured at hourly intervals. Three readings were obtained for each tested condition. The length of each profile was 10 mm with a scan time of 120 s.

SEM was carried out using FEI Nova NanoSEM, fitted with Everhart-Thornley and through-the-lens secondary electron detectors, and an in-lens type backscattered electron detector for microstructural characterisation, operated at 10–15 kV and a working distance of 4–13 mm. Phenom Pro X desktop SEM fitted with silicon drift detector was used to obtain elemental information of granite. Electron backscattered diffraction data was obtained by using FEI Quanta 3D 3D FEG-SEM with a step size of 0.4–0.5 μm and the data was analysed using Oxford Instruments AZtecHKL.

3. Results and discussion

Fig. 1 shows the hot-rolled structure exhibiting severely pancaked unrecrystallized austenite grains, which contain deformation bands. These defects ensure a fine martensite structure which is conducive to good toughness since the tendency to crack under load decreases with plate size [32]. Further, it is proven experimentally that a decrease in...
prior austenite grain size reduces the packet and block size \([33-35]\). In this condition, the steel has a hardness of \(561 \pm 23\) HV30 and a fracture toughness of \(72.0 \pm 1.5\) MPa m\(^{0.5}\).

To investigate the role of fracture toughness on impact-abrasion, a simple experiment was designed in which the hot-rolled steel was reaustenitised at 900 °C for 1 h and quenched so that the scale of the microstructure increases and the toughness decreases. The resulting microstructure is shown in Fig. 2. The austenite grain size was measured with the linear intercept method and found to be \(12.3 \pm 1.5\) μm.

The steel plate thickness of 6 mm prevents conventional fracture toughness tests. Tensile tests were therefore carried out to determine the ductility. It is evident from Fig. 3 that the quenched steel broke in a brittle manner before plastic yielding, whereas the hot-rolled steel behaved in a ductile manner. Fig. 4 shows the mixed mode tensile fracture surface of the rolled sample, consisting of ductile dimples and quasi-cleavage. In contrast, brittle cracks and cleavage facets are evident in the case of quenched samples.

The (100) pole figure of the martensite from a single parent austenite crystal for the hot-rolled, and the quenched sample is shown in Fig. 5. Each austenite grain in the hot-rolled steel is severely deformed and fragmented, gaining a large spread of misorientation in the martensite generated on cooling. In contrast, the martensite that formed in the undeformed austenite has a much smaller spread in orientations. The martensite in the hot-rolled structure expected to be much tougher, for two reasons. Firstly, the crystallographic grain size, which controls the cleavage mode of fracture \([36]\) and secondly because fine plates of martensite have a reduced tendency to crack \([32]\). Therefore, from the (100) pole figures, the tensile test results and fracture surface analysis, it can be assumed that the fracture toughness in the austenised and quenched is lower compared to the rolled steel.

In the discussion that follows, the hot-rolled steel will be referred to as “hot rolled” and the reaustenitised steel as “quenched”.

### 3.1. Wear test results

The relative wear loss data, the weight losses relative to that of a reference sample, R400 with 400 BHN, are plotted in Fig. 6 and listed in Table 3. The tests were done in conditions comparable to those of the published work \([30]\). Fig. 6 shows that the wear loss of the reference samples (R400, 450, 500) indeed correlate with hardness, but it is evident that our hot-rolled steel, which is softer than the reaustenitised and quenched version, has better wear performance, confirming that its better toughness prevails. Furthermore, at essentially the same hardness, the hot-rolled steel performs far better than steel R500 \([25]\). The relative wear loss of the rolled samples is about 17% less than that of the quenched samples. The standard deviation of the many samples tested in the impact-tumbler test evaluated to be less than 4% \([30]\), and

![Fig. 2. Martensitic microstructure of the reaustenitised and quenched steel, showing coarse and equiaxed prior austenite grains.](image)

![Fig. 3. Engineering stress - strain curves of the rolled steel, and of the reaustenitised and quenched steel. The quenched steel fractured at about 1.16 GPa with negligible plastic deformation.](image)

![Fig. 4. (a) Micrograph of a fractured rolled steel revealing ductile and quasi-cleavage features. (b) Brittle fracture of the quenched steel.](image)
it is about 2% for the reference samples in these tests. Therefore, it is evident that the wear loss in the much harder quenched samples is at least 10% higher than that of the rolled samples.

A novelty of the present work is that it reports experiments where toughness is varied greatly, while maintaining a martensitic microstructure and hardness. The martensite in the hot-rolled sample is in a greatly refined state, reflected in its high toughness and ductility. A previous study could not be conclusive because hardness, toughness, microstructure and alloy composition were not controlled to enable clear comparisons [37].

3.1.1. Surface roughness

Surface roughness of the tested samples as well as comparative data on pearlitic and bainitic steels tested in dry sand rolling/sliding wear tests are listed in Table 4. All the impact-tumbler test results shown were generated under identical conditions. Compared to pure abrasion, impact-abrasion exacerbated roughness. Pure abrasion involves material removal through microcutting and micro-fatigue, so it is not surprising that it leads to a lower roughness. Impact-abrasion, in contrast, includes chipping and fragmentation. Fig. 7 shows that the roughness does not correlate well with hardness for any of the samples. The newly developed steel shows similar roughness values, although the roughness of the rolled sample is marginally lower. To understand these observations, the worn surface was characterised using a number of techniques.

Unlike in the case of pure abrasion, the wear caused by impact-abrasion is not uniform across the sample surfaces (Fig. 8). The worn sample edge resembles the rounded tip of the cutting edges of a typical mining loader bucket [39]. Samples for the surface as well as for the...
cross sectional microstructural studies were cut as marked in Fig. 8b. Sample 'A' (10 × 10 mm) was used to characterise the surface, while sample 'B' (10 × 5 mm) was used for the cross sectional studies.

A typical surface of the tested sample is shown in Fig. 9. The back-scatter electron images reveal darker-contrast regions containing granite, which contains silicates and oxides with low atomic number elements, including Si, Al, and O, as confirmed using energy dispersive X-ray spectroscopy, Fig. 10 and Table 5. The topography of the same area as in Fig. 9a can be seen in 9b. A typical impact crater and abrasion are marked in Fig. 9b. The abraded regions are relatively bright compared to the regions of impact, and uniform in their contrast due to their small roughness. The rougher impact regions are darker and less resolved. It is noteworthy that the directions of the abrasion scratches are not constant, as would be expected from three-body or two-body abrasion wear. Some areas indicate delamination, which is one of the key damage mechanisms in sliding or abrasion wear [40].

The damage modes observed in impact-abrasion are shown in Fig. 11. The test consists of many chaotically moving granite particles impacting the test surface at different angles from 0 to 90° and also at varying velocities. Near 0°, the damage is abrasive, involving micro-cutting, wedge formation and microploughing. 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. An example is illustrated in Fig. 11a, where the impact was at an acute angle with material piling up on the sides of the crater. The crater itself contains some of the granite responsible for the damage. At the exit side of the impact, small

| Element | At. conc. | Wt. conc. |
|---------|-----------|-----------|
| O       | 0.50      | 0.33      |
| Si      | 0.26      | 0.31      |
| Al      | 0.11      | 0.12      |
| Fe      | 0.08      | 0.18      |
| Na      | 0.03      | 0.02      |
| Ca      | 0.02      | 0.03      |
| K       | 0.006     | 0.01      |
Fig. 11. Surface topography of the tested samples after 4 h of testing. The images illustrate the impact-abrasion wear in general, (a) and (b) showing craters formed by impacts, (c) and (d) cutting by the abrasives, and (e) and (f) abrasion due to moving granite particles. (a), (c) and (e) are from the quenched steel, while the rest of the images are from the hot-rolled steel.

Fig. 12. Surface topography following 4 h of testing, (a) a hot-rolled sample, (b) quenched sample.
chips of the steel can be noticed, and hence the process of such removal can be classified as microchipping.

Other impact incidents where the sharp edges of granite particles has caused the formation of a groove and lips are shown in Fig. 11c and 11d. The removal of material is similar to that of micromachining reported in the previous investigations [41]. However, in the impact shown in Fig. 11d, in which there is no debris left as in the previous impact example, the lips are severely strained. Any lips that form also act as obstacles for the abrasion by granite and hence can be removed by subsequent action. Intense shear of remaining material can occur during the removal process. A case of abrasion after an impact event is shown in Fig. 11b. There are two craters, one containing granite (on the left hand side of the image), and another without any debris.

It is possible that the embedding of hard granite particles in the steel during the process of impact abrasion actually enhances its resistance to further damage, but creating in effect a metal matrix composite. It is known that in the case of quartz particles, that their embedding leads to a better pin-on-disc wear resistance when the substrate has a hardness in the range 400–800 HV, but spalling becomes easier when the substrate is soft [42]. The steels characterised in this study fall in a fairly narrow hardness range of 525–675 HV, so the mechanism of embedded particles should be identical and therefore not affect the ranking in terms of wear loss. There is a caveat to the comparison with the quartz experiments, that the present study involves both severe impact and abrasion, so there are many cracks created in the embedded granite particles, which may render them liable to detachment. However, these phenomena warrant further studies.

Fig. 12 shows a comparison between the hot-rolled and quenched samples. Although the same mechanisms of damage are apparent in both samples, the quenched samples show much more brittle behaviour with smaller extents of microcutting regions.

### 3.2. Microscopy of sections

Dominant wear mechanisms in the cross section sample ‘B’ are shown in Fig. 13. Representative micrographs from the abrasion and impact dominant mechanisms are presented in Fig. 14. Data from about ten for the hot-rolled and about twenty for the quenched measurements are listed in Table 6. In general, the hot-rolled and quenched steels show similar abrasion resistance, although the material within the abraded regions seems to be more damaged in the latter case (Fig. 14). On the other hand, the craters in the impact zone, which represent the biggest surface of the impact-tumbler sample, are largest for the
quenched steel, and there also seem to be cracks associated with the craters in the steel. This must be a consequence of the low toughness in quenched steel compared to the hot-rolled steel, which explains why the wear rate is greater for the quenched steel even though it is much harder than the hot-rolled grade.

Further, the hot-rolled steel strain hardens during wear to a greater extent than the quenched grade (Fig. 15), presumably because of its greater ductility. It is well known that surface hardening, leads to im-

Table 6
| Sample         | Abrasion dominated region | Impact dominated region |
|----------------|--------------------------|------------------------|
| Hot-rolled steel | 5.0±1.7 μm              | 7.5±3.7 μm            |
| Quenched steel  | 6.2 ± 2.0 μm            | 15.8±5.5 μm           |

4. Conclusions

This study is the first of its kind to develop steels with two levels of toughness without changing either composition or microstructural phase, and at similar hardness level. We have demonstrated here that under the given circumstances, the steel with a better toughness out-

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wear.2019.03.028.

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