Abrasive wear of alloys for ground engaging tools

by

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Abstract

The present work investigates the wear behaviour of ground engaging tools (GET) by forensic examination of a worn digger tooth, used in an iron ore mine site. The study also evaluates potential steels using Impeller tumbler and scratch testing.

The wear performance of different steel microstructures including next generation of alloys such as carbide free fine grained bainitic and fine pearlitic steels were investigated and compared with the existing microstructures used in digger teeth. Quenched and tempered steels with martensitic microstructures are the common materials for such applications mainly due to the high hardness of the martensitic phase. However, the components need to be replaced after a short service period due to extreme wear and abrasion.

The digger tooth material subjected to failure analysis was a low alloy steel with ~0.3% carbon having a tempered martensitic microstructure. Despite the considerable hardness of the tooth material (~500 HV), the surface of the tooth suffered significant impact and grooving wear by the harder ore particles. The significant wear rate during operation was manifested by severe plastic deformation and material removal by cutting mechanism. Optical profilometry was used to scan the worn surface of the digger tooth to measure the geometry of the scratches (i.e. depth, width, and length) and correlate them to the severity of the abrasive wear. The degree of wear $f$ is plotted as a function of depth of the scratch normalised by the radius $\delta$ of the groove. As the penetration depth increases the wear mechanism changes from ploughing to cutting. Material loss was observed for grooves deeper than ~25 $\mu$m. Full cutting was observed for grooves deeper than ~100 $\mu$m. The microstructures of the worn tooth revealed a white layer followed by a softened layer, and deformed subsurface. The
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significant impacts create heating effects on the surface and subsurface of the material. This led to softening and formation of adiabatic shear bands which might have facilitated the particle penetration enhancing the wear rate. There was a common feature of the entrapment of ore particles at the surface.

Based on the literature review, several alloy microstructures were chosen for evaluation. A high carbon and silicon grade steel with three distinct microstructures: a) Carbide free bainite (571 HV) with finely distributed ferrite laths and ~20% retained austenite, b) tempered martensite with a high hardness (677 HV) and c) fine pearlite (323 HV) were used for the wear tests. A Hadfield grade steel of ~12% Mn was also examined to study the effect of workhardening. The current tooth steel (0.3% carbon, tempered martensitic microstructure, 475 HV) was used for comparison with other steels. Mild steel equivalent to AISI 1018; being a softer material (190 HV) was used for initial trials. Thus, the steels chosen covered a range of hardness and workhardening properties which provided a deeper knowledge of the wear behaviours at different wear conditions.

An Impeller tumbler wear testing machine was commissioned for the study. Material loss during Impeller tumbler testing was examined for different microstructures, using Impeller speeds of 800 RPM and 10 kg charges of 50-80 mm Basalt aggregate. The worn surfaces and microstructures shared common features with the commercial tooth. The worn surface of the Impeller tumbled samples showed white layer formation followed by a workhardened subsurface. However, the thickness of the white layer was lower compared to the white layer found on the digger tooth. Entrapment of aggregate particles was also found in the tumbled samples.

The current tooth steel provided a ~65% reduction in wear loss relative to the mild steel. Bainite exhibited further reduction in wear loss by ~40% with respect to the current tooth steel. The wear resistance of Hadfield steel was similar to
the digger tooth grade though its hardness was lower. There is clearly a benefit of workhardening capacity in the present application.

Scratch testing was conducted on the same steels in their workhardened and undeformed states. A material property parameter “scratch ductility” was introduced that characterizes wear response. It was demonstrated that the material with higher scratch ductility exhibits higher wear resistance. The scratch results ranked the materials in accordance to their hardness.

Finally, the wear performance of the steels was compared for both test methods. The results revealed that both the Impeller tumbler and scratch tests provide a similar ranking. The wear resistance correlates with hardness but this is more prominent for scratch tests than that of the tumbler tests. The lower dependence of tumbled results on hardness is attributed to the contribution of impacts during tumbling. The corresponding \( f \) plots of the unworn and worn current tooth steel were compared with the commercial worn tooth. Reasonable agreement was given the different conditions involved.
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<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>$a$</td>
<td>Groove half width</td>
</tr>
<tr>
<td>$A_1$ &amp; $A_2$</td>
<td>Ridge area</td>
</tr>
<tr>
<td>AISI</td>
<td>Australian Industrial Systems Institute</td>
</tr>
<tr>
<td>ASB</td>
<td>Adiabatic shear band</td>
</tr>
<tr>
<td>Av</td>
<td>Groove area</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer aided design</td>
</tr>
<tr>
<td>CPS</td>
<td>Critical particle size</td>
</tr>
<tr>
<td>$d$</td>
<td>Depth of penetration</td>
</tr>
<tr>
<td>DSRW</td>
<td>Dry-sand rubber wheel wear test</td>
</tr>
<tr>
<td>EBSD</td>
<td>Electron backscatter diffraction</td>
</tr>
<tr>
<td>EDX</td>
<td>Energy Dispersive X-Ray</td>
</tr>
<tr>
<td>$E_{\text{theo}}$</td>
<td>Theoretical energy</td>
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<tr>
<td>$F$</td>
<td>Normal load</td>
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<tr>
<td>$f$</td>
<td>Degree of wear</td>
</tr>
<tr>
<td>$F_B$</td>
<td>Bucket curling force</td>
</tr>
<tr>
<td>$F_s$</td>
<td>Arm crowd force</td>
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<tr>
<td>FCC</td>
<td>Face centre cube</td>
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<tr>
<td>GET</td>
<td>Ground engaging tools</td>
</tr>
<tr>
<td>$H$</td>
<td>Brinell hardness</td>
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<tr>
<td>HSLA</td>
<td>High strength low alloy steel</td>
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<tr>
<td>$K$</td>
<td>Wear coefficient</td>
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<tr>
<td>MPa</td>
<td>Mega Pascal</td>
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<tr>
<td>Symbol</td>
<td>Definition</td>
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<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of impacts</td>
</tr>
<tr>
<td>$N_{red}$</td>
<td>Reduced number of impacts</td>
</tr>
<tr>
<td>OM</td>
<td>Optical microscopy</td>
</tr>
<tr>
<td>OPS</td>
<td>Oxide polishing suspensions</td>
</tr>
<tr>
<td>POD</td>
<td>Pin-on-drum abrasive wear test</td>
</tr>
<tr>
<td>$R$</td>
<td>Radius of curvature</td>
</tr>
<tr>
<td>RPM</td>
<td>Rotation per minute</td>
</tr>
<tr>
<td>$S_a$</td>
<td>Average height of the selected 3D surface</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>SE</td>
<td>Secondary electron</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscopy</td>
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<tr>
<td>$S_p$</td>
<td>Maximum peak height of the selected 3D surface</td>
</tr>
<tr>
<td>$S_q$</td>
<td>Root-Mean-Square height of the selected 3D surface</td>
</tr>
<tr>
<td>$S_v$</td>
<td>Maximum valley depth of the selected 3D surface</td>
</tr>
<tr>
<td>TRIP</td>
<td>Transformation induced plasticity</td>
</tr>
<tr>
<td>$w$</td>
<td>Groove width</td>
</tr>
<tr>
<td>WC</td>
<td>Tungsten carbide</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Degree of penetration</td>
</tr>
<tr>
<td>$\delta_c$</td>
<td>Scratch ductility/critical normalized depth</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Ratio of the number of particles before and after test.</td>
</tr>
<tr>
<td>$\Phi_{drum}$</td>
<td>Impeller drum diameter</td>
</tr>
<tr>
<td>$\Phi_{impeller}$</td>
<td>Impeller hub diameter</td>
</tr>
<tr>
<td>WL</td>
<td>White layer</td>
</tr>
</tbody>
</table>
To my parents, wife and daughter Ezaya
Chapter 1. Introduction

1 Introduction

Materials wear out. Undesirable dimensional change with time and wear failures impact the economy and the environment. A report in 1995 shows that the automobile industries in United States could save $120 billion per year by minimizing wear and friction [1, 2]. In mining industries, wear is a major contributor to the cost of production. The failure of machine component due to wear not only increases material cost but also delays production. A study disclosed that excavator bucket teeth replacement can consume 6350 kg of steel in every six months per bucket for digging and carrying of loose, soft soil and small gravel [3]. The material loss of crushers was found to be 24 kg per 1000 tons of processed ore [4]. Materials with higher wear resistance offer lower material wastage and higher productivity. In addition, wear resistance allows use of lower thickness of materials for the same application. Thus, reducing weight of the machines decreases fuel consumption [5].

Digger teeth are ground engaging tools (GETs), used in mining for excavation and lifting of rocks and ore. During excavation, the digger teeth disrupt the hard material and protect the bucket from wear [6, 7]. The contact conditions of the tooth material with the rocks and ores require significant hardness combined with a good toughness. The hardness resists the penetration of the abrasives into the surface and toughness provides resistance to impact loads. Generally, martensitic steels are used to manufacture digger teeth. Hard facing of wear resistant materials is sometimes practiced [6, 8].

The current work aims to study the abrasive wear mechanism of an excavator digger tooth. The study also includes development of a wear test rig that closely simulates the wear mechanisms of the worn digger tooth.

The research objectives are;
Chapter 1. Introduction

- To distinguish the predominant mechanism that caused the wear of digger tooth.
- selection of most reliable wear test methodology and steel surface conditions that closely approximates the field wear and,
- Investigation of variety of steels with a range of hardness and workhardening propensities to recommend the most suitable alloy.

A comprehensive Literature review on wear in context of digger teeth is provided in Chapter 2. Chapter 3 describes the Research hypothesis and methodology. A worn tooth operated in an iron ore mine was subjected to forensic examination. The results of tooth analysis are provided in Chapter 4. A 3D CAD representation of the worn tooth provided critical information about the worn surface. The 3D CAD models were used to compare the worn tooth profile with a new tooth profile to identify the high and low wear zones. Surface grooves were analysed with optical profilometry. A microstructural investigation was carried out to understand the role of subsurface during wear. A correlation was obtained between the thickness of surface white layer with groove depth as a function of load. EBSD mapping was conducted to evaluate the white layer grain size. The critical wear features obtained from the worn tooth analysis were used as references for the development of a laboratory wear rig. The tooth wear references were also used as severity indices to benchmark the most aggressive operating parameters of the wear test rig.

The next phase of work was to develop a laboratory wear test rig that would closely recreate the similar wear references obtained in digger tooth analysis and discussed in Chapter 5. The Impeller tumbler [9-13] test was introduced due to its potential to combine impact with sliding. Scratch tests using a spherical indenter of 0.82 mm radius and with 500 N and 1000 N loads were performed to illustrate the grooving wear of the steels (Chapter 6). The scratch test was conducted on the Impeller tumbled worn
samples to approximate the real life workhardened digger tooth surface. A plot of degree of wear $f$ as a function of critical normalized depth $\delta$ was constructed and a material property parameter “scratch ductility” was introduced. Scratch ductility is the critical normalized depth that determines transformation of wear mechanism from ploughing to cutting.

Finally, the wear results of the steels obtained from Impeller tumbler and scratch tests were compared, details given in Chapter 7. The comparison clearly demonstrates that the test methodology must be chosen in accordance with the mining tribo-conditions. The scratch test on the unworn and worn surfaces of the current tooth steel was also compared with the commercial worn tooth surface. The study provides more insights of the field operating conditions that resulted grooving wear.
2 Literature review

2.1 Wear

Wear is the progressive loss of material from the surface of a solid by the mechanical action of an abrasive particle, when they are in relative motion [14-26]. Wear is not an intrinsic property of a material but a system property [27], which is called a tribo-system. A tribo-system is composed of material, counter-body/abrasive, medium such as foreign particles or lubricant and environmental conditions. Thus, the wear process depends on the boundary conditions of the tribo-system that comprises mating of wear material and abrasive particle and the relative motion between them under load. Since in a tribo-system, the parameters involved are highly inter-dependent, it is necessary to describe the wear behaviour based on the dynamics of the whole system [27, 28].

Due to complex nature, wear is classified in different ways in literature, e.g., sliding, fretting, adhesive, abrasive and corrosive wear. Peterson [29] classified the wear process in several broad categories as sliding, rolling, oscillation, impact and erosive wear based on the kinematics of the tribo-system. Other classifications are related to the physical states of the abrasive particles. Two-body and three-body wear are related to the interfacial element. The trapped solid particles in between two bearing surfaces are one of the interesting characteristics which influence this kind of wear [29]. Kato and Adachi [30] summarized the key wear processes and their interrelations (Figure 2.1). They classified wear with respect to contact conditions, for example, normal or oblique compression and detachment, unidirectional sliding, unidirectional rolling, reciprocal sliding, reciprocal rolling, and rolling with slip. The corresponding wear is termed as sliding wear, rolling wear, impact wear, fretting wear, or slurry wear. They also
argued that for wear mechanisms, consideration must be given to the elastic and/or plastic contact types [30].

The major four wear mechanisms are; 1) surface fatigue, 2) abrasion, 3) adhesion and 4) tribo-chemical reaction. However, the material removal may occur by different simultaneous mechanisms [25, 29-31].

Figure 2.1. Key wear terms and their interrelations [30].

Surface fatigue occurs through growth of cracks by alternate loading where debris particles are detached from the base body/wearing material and counter-body/abrasive particle [25].

In abrasive wear, repeated ploughing causes fatigue and microcutting. This leads to the fracture of the base body by the counter-body’s hard asperities or by hard particles in the interfacial medium [25].

In adhesion, protective surface layers are broken through plastically deformed
micro-contacuts between the base body and counter-body. If the strength of
the adhesive bonds is greater than that of the softer material, it eventually
detaches from the deformed surface of the softer material and is transferred
to the harder one [25].
In tribo-chemical reactions, friction-induced activation of loaded near-surface
zones causes elements of the base body and/or counter-body to react chemically
with elements of the lubricant or ambient medium. Compared with the base
body and counter-body, the reaction products exhibit a change in properties as
wear progresses. Once it reaches a certain thickness chipping occurs in a brittle
manner [25].

2.1.1 Abrasive wear

Among different wear mechanisms, abrasive wear alone has been estimated to
be the major contributor for the enormous economic losses of the industries [19,
20, 32]. It is the most common type of wear process for the failure of machine
components used in mining and agriculture, ground engaging tools (GET), drilling
machines, earthmoving and transportation vehicles [33].

Abrasive wear occurs mechanically over a softer surface by a hard surface when
the two surfaces are in relative motion. It takes place by the ploughing and
cutting mechanisms of the material by the counter-body/abrasive particle. The
term ‘abrasive wear’ comprises of two-body and three-body situations [15]. The
two-body abrasive wear occurs when a rough hard surface or fixed abrasive
particle slides against a softer surface. The three-body abrasion is caused by the
action of sliding of loose hard particles and rubbing surfaces [34-36].

Figure 2.2 demonstrates the schematic view of two-body and three-body modes
of abrasion wear. The action of two-body wear often produces scratches on the
material surface and the three-body wear mode causes rolling marks. For these
actions, sometimes the former is termed as grooving wear and the latter is called rolling abrasive wear [37]. It is actually difficult to categorize a wear process into pure two-body or three-body modes. They often work simultaneously. The wear conditions of the system determine the dominant wear mode [37, 38].

Figure 2.2. Wear modes: a) two-body and b) three-body [26].

According to Zum Gahr [31], abrasive wear may be further classified by micromechanisms. He assumed two body abrasive wear for pin-on-abrasion test where a portion of the material volume is removed during the formation of grooves and the remainder is displaced to the sides of the grooves. Four types of interactions between abrasive particle and wear material were proposed; microploughing, microcutting, microfatigue and microcracking. Figure 2.3 represents the schematic wear mechanisms between an abrasive particle and
the wear material.
During microploughing a prow is formed in front of the abrading particle and the material is displaced at the adjacent sides to form ridges. Ideally no material is removed in this mechanism. But the wear loss during microploughing is attributed to the break off of the adjacent ridges by the rolling particles by low cycle fatigue mechanism.

Pure microcutting occurs when the loss of material equals to the volume of the wear groove.
Microcracking mainly takes place on the surface of the brittle materials. Formation and propagation of cracks at the surface and subsurface layers are the mechanisms of microcracking. Microploughing and microcutting are the dominant processes on ductile materials while microcracking becomes important on brittle materials [31].

Figure 2.3. Abrasive wear micromechanisms [31].
Hokkirigawa and Kato [39, 40] conducted pin-on-disk abrasion tests and proposed another classification of abrasive wear based on three wear mechanisms. They introduced degree of penetration as the severity index of wear. The degree of penetration is the ratio of the depth of groove and half width of the groove. The depth of penetration is a function of normal load, pin radius and hardness of the material [41].

i) Ploughing mode of wear takes place when material is plastically displaced without removal, characterized by lower load and degree of penetration.

ii) Wedge formation is the non-steady state wear behaviour. A wedge like particle is formed and grows as the groove progresses. A combined effect of adhesion and shear fracture manifests wedging wear mode.

iii) The most severe wear occurs in the cutting mode at higher penetration depth. Material is removed by chip formation due to high load.

The present study mainly involves high stress impact and grooving wear between the surface of an excavator digger tooth and hard iron ore particles. In the following, these two types of wear mechanisms are discussed in more detail.

### 2.1.1.1 Impact abrasive wear

Impact wear occurs when two solid bodies collide with each other [42]. The collision may take place at any angle to the plane of contact. However, the material is removed by the basic wear mechanisms of adhesion, abrasion and fatigue [43]. The definition of impact wear given in ASTM G40–15 as “wear due to collisions between two solid bodies where some component of the motion is perpendicular to the tangential plane of contact” [42]. Impact wear can be subcategorized as erosive and percussive wear [44].
2.1.1.1.1 Erosive wear

According to ASTM G40 – 15, “erosion is the progressive loss of original material from a solid surface due to mechanical interaction between that surface and a fluid, a multicomponent fluid, or impinging liquid or solid particles” [42]. Generally, the size of the erodent particles is small and they engage with the target surface randomly [33]. During erosion, the eroding material may undergo a significant deformation at very high strain rates in the range $10^4$ to $10^7$ s$^{-1}$. Such a high strain rate may cause plastic deformation under fully adiabatic conditions [45]. Several erosion models were proposed based on quasistatic mechanical testing to obtain material properties such as; hardness, yield strength, ultimate tensile strength and ultimate strain. However, for more accuracy the erosion models should account for the high strain-rate generated by the stress waves during impact conditions. The stress waves at subsurface may change the material properties and corresponding erosion characteristics [46].

The model of Rabinowicz [47] predicts the wear rate to be inversely proportional to surface hardness. When applied the model in erosion study suggests that the hardness is essentially a measure of resistance to penetration. However, the model fails to explain the erosion behaviour of ductile materials as the effect of impact angle is not included in the model. Finnie et al [48] worked with annealed FCC metals which had similar stress-strain characteristics in terms of strain-hardening effect and reported that the erosion rate was inversely proportional to the hardness. In contrast, materials with low strain-hardening capacity exhibit increased erosion rate, see Figure 2.4. But this is typical of materials those have been heat-treated for increased hardness. Thus, the work of Finnie et al [48] revealed that the hardness is not necessarily a relevant parameter to predict erosion for heat-treated steels.
Figure 2.4. Erosion resistance as a function of static hardness for selected materials [48]. Erosion was generated by 250 μm SiC particles impinging at the surface at an angle of 20° with a velocity of 76 ms\(^{-1}\).

Field and Hutchings [49] proposed the damage number \(D\) which indicates the magnitude of inertial forces with respect to the yield strength of the impacted material, and is defined as:

\[
D = \frac{\rho V^2}{\sigma_{\text{yield}}}
\]  

Equation 2.1

Where \(\rho\) and \(V^2\) are the density and velocity of the impacting particle and \(\sigma_{\text{yield}}\) is the yield strength of the wear material. The damage number represents a scaling factor about the erosion mechanism that may occur for a certain velocity range. For \(D < 10^{-5}\), (particle velocity < 1 ms\(^{-1}\)) a little damage is caused by an impacting particle to the target material and fatigue mechanism is responsible for the erosion. The range \(10^{-5} < D < 1\) corresponds to the most industrial erosive
environments regime, where the particle velocity can range from 5-500 ms\(^{-1}\). Ductile materials in this regime exhibit plastic flow while brittle materials fail by fracture with a little plastic flow. The range \(D > 1\) is applicable for the ballistic impact events with velocity 500 - 3000 ms\(^{-1}\) which is beyond the scope of the present study. Further improvement of the erosion model was reported by Hutchings [50], where the wear rate was expressed in terms of the ratio of the kinetic energy of the impact particle to the hardness of the wear surface \(H\).

\[
W = \frac{k \rho v^2}{2H}
\]  
Equation 2.2

The coefficient \(k\) ranges between \(5 \times 10^{-3}\) to \(10^{-1}\) for ductile materials and implies the efficiency of material removal by a number of particle impacts.

**Parameters affecting erosion**

**Time**

A linear relationship was reported between mass loss of the wearing material with the mass of erodent used. Generally, the ductile materials depict an initial incubation period at high impact angles with a low erosion rate. After the incubation period, the mass loss increases with time. No such incubation period has been observed for the brittle materials [51].

**Impact Velocity**

For both brittle and ductile materials, the erosion rate follows a power law function of velocity; \(\varepsilon = kv^n\). The exponent, \(n\), is typically in the range of 2 to 3 for ductile metals, and 2 to 4 for ceramics [52].

**Impact Angle**

*Figure 2.5* depicts the effect of impact angle on ductile and brittle materials [48]. Maximum erosion rate for the ductile materials is at shallow impact angles (20°
to 30°) that tends to decrease towards normal incidence. An increasing erosion trend is evident for the brittle materials with impact angle reaching maximum at normal incidence. The toughness of the ductile materials allows to absorb the impact energy as elastic strain energy by elasto-plastic deformation of the wear surface resulting in a lower erosion rate at high impact angles. The limiting deformation capability of the brittle materials is responsible for the higher erosion rates at high impact angle. The main cause of brittle materials to perform better at low impact angles is the lower particle penetration which minimizes the effects of cutting and chip removal from the surface [46, 48].

Figure 2.5. Effect of impact angle $\theta$ on erosion [48]; a) Ductile metals showing peak erosion at a shallow impact angle, b) brittle materials showing maximum wear for normal incidence.

**Particle Size**

The erosion of ductile materials increases with increasing particle size up to a critical diameter of around 100 μm above which the erosion rate remains constant. Misra and Finnie [53] attributed the size effect to the increase in flow
stress with indentation size. As predicted by the elastic-plastic fracture mechanisms, the brittle material erosion follows a power law with exponents between 3 and 4.

**Material Properties**

Material properties have complex relation with erosion rate because during erosion the materials experience high strains and strain rates. An inverse relationship between hardness of annealed metals and erosion rate is evident in Figure 2.4, although thermal and work hardening have no effect. This is because the limiting hardness of the material surface that underwent heavy cold working during steady state erosion [48].

**Particle Shape**

Cousens and Hutchings [54] reported a ten-fold increase in the erosion rate of mild steel with crushed glass compared to the glass spheres. This indicates that the erosion rate of the ductile materials increases with particle angularity. The cutting mechanism is favoured by the sharper corners of the erodent. Brittle materials when engaged with soft and blunt particles tend to cause purely elastic deformation resulting in the formation of conical Hertzian cracks. Hard angular particles cause some plastic deformation and generate radial cracks. TEM evidences of the plastic flow at the impact sites of ceramics were reported by Hockey [55].

**Particle Hardness**

For ductile materials, the erosion rate decreases when the ratio of particle hardness to target hardness \((H_p/H_t)\) is less than 1. A numerical relationship between erosion rate and the ratio of particle hardness to target hardness was proposed by Wada et al. [56], given as \(E \propto (H_p/H_t)^b\). The value of \(b\) is positive for brittle materials irrespective of erosion mechanism.
Particle flux

An increase in particle flux reduces the erosion rate. The reason is the shielding effect of the rebounding particles with incident particles [57].

Temperature

In the absence of corrosion, the temperature effect on erosion has been found complex. With increasing temperature, some materials erode rapidly, however the opposite behaviour is also common. A review article presenting temperature effect on erosion can be found in [58].

2.1.1.1.2 Percussive wear

Percussion refers to the type of impact wear, where a solid surface is engaged under the repetitive exposure of a dynamic contact by another solid body. Usually, the engaging bodies are large and they mate in a controlled manner at a well-defined location in contrast to the erosive wear [33]. Engel [44] used the term compound impact wear which describes both impact and rolling sliding actions. Figure 2.6 depicts mainly two modes of impact wear; i) when the relative approach of the impacting bodies does not have any tangential or sliding movement, this is pure normal impact wear, b) compound impact occurs if a normal impact contains component of sliding or the bodies impact at a tangent. Generally, compound impact situations are most common resulting in a higher wear rate in contrast to the normal impact [59, 60]. The higher rate in compound impact wear has been attributed to the addition of a shear component due to sliding [61].
The compound impact wear process in Figure 2.7 shows an initial incubation period where deformation takes place without any measurable material loss, similar to the erosion process [44]. As the incubation period ends, the measurable wear regime starts. The end point of the wear regime during incubation period is termed as zero-wear limit. The measurable wear regime attracts more attention of the tribologists because most machine components function beyond zero-wear limit without any problem. The measurable wear regime may progress in different rates as indicated in Figure 2.7, depending on the impacting material and the severity of the contact conditions.
Figure 2.7. Zero and measurable wear [62].

The wear model of declining wear rate, similar to the erosion studies can be successfully applied to predict the wear of percussive impacts of large bodies [61, 63].

\[ W = K N e^n \]  
Equation 2.3

Where \( e \) is the impact energy per cycle, \( N \) is the number of cycles, \( K \) and \( n \) are wear constants.

\[ e = \frac{m v^2}{2} \]  
Equation 2.4

Where \( m \) is mass and \( v \) is velocity.

The model has two drawbacks; a) it does not account the workhardening of the wearing surface which reduces the wear rate with time and b) it does not consider the effect of sliding component. Based on the experiments with soft ball/cylinder worn by a hard plane and a soft plane worn by a hard ball/cylinder, Engel proposed several semi-empirical solutions, details can be found elsewhere [64]. The percussive impact wear model was further simplified and improved by
the Introduction of the parameters such as; sliding wear coefficient and the change in pressure at the interface caused by work hardening [61].

2.1.1.1.3 Deformation and material removal mechanisms

The microstructural deformation of the target body during impact wear is schematically shown below (Figure 2.8);

![Figure 2.8. Schematic representation of subsurface zones found beneath surfaces subjected to repetitive impact loading [65].](image)

Bodies subjected to impact wear show three characteristic subsurface regions (Figure 2.8). At the interface, a compositionally and morphologically different layer from the base material is formed in-situ. It is homogeneous and very finely structured zone, consisting of both the specimen and counterface material. The
layer displays high hardness and no response in chemical etching. Thus, under optical microscopy this layer is white and featureless in appearance, and is termed the “white layer”. The region beneath the white layer is plastically deformed zone formed due to repetitive stress cycling. The increased hardness at this zone is attributed to workhardening [66, 67]. The furthest layer from the contact surface consists of undisturbed base matrix. Both the surface white layer and deformed subsurface maintain a quasi-equilibrium state where the surface layer continuously wears away and the subsurface continues to replenish the surface layer [66].

2.1.1.3.1 White layer formation in steels: a general review

Generally, white layer in steels mainly refers to the untempered martensite at the surface. This is generated due to the rapid heating-quenching effect or high stresses by the abrasive particles. White layers are commonly observed in drilling, grinding, milling and abrasive cutting operations. Several hypotheses on white layer formation are available in literature. However, the white layer formation is specific for each kind of operation depending on similar materials and under similar loading and contact conditions [68]. The inherently high hardness and brittleness of the white layer deteriorates fatigue life, wear behaviour and prone to stress corrosion cracking causing failure of the material. The section below outlines some basic processes of white layer formation with respect to their specific service conditions.

White layer formation by plastic deformation

Turley et al. [69] observed a white layer at the surface of an abrasively-machined steel. With the help of previously published electron diffraction results and TEM studies they concluded that the white layer had a very fine sub grain structure. Other than heating effect they concluded that there was a significant contribution of plastic deformation in the formation of white layer. Ramesh et
al. [46,47] analysed the white layers (2 - 3 µm) formed in hard turning of AISI 52100 steel (62 HRC) with TEM, XRD and Energy Dispersive Spectra (EDS). Cementite was absent at higher cutting speed indicating a thermally-induced martensitic phase transformation. In contrast cementite was observed at lower cutting speed and the white layer formation was attributed to the mechanical grain refinement caused by plastic deformation. White layer formation is a common phenomenon in railway steels. The high hardness 1200 HV [70, 71] and brittleness is detrimental as it favours crack formation. Newcomb and Stobbs [72] investigated a pearlitic rail steel and observed the presence of white layer thickness of 20 - 40 µm range. They reported that the white layer was a martensitic phase containing dislocations supersaturated by carbon transferred from the carbides. It was unlikely that the temperature of the rail-wheel contact zone reached austenitization indicating that the phase transformation occurred by severe plastic deformation. However, the work of Wang et al. [73] detected retained austenite and martensite in white layer and suggested that the formation of white layer was due to the loading accompanied by a significant rise in temperature. The white layer thickness reported in this work was 10 - 100 µm range. Some other evidences are also available in the literature where white layers formed by high torsional straining [74] and nanocrystalline structure formation occurred by sliding and rolling motion [75]. Bulpet et al. [76] conducted failure analysis of a worn digger tooth. The steel was a low alloy material which had undergone hardening and tempering treatments. The worn tooth with other teeth fitted in front of a bucket was used to extract gravel particles of approximately 60000 tonnes. The gravel particles were mainly silica based sand particles (size 150 µm) and large stone particles (8 - 120 mm) of hardness range 1100 - 1200 HV [7]. The failure investigation revealed an appearance of white layer of some 30 µm thickness. TEM analysis revealed that the white layer was a localized transformation of the matrix to a fine grained
(200 nm), chemically and structurally micro-homogeneous, equiaxed form of martensite with a distribution of very fine M$_3$C and M$_7$C$_3$ carbides [76]. A mechanism of thermomechanical deformation with strain localization was proposed that lead to the formation of the white layer. Microprobe analysis did not reveal any environmental pick up of Oxygen and Nitrogen which could have contribution to the high hardness of the white layer (1200 ± 30 HV). The extreme hardness of the white layer was attributed to the Hall–Petch effect by the extremely fine grain size [76].

**White layer formation by rapid heating and cooling**

Another factor responsible [77] for the white layer formation is due to the local rise of the steel surface temperature at the contact zone by rubbing or impact. The severe temperature rise is sufficient to cause austenitization with subsequent rapid cooling effect by the bulk mass of the body resulting in a transformed surface layer. The high hardness of the steel surface layer often attributed to the formation of a fine grained untempered martensite [77]. Etch-resistant white layer of untempered martensite with a presence of retained austenite was observed in the shear band. The shear band was formed due to adiabatic heating, produced by the impact of a 0.8% C hammer steel [78]. Akcan et al. [79] compared AISI 52100 hardened steel (60~62 HRC), 4340 hardened steel (56~57 HRC) and M2 steel (60~62 HRC) in terms of their different A$_3$ temperatures. AISI 52100 and 4340 have an A$_3$ temperature of 800°C while M2 has an A$_3$ temperature of 1200°C. The steels were machined with a worn tool (200 μm flank wear) at a cutting speed of 150 m/min. A white layer was observed in AISI 52100 and 4340 steels but no white layer was detected in M2 steel. The results clearly indicate a temperature effect in white layer formation. Akcan et al. [80] reported a very high hardness of white layer of 12.85 ± 0.80 GPa for the hard steels by machining compared to the untempered martensite. The
high hardness was attributed to the very fine grain size typically between 30 and 500 nm.

**White layer formation by chemical interaction**

Other than the above two processes, white layer may form during surface treatment processes such as nitriding [81, 82] and carburizing [83]. Atomic nitrogen or carbon is diffused into the surface of steels causing white layer formation with high hardness due to dislocation without phase transformation.

### 2.1.1.3.2 Material removal by impact loading

Impact wear occurs by an adhesive wear mechanism when the impacting particles possess lower mass, velocity and impingement angle. At the contacting interface the material is smeared and transferred from one contacting body to the other [84], schematically shown in Figure 2.9. With continued wear, cracks are nucleated in the workhardened asperities which promote material removal.

![Figure 2.9. Schematic diagram of the formation of an adhesive transfer particle; a) adhesive contact by impact, b) formation of welded junctions at the workhardened asperities, c) nucleation of cracks at the workhardened asperities, d) smearing and transferring of material [33].](image)

Higher impact loads and velocities lead to abrasive wear. The impacts increase the roughness of the contact surface due to the formation of deeper ploughing grooves. The removal of material by repetitive impacts occurs in two steps; i)
nucleation and propagation of cracks at the subsurface and ii) the formation of debris in the form of platelets from the grooves [67, 85]. Levy and Bellman [86, 87] also reported a similar material removal mechanism. They proposed that the particle impacts create craters, smeared regions and platelets. The platelets are forged and extruded on the workhardened layer which acts as an anvil. Generally, the white layer at the surface and the deformed subsurface show a fatigue failure. The repetitive impacts by the impacting bodies form a white layer at the surface and an intensely work hardened subsurface. Microcracks are easily nucleated within the white layer and propagate through the interface of the deformation zone and white layer. Finally, the material is removed by delamination [66, 88-90]. The wear mechanism is different than the proposed conventional delamination theory [91, 92] where nucleation of cracks were attributed to the shear deformation and piling-up of subsurface dislocations.

2.1.1.3.3 Thermo-mechanical mechanisms

Hutchings [93] showed that for an inelastic impact, at least 8% of the kinetic energy is dissipated into heat which increases the temperature of the contact area. Hutchings considered thermal softening as one of the material removal mechanism during impact which leads to the formation of low strength lips at the edge of an impact crater [94]. Levy [87] suggested that the impact wear mechanism involves thermal softening and recrystallization of the eroded surface. Thus, the parameters surface melting, surface recrystallization and the formation of adiabatic shear bands (described below) are responsible for the material removal.

Surface melting caused by particle impact

The melting of the impact target surface was first suggested by Smeltzer et al. [95]. They claimed that a sharp cornered particle decelerates rapidly over a small
contact area. This causes an intense heating which may melt the contact surface of the material. However, the maximum deceleration is achieved if the contact area is maximised. Jennings et al. [96] reported surface melting in their erosion studies of several metals at particle velocities of 145 m/s. Christman [97] in his study on single projectile impacts on aluminium alloys reported presence of intense shear bands as a characteristic feature. The study in few cases suggested that local melting facilitated material removal at particle velocities of 185 m/s. These velocities are considerably higher than those encountered in ground engaging applications, which are typically of the order of 1-10 m/s.

**Recrystallization caused by particle impact**

Brown and co-workers claimed that impact takes place by a continuous process of plastic deformation and dynamic recrystallization [98-100]. They also suggested that embedding particles contribute to the recrystallization process. Significant plastic strain and localized heating effects are mainly beared by the metallic surface than that of the embedded particle which has significantly low ductility and thermal conductivity. Thus, the presence of embedded ore particle has been reported to promote recrystallized surface flakes which are detached during the process. This is also enhanced by the poor thermal contact of the particle with the underlying bulk material [101].

**Adiabatic shear bands (ASB) caused by particle impact**

Adiabatic shear band formation was introduced in the previous Section of ‘Thermo-mechanical mechanisms’ by the impacting particles. During plastic deformation, a large quantity, approximately 90% of the plastic work is converted into heat [102]. The localized heating manifested by intense localized shearing may cause plastic flow. Zener and Holloman [103] called the localized shearing as adiabatic shearing. The term ‘adiabatic’ implies that in absence of
heat conduction, the thermal softening becomes intense. Thus, the localized shearing caused by the intense thermal softening becomes larger than the rate of strain hardening [104]. However, in reality some heat generated during plastic flow is dissipated away from the deforming zone which depends on the thermal diffusivity of the deforming material [104]. Many metallic microstructures when subjected to significant impact, they display a narrow white etching bands attributed to the localized heat effect and strain concentration [101]. Rogers [105] described the adiabatic plastic deformation as severely deformed material which follow slip line trajectories. Shear bands of two types were proposed, a) intensely deformed bands by shear mechanism but without structural transformation and b) a shear band with appreciable width and transformed structure.

The influence of adiabatic shear bands on the erosion process has been discussed by several authors [106-110]. Hutchings [94] in his impact experiments of mild steel with hard steel particles, found a deformation by lip formation characterized by bands of localised shear. He attributed the material removal mechanism mainly to the mechanical effect with a minor role of melting. Sundararajan [110] reported the presence of adiabatic shear bands beneath the impact craters, within the bulk material (Figure 2.10). Sundararajan [110] proposed two material removal mechanisms by adiabatic shear deformation. The first mechanism was; a) for ductile materials during an impact process the lips of the material are raised around an impact crater (shear bands I in Figure 2.10, beneath lips of the impact craters). Once they meet the adiabatic shear bands, detached from the material. b) For the hard materials, a network of shear bands is formed underneath of the impact crater (shear bands II in Figure 2.10). Once the ASBs intersect each other, materials are removed as chunks.
There are distinctive differences between ASBs and other deformation bands. The stress state is the sensitive factor for the onset of ASBs. ASBs often form at the face of a projectile which remains under compression. On the contrary a few literature reports that ASB formed in tensile stresses, even at high strain rates [105]. The shear localization, responsible for ASB is significantly different from the necking type localization in ductile fracture. A plastic shear deformation takes place in a narrow band under tensile stresses causing local necking. This type of band formation is related to the geometrical softening in contrast to the ASB which is associated with a thermal softening [111]. Generally, an ASB is a very thin band formed due to high strain rate, strain and temperature effects. A fine grain with a distorted structure accounts for the high hardness of ASB. When compared to slip bands, the adiabatic shear bands are usually transgranular and have no any preferred crystallographic orientations. In contrast, slip bands have active crystallographic planes and remain confined to a single grain [111]. Lüders bands are the localized bands commonly observed in low-carbon steels when they experience plastic deformation due to the tensile stresses. This is related to the discontinuous yielding where this kind of band appears at the upper yield
point and propagate either side of the specimen as the loading progresses. Finally, the band disappears when the specimen becomes fully plastic. The mechanism is completely different than the ASB formation mechanism [111]. Localized shear deformation is also found in a rigid perfectly plastic material under tension by slip-lines. But adiabatic shear bands are not formed under tension [111]. Isothermal shear bands are formed in strain hardening materials due to yield surface vertex, governed by the discrete crystallographic slip [111]. Shear bands in isothermal rate dependant deformation of material are mainly due to the presence of band like imperfections [112]. None of these shear bands involve thermal softening which is a mandatory criterion for the onset of ASB.

**Modelling of ASB based on shear band instability**

The occurrence of narrow adiabatic shear bands indicates a localized deformation in continuum mechanics. A transition in deformation mode occurs when a material starts to deform with decreasing work imposed to the system. Drucker [113] proposed the onset of unstable deformation mode after a maximum stress where material is deformed plastically with decreasing stress, see Figure 2.11.

![Figure 2.11. Stable and unstable plastic behaviour of material [114].](image-url)
The idea for the onset of adiabatic shearing in accordance with the maximum shear stress criterion was put forward by Recht [115], Culver [116] and other researchers. The tension test criterion was not considered as there was no change in the cross-section area in simple shear. Neglecting the effects of elastic deformation, previous strain rate and temperature effects, a numerical model for shear stress can be written as a function of shear strain $\gamma$, shear strain rate $\varepsilon$, and temperature $T$ as follows;

$$\tau = f(\gamma, \varepsilon, T)$$  \hspace{1cm} \text{Equation 2.5}

In incremental form, the shear stress can be written as;

$$d\tau = \left(\frac{\partial \tau}{\partial \gamma}\right)_{\varepsilon, T} d\gamma + \left(\frac{\partial \tau}{\partial \varepsilon}\right)_{\gamma, T} d\varepsilon + \left(\frac{\partial \tau}{\partial T}\right)_{\gamma, \varepsilon} dT$$  \hspace{1cm} \text{Equation 2.6}

The physical interpretation of the partial differential terms in context of adiabatic shear band localization is explained below;

$$\left(\frac{\partial \tau}{\partial \gamma}\right)_{\varepsilon, T}$$ implies shear strain hardening rate at instantaneous strain rate and temperature.

$$\left(\frac{\partial \tau}{\partial \varepsilon}\right)_{\gamma, T}$$ refers shear strain rate hardening rate at instantaneous strain and temperature.

$$\left(\frac{\partial \tau}{\partial T}\right)_{\gamma, \varepsilon}$$ is the thermal softening rate at instantaneous strain and strain rate.

The condition for maximum shear stress criterion requires $d\tau = 0$, suggests the starting point for instability where the onset of thermal softening outweighs strain and strain rate hardening. Most engineering applications ignore strain rate hardening because it occurs only at very high strain rates. Therefore, neglecting the strain rate hardening term and setting $d\tau = 0$, Equation 2.6 becomes;
\[ \tau = (\frac{\partial \tau}{\partial \gamma})_{\epsilon, \tau} + (\frac{\partial \tau}{\partial T})_{\gamma, \epsilon} (\frac{\partial T}{\partial \gamma}) = 0 \]  
Equation 2.7

The increase in temperature due to the plastic work in adiabatic condition becomes;
\[ dT = (\frac{\beta \tau}{\rho c}) d\gamma \]  
Equation 2.8

where \( \rho \) is the material density, \( c \) is the specific heat, and \( \beta \) is the fraction of plastic work converted into heat. Therefore, Equation 2.8 demonstrates that the formation of adiabatic shear zone depends on both temperature and strain. The factor \( \beta \) has significant contribution on the formation of ASB as it determines that amount of plastic work required to be converted into heat energy.

Timothy [117-119] investigated the impact conditions to suggest the onset criteria for the formation of ASB. Titanium alloys were impacted with spheres of different sizes and densities. The strain induced and mean strain rates were varied by varying the impact velocity of the projectiles. Thus, a critical strain criteria based on impact velocity was proposed leading to ASB formation [120]. Molinari et al. [121] analysed the serrated chips obtained from orthogonal cutting of Ti–6Al–4V in the range of cutting velocities 0.01 m/s ≤ V ≤ 73 m/s. It was demonstrated that serration of chips was facilitated by the formation of ASB. They reported that at lower cutting velocities 1.2 m/s, the formation of ASB was less favoured due to the weak thermomechanical instability and attributed to the lower velocity of cutting tool. However, a clear presence of ASB was reported in case of velocities higher than 12 m/s. As discussed earlier that the \( \beta \) factor in Equation 2.8 determines the plastic energy converted into thermal energy required for the ASB formation and the plastic energy comes from the impact energy. The FEM simulations in [114] depict, how the loss in kinetic energy due to plate thickness affect ASB formation as it transforms to strain energy and viscous dissipated energy. Since the kinetic energy is a function of
impact velocity, it indicates the strong dependence of ASB formation on impact velocity.

However, the Impact angle is also an important factor as the kinetic energy transferred during a normal impact to the target should be different when the impact angle is oblique and in that case, one need to consider the effect of tangential component of the impact velocity. Winter [122] reported the formation of adiabatic shear bands in titanium when the flat ended steel cylindrical rods (D = 4 mm, L = 20 mm) were impacted at normal incidence angle at a speed of 330 m/s. The targets were titanium rods (D = 16 mm, L = 25 mm). A shear band of a V-shape pattern was observed in titanium by TEM analysis. In contrast Hutchings [123] performed impact test on titanium using hardened steel rod (mass = 0.5 g, length = 5 mm and diameter = 4 mm). The particles impacted at an angle of 25° to the target surface at speeds of 120 and 175 m/s. A narrow shear band formation was reported resulting from localized deformation and thermal softening. The two examples indicate that ASB can form at oblique angle impacts also. The tangential components of the impacting particles generate high friction to the target surface [124]. Thus, a plastic strain rate and a local state of stress produces a velocity discontinuity across a slip surface. In this way an inhomogeneous shear occurs which triggers the formation of ASB [115].

2.1.1.2 Grooving wear

Grooving wear occurs when a harder particle penetrates a softer surface of a solid during sliding contact [41, 125]. In a broader view, the grooving wear is a sub classification of abrasive wear as the dominant mechanism is abrasive. However, the mechanism could be a combination of adhesion, surface fatigue or other tribo-chemical mechanisms [31]. Zum Gahr [31] identified the influencing
factors of grooving wear in dry and unlubricated conditions (Figure 2.11).

![Diagram showing factors influencing abrasive wear](image)

Figure 2.12. Influencing factors of abrasive wear [31].

In grooving wear, there is a strong correlation between depth of penetration and volume of wear [40]. The lower depth of penetration indicates lower wear loss as the dominant wear mechanism is ploughing. Ploughing is manifested by the displacement of material plastically at the adjacent groove ridges but the material is not detached from the surface. However, once the depth of penetration exceeds some critical value the wear mechanism transfers from ploughing to cutting. In cutting wear material is removed as chips resulting in a higher wear loss. A mathematical approach is discussed below to describe the effect of depth of penetration;

Zum Gahr [16, 31, 125] proposed a grooving wear model of a hard particle sliding
over a soft surface. It represents the variation of cutting to ploughing ratio with degree of penetration. According to Figure 2.13;

\[ f = \frac{A_v - (A_1 + A_2)}{A_v} \]  \hspace{1cm} \text{Equation 2.9}

\[ D = \frac{d}{a} \]  \hspace{1cm} \text{Equation 2.10}

Where \( A_v \) = groove area, \( A_1 \) and \( A_2 \) = ridge area, \( d \) = penetration, \( w \) is groove width, \( a \) = groove half width, \( R \) = radius of curvature and \( D \) = depth of penetration normalized by groove half width.

![Figure 2.13](image)

Figure 2.13. Schematic diagram of groove and ridges, delineating mathematical expressions of degree of wear \( f \) and depth of penetration \( D \).

Generally, \( f \) versus \( D \) plot exhibits a S - type curve (Figure 2.14) [30, 40]. If \( f \) is close to 0, it indicates ploughing, i.e, material is plastically displaced without removal. Ploughing is dominant at lower values of load and depth of penetration. If \( f \) is close to 1 a cutting mode is dominant. Cutting prevails at higher penetration depth and material is removed by chip formation. Hardened materials tend to exhibit higher values of \( f \) leading to a cutting wear mode. Ductile materials exhibit reduced \( f \) values due to extensive plasticity [126, 127].
Figure 2.14. Degree of wear $f$ as a function of degree of penetration $D$. Three wear mechanisms are apparent with increase in penetration depth $d$. Ploughing is dominant at lower penetration depth and higher depth leads to cutting mechanism. Wedging represents the transition between ploughing to cutting.

The volumetric wear loss $W_v$ per unit length of scratch for a single scratch of length $s$ may be written as;

$$\frac{W_v}{s} = f A_v$$

Equation 2.11

Hokkirigawa and Kato [40] carried out scratch tests with a hemispherical pin on different heat treated bearing steel flat specimens. The in-situ scratch experiments under scanning electron microscope revealed three wear mechanisms ploughing, wedging and cutting, described in Section 2.1.1. An abrasive wear diagram (Figure 2.14) was proposed where degree of wear $f$ varies
as a function of degree of penetration $D$. The major findings were [40];

- The critical degree of penetration at the transition from ploughing to wedging wear mechanism is independent of hardness.

- The critical degree of penetration decreases with increasing hardness during transition between wedging and cutting mechanisms.

- The degree of wear $f$ increases with increasing hardness in cutting mode.

As discussed earlier that $f$ versus $D$ shows a S - type curve (Figure 2.14, Section 2.1.1.2). The degree of wear was plotted as a function of depth of penetration for different heat treated steels (Figure 2.15) [40]. Some interesting features of the curve are;

i) As the hardness of the specimen increases the corresponding graph shifts to the left. This is evident that harder material resists penetration more which decreases the penetration depth ($d$) and shifts the curve towards left.

ii) The softer specimen displays a less steep plot than that of the harder specimens. It is evident that softer material offers lower resistance to the penetration which shifts the plot towards right. But the lower steepness indicates a workhardening effect during transition from ploughing to cutting mode.

iii) Also at a given depth of penetration there is less degree of wear in softer materials.
Figure 2.15. Degree of wear \( f \) as a function of degree of penetration \( D \) observed with heat-treated steel of different hardness \( H \) (kgf/mm\(^2\)) [40].

**Implication of \( f \) model to understand grooving wear of different materials**

*Figure 2.16* represents wear resistance as a function of hardness of various engineering materials. Zum Gahr [16] explained the wear mechanisms considering \( f \) model and deformation capacity of the wearing material. \( f \) values were experimentally determined from single wear grooves formed by pin-abrasion tests [16]. The \( f \) model helps to understand the relation between wear resistances, hardness and wear process. For a given hardness, materials with higher wear resistance are those with low values of \( f \).
Figure 2.16. Schematic representation of abrasive wear resistance against hardness of material with the help of $f$ model [16]. The $f$ is represented in this Figure as $f_{ab}$. At a given hardness higher $f$ value indicates higher wear rate due to microcutting and microcracking and lower $f$ value shows microploughing resulting in low wear rate.

It is interesting to note in Figure 2.16 that prior cold working increases the material hardness but imparts no significant effect in increasing of wear resistance. While cold working increases hardness and consequently reduces groove depth, it also reduces ductility leading to higher values of $f$ [128].
2.1.2 Influence of abrasive particles

2.1.2.1 Abrasive hardness

The properties of abrasive particles have a significant role in a wear process. The hardness has a key influence during penetration on the wearing material. Richardson [129-131] studied the effect of soft and hard abrasives. Richardson considered a material of hardness $H$ at unstrained condition and if the material is plastically strained then the maximum hardness it can attend is $H_m$. $H_a$ is the hardness of the abrasive material. The criterion for wear is, $H_a/H_m \geq 1.25$, which means that the hardness of the abrasive must be higher than the surface hardness of the material at least by a factor of 1.25 to create wear. The slip line model of Torrance [132] supported Richardson’s hardness criterion for wear.

2.1.2.2 Abrasive particle size

The abrasive particle size also has a significant effect on the wear behaviour of a material for a given tribo-system. Moore [133] proposed that abrasive wear generally increases as the abrasive size increases. It was suggested that only a lower fraction of the fine abrasives (micron scale) is responsible for material removal. This is because i) majority of the particles make elastic contact and ii) loose wear debris hinder the contact of some particles. However, for the fine particles the wear rate increases proportionally with increase in abrasive particle size up-to a critical particle size (CPS) and then the rate changes. Anvient, Goddard and Wilman [134, 135] proposed that the CPS is controlled by clogging of the smaller sized abrasives. Nathan and Jones [136] reported that material removal increases linearly with the size of the abrasive particles up to 70 μm. Between 70 μm and 150 μm, the gradient continuously decreases, and above 150 μm, it presents a linear relationship at a lower rate. Misra and Finnie [53]
with three-body abrasive wear and erosion tests established that once the abrasive particle size exceeds 100 μm, the wear rate is little affected by the increase in abrasive size in contrast to the depth of the hardened surface. A limited information is available about the influence of coarse abrasives on wear properties of materials. In millimetre scale, both increasing [137] and decreasing [138, 139] of wear with increasing particle size are reported in the literature. Generally, the coarse particles fracture into fine abrasives due to loading [33]. The fractured particles generate fine abrasives of sharp facets which increases wear rates. Thus, it depends on the loading conditions of the tribo-system. As in absence of sufficient loading effect, the coarser particles do not fracture, which may reduce the wear rate.

2.1.2.3 Geometry and attack angle

The shape of the abrasive particle determines the nature of the penetration into the wearing material. Thus, the sharpness and the corresponding attack angles become important factors to control the wear behaviour of a material in that particular tribo-system. Mulhern and Samuels [140] introduced the concept of attack angle of contacting abrasive particle with the material surface. It was assumed that microchips are produced by a cutting action only when the attack angle exceeds some critical value. Zum Gahr [16, 31, 125] suggested that a gradual transition from micropolishing to microcutting occurs when the attack angle increases (Figure 2.17). Kato et al. [41, 141] showed in their experiments that at a low attack angle the wear rate is low and the abrasive mechanism is ploughing. Higher angle onsets cutting wear mechanism increasing the wear rate. Coronado and Sinatoria [142] proposed that larger particles have blunt facets which engage with the material in low attack angles decreasing the wear rate. Gåhlin and Jacobson [143] argued that if the particles have ideally sharp facets then the size effect has no influence on wear but blunt particles exhibit size
effect [144].

Figure 2.17. Ratio of cutting to ploughing as a function of the ratio of the attack angle to the critical attack angle [31]. Change in wear mechanism is apparent with increasing attack angle.

2.1.3 Influence of steel properties

2.1.3.1 Hardness and carbon content

Hardness of a material has a significant influence [19, 21, 23, 40, 145-151] on its wear resistance. Khrushchev [151] showed that the abrasive wear resistance of a large number of pure and annealed metals was directly proportional to the hardness of the metals (Figure 2.18a). The wear resistance of the metals also increases with increasing carbon content (Figure 2.18b). The effect of carbon on wear resistance of steels was studied by Serpik and Kantor [152] and Moore [133].
Figure 2.18. a) Effect of hardness on the abrasive wear resistance of different steels [151], b) Variation of relative abrasive wear resistance of steels with carbon content [152].

Figure 2.18a depicts that prior work hardening of the material through cold working is unable to increase the wear resistance. The surface of the metal under abrasion work hardens to a very high degree. Thus, prior work hardened metal becomes no more abrasion resistant than the annealed metals. Figure 2.18b
displays an increasing wear resistance with carbon content. The wear resistance of hypoeutectoid steels increases with increased volume fraction of pearlite and decreasing the pearlite interlamellar spacing [150, 152, 153]. In the case of hypereutectoid steels wear resistance increases with carbon content up to a certain limit. Higher concentration of carbon leads to formation of cementite carbides (Fe₃C) at the grain boundaries. The carbide precipitates at the grain boundary network impart brittleness compromising the wear resistance [154]. It has been found that for a given carbon content, abrasive wear decreases with increasing grain size of the steel [154]. Wear resistance can be improved significantly for steels up to 0.8%, above which it increases very slowly with increment of carbon [155]. Further work of Larsen Badse [150], who repeated Khrushchev’s experiments, anticipated that both the hardness and its work hardening exponent mutually influence the abrasive-wear resistance. Richardson [131, 156] and Tylczak [157, 158] suggested that the change of material hardness caused by the deformation should be taken into account as plastic deformation of wearing surfaces takes place during abrasive wear.

2.1.3.2 Steel microstructures

The microstructure also contributes to determining the wear mechanism and rate [15, 129, 131, 136, 146, 147, 149-151, 154, 156, 158-173]. Ferritic steels which are softer along with larger grain sizes display limited wear resistance [174, 175]. Moore introduced pearlite into the ferritic matrix which enhanced the wear resistance of the alloy significantly [149, 164]. Moore [133, 164, 176] claimed that wear resistance of a pearlitic steel is a function of pearlite volume fraction and that for martensitic steels the wear resistance is a function of the square root of carbon content. Further improvement on wear resistant steels was achieved by the bainitic microstructures with low carbon level than that of high carbon pearlitic steels. The higher wear resistance offered by bainitic steel
was attributed to the toughness and ductility of the microstructure [177-180]. Above a critical carbon level a drastic drop in wear resistance occurs due to loss in toughness and ductility [131, 181-183].

**Role of steel microstructures at rolling sliding and impact conditions**

The wear response of steel microstructures varies significantly with changing wear conditions. Zum Gahr [31] compared the sliding wear resistance of different microstructures as a function of hardness at high and low loading conditions. At high load, the bainite showed higher wear resistance compared to martensite. Presence of retained austenite in bainitic structure increased wear resistance in this condition. A similar observation was reported where Salesky et al. [181] introduced retained austenite in the martensitic structure to increase toughness of the material. The austenite-martensite microstructure displayed improved sliding wear resistance compared to bainite-martensite or 100% martensite steels. However, under low loading condition [31] an opposite behaviour is apparent. Hardness played the key role in mild condition. Retained austenite deteriorated the wear resistance of bainite and pearlite offered similar wear resistance compared to bainitic. The increase in wear resistance of the pearlitic structure was attributed to the formation of adherent and cohesive tribo-chemical layer at the surface of the wearing material. Garnham et al. [183] claimed in another experiment that dispersion of hard carbide plates at the wearing surface of pearlitic steels increases its wear resistance than bainite in rolling sliding abrasion. Similarly, materials which displayed a higher wear resistance in rolling sliding may show higher wear rate in impact wear. Hawk et.al [184] conducted pin-on-drum and Impeller-in-drum tests (Figure 2.19) on commercial wear resistant martensitic steels (Hardness range 360 - 520 HB), used in mining industries.
Figure 2.19. Wear loss as a function of hardness of martensitic steels; a) pin-on-drum for sliding, b) Impeller-in-drum test for impact abrasion conditions [184].

Abrasive cloth, either Al₂O₃, SiC, or garnet was used in pin-on-drum test whereas high silica quartzite was used as abrasive particles in Impeller-in-drum tests. The pin-on-drum and Impeller-in-drum tests represent low stress pure abrasive wear and impact abrasive wear respectively. The volume loss of the martensitic steels is plotted as a function of hardness (Figure 2.19). The pin-on-drum test results (Figure 2.19a) depict that volume loss decreases with increase in hardness but
the Impeller-in-drum test does not correlate the wear loss with hardness (Figure 2.19b). Perhaps an increasing trend in volume wear is indicative with increasing hardness. The low wear resistance of the harder steels is due to the lower toughness and ductility of the materials in impact loading conditions [184, 185]. Thus it is important to know how steel microstructural features behave in specific wear condition to design a wear resistance steel [181, 184].

### 2.1.3.3 Effect of carbide volume fraction

The carbide [31, 168] volume fraction in a microstructure also contributes in wear behaviour of materials. Generally, wear loss decreases [31, 166] with increase in the volume fraction of carbide. This is because increase in carbide volume fraction results in decreasing inter-carbide spacing. However, increased carbide volume of a material can be detrimental due to fragmentation of the carbides by the hard and large abrasive particles [14]. Zum Gahr [31] described the interactions between carbides and abrasive particles by digging, cutting, cracking and pulling out from the matrix. Ductile carbides which are in larger size compared to the average wear grooves are cut by the harder abrasive particles whereas brittle carbides are cracked. Softer abrasive particles are unable to dig out the hard carbides as they resist the penetration effectively. But the large carbides which are not bonded to the matrix firmly are pulled out easily by the soft abrasive particles. Carbide shapes [31] are also important as carbides of circular cross-section are less prone to microcracking than the rectangular cross-section. Non-spherical carbides increase wear rate even by the soft abrasive particles due to structural anisotropy.

Chromium, vanadium, niobium, tungsten, titanium and molybdenum are the major carbide forming elements in steels [165]. An alloy steel of martensitic microstructure with some retained austenite and uniformly dispersed fine
carbides efficiently resists abrasive wear [170, 186, 187]. However, the carbide content should not be compromised by the retained austenite in the microstructure. It was reported that wear resistance of several high-speed steels increased with the increase in volume fraction of VC/V₄C₃ carbides in the microstructure [188, 189]. The effect of different carbides in austenitic matrix exhibited no difference in wear resistance up to a carbide content of 5-7%. After 7% it was found that vanadium and niobium carbides exhibited better wear resistance than that of the chromium and tungsten carbides. The former carbides had undergone destructive penetration by the hard abrasives whereas the later suffered severe damage. It was argued that carbides protect the matrix at initial stages of wear during penetration but at the secondary stage where relative abrasive movements are involved, the carbides failed to protect the matrix further [167, 168, 172]. Impact abrasive tests were conducted at different conditions [190] on martensitic steels of different hardness grades 500–750 HV. Among which the material with hardness value of 750 HV was a martensitic microstructure with dispersed chromium carbide (Cr₇C₃). The carbide reinforced matrix was reported to be higher wear resistant material compared to the other steels, however, it was prone to crack initiation and propagation. It was also recommended that these materials are not suitable for high energy impact environments.

The above discussion highlights a generic review of the beneficial or detrimental effects of carbides in the respective matrices at various wear conditions. However, the reader is informed that the steels involved in the present research work have no such dispersed carbides.

**2.1.3.4 Effect of retained austenite**

Serpik et al. [152] showed that at the same hardness, wear resistance increases
progressively as the microstructure is changed from martensite to bainite. Zum Gahr [191] attributed the increase in wear resistance to the retained austenite in the bainitic microstructure. Kwok et al. [192] reported that dislocated lath martensite combined with retained austenite displays higher wear resistance than bainite-martensite or pearlitic microstructures. In a pin abrasion test with SiC abrasive particles, predominantly austenitic matrix displayed lower wear rate than a martensitic microstructure due to higher workhardening capability and ductility of the former [193]. Zum Gahr [31] experimentally showed that the microcutting to microploughing ratio or $f$ values of two Hadfield type steels decrease with increasing amount of retained austenite. This suggests that the wearing material undergoes deformation induced transformation during abrasion. A transformable amount of retained austenite (10-30%) in a martensitic [194] or bainitic [31, 191] microstructure is beneficial which is transformed to martensite (i.e TRIP effect) during deformation [195-199]. Retained austenite in the structure of the carburized case inhibits the nucleation and propagation of fatigue cracks during deformation [161, 196, 198]. Bhat et al. [200] suggested that under high stress two body abrasive wear a low alloy steel microstructure should be either martensite or lower bainite combined with retained austenite. The Face centred cubic (FCC) structure of austenite offers an increased deformation capacity to the microstructure by providing numerous slip systems during wear process [201]. Thus, the high toughness reduces the cutting efficiency of the abrasive particles increasing the wear resistance [31].

2.1.3.5 Effect of grain size and morphology

Grain size

A smaller grain size generally offers better wear resistance [11, 197, 202]. Bhattacharyya et al. [203] showed that prior austenite grain refinement
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improves tool steel wear performance significantly. During turning process cracks are nucleated within grains and at the grain boundaries due to stress concentrations, low cycle fatigue and thermal effects. Grain refinement restricts crack initiation and propagation reducing wear. The pure sliding wear properties of a bearing steel at quenched-tempered and austempered conditions was investigated by Wang et al. [204]. The austempered microstructure displayed a little higher wear resistance than the quenched-tempered microstructure due to the formation of ferritic nano-sized grains at the contact surface. Zhang et al. [205] reported that austempering treatment of a carburized low-C steel improved its sliding wear performance by 80% (steady state wear rate) than that of 20CrMnTi bearing steel in quench and tempered condition. This was attributed to the formation of nano-structured bainite which had; i) higher strength and toughness due to the microstructural refinement at low transformation temperature, ii) uniform distribution of carbon enriched austenitic film between ferrite laths that efficiently retarded the crack initiation and propagation and iii) the higher hardness of extremely fine ferrite laths. The reciprocating sliding wear property of high-silicon nano-bainitic steels (transformation temperature 200°C) and conventional lower bainite (transformation temperature 450°C) was studied by Rementeria et al. [206]. An order of higher wear resistance was recorded for the nano-structured microstructure which was attributed to the highly refined microstructure and the strain-induced transformation of austenite films.

Fine pearlitic structure (380 HV) reportedly displayed higher wear resistance than untempered martensite (740 HV) and a comparable wear resistance with nano-structured bainite (620 HV) in three body Dry sand rubber wheel test [198]. A significant plastic deformation resulting in a good adhesion with the damaging surface led to lowering the wear rate for fine pearlite and nano-structured bainite samples. Fragmentation of the surface increased the wear rate of
untempered martensite. However, finer structure does not always increase the wear resistance of materials as grain refinement can increase strength in expense of toughness [207].

**Morphology**

The structure of retained austenite whether film or blocky and the distribution into bainitic ferrite laths are important factors that influence the wear property of a material [204-206, 208-210]. Similarly, the structure of martensite, i.e, lath martensite or blocky martensite is also a factor which may affect the wear property [207, 211-213]. Hu et al. [208] studied the effect of retained austenite in nano-structured bainite (642 HV, 28% retained austenite) and quenched-partitioned steels (674 HV, 36% retained austenite) in stirring wear process. The nano-structured bainitic displayed a lower wear resistance which was attributed to the ineffective TRIP effect of the retained austenite during wear. The efficiency of the positive TRIP effect depends on the stability of the retained austenite during deformation which in turn governed by carbon content, size, morphology and distribution within the microstructure [208]. The high carbon concentration in retained austenite retards its transformation to martensite during wear. Large blocky austenite grain structure and its uneven distribution reduced the stability of the austenitic grains which could not provide toughness to the microstructure during abrasion [214].

### 2.1.3.6 Fracture toughness and ductility

Fracture Toughness [31, 145, 215-217] also plays an important role on materials wear property. Fischer et al. [218] varied the Yttria content in Yttria-doped zirconium oxide to prepare fully tetragonal, mixed tetragonal and cubic, and the fully cubic phases of fracture toughness values 11.6, 8.7, and 2.5 MPa√m respectively. The toughest structure exhibited 1200 times higher sliding wear
resistance measured at 1 mm/s speed and 9.8 N load. They attributed the wear mechanisms predominantly plastic deformation in tougher zirconium oxide (fully tetragonal) and fracture in the brittle (cubic) material. However, the present research work neither includes ceramic materials nor untempered brittle martensitic phases. But one dealing with hard brittle phases must give considerable importance to the fracture toughness properties of the microstructures. This is evident from Figure 2.18, that unlike pure metals and annealed steels, the abrasive wear resistance of heat treated steels do not pass through the origin when plotted as a function of hardness. The decrease in wear resistance is attributed to the formation of microcracks during abrasive wear which is less prone to the pure metals [159]. Hornbogen [216] proposed that the cracks initiate when the strain of the wearing surface exceeds a critical value and the wear rate may decrease or increase with hardness depending on the fracture toughness property of the material. Atkins [219] proposed a correlation among fracture toughness, plasticity and friction in abrasive wear. He suggested that for non-heat-treated steels the material is removed by cutting whereas in heat treated steels cutting and fracture are the dominant mechanisms. Zum Gahr [191, 215] explained the wear resistance of materials with their hardness and fracture toughness properties, illustrated schematically in Figure 2.20. The plot demonstrates that the materials which have lower fracture toughness (< 14 MPa√m) shows an increasing wear resistance with increase in fracture toughness, despite of considerable decrease in hardness [31, 215]. The dominant wear mechanism for these materials is fragmentation. But the reduced hardness and corresponding increase in fracture toughness introduces cutting and ploughing mechanisms resulting in a reduced wear rate. For the higher fracture toughness materials the dominant wear mechanisms are cutting and ploughing [31, 215]. These wear mechanisms are manifested by indentation resistance and highly dependent on hardness. Thus, for the higher fracture
toughness materials wear resistance decreases with decrease in hardness.

Figure 2.20. Relationship between wear resistance, hardness, and fracture toughness [217]. Low fracture toughness materials wear by fragmentation. Increasing fracture toughness and decreasing hardness reduces wear rate due to the introduction of ploughing and cutting mechanisms in place of fragmentation. Wear resistance of high fracture toughness materials is decreased with decrease in hardness due to reduced indentation resistance.

### 2.1.4 Wear testing methods

Wear behaviour of a material depends on the entire wear system. Impact wear is typical for impacting crushers, ground engaging tools (GET), rock excavation and processing machineries. The operation process of GETs during rock excavation, chutes, pulverizing mills involves direct impact and gouging actions of the metallic components with the rocks and minerals [33]. The abrasive
particles cause significant localized stresses, material is removed by ploughing and cutting actions lead to the formation of large gouges and scratches. Thus, the alloys require appreciable hardness with a significant work-hardening property. Crushers undergo high stress abrasion when abrasive particles are crushed between two loaded surfaces normally. Such high loads can damage the crusher material surfaces by scratching caused by particle penetrations and fatigue [33]. It is worth mentioning that impact wear includes the abrasion process where relative movement of the acting bodies in the system are expected. The wear process highly depends upon loading conditions and material properties [44, 220]. The impact conditions also depend on the direction or impingement angle of the impacting particles [166]. Higher angle impacts lead to cutting wear processes. In low angle impacts ploughing is dominant [41]. It was described earlier that the combined effect of the tribo-system determines the wear behaviour of a material. For a closed impact abrasion system with large abrasives, the wear rate of the material may decrease with time due to loss of energy arising from comminution of the large particles into small particles [221]. In summary, it is difficult to predict the wear behaviour of a material if the wear conditions are not known. Thus, to develop a specific material for a specific application, the wear conditions must be investigated carefully.

It is always difficult to simulate the exact field wear conditions in laboratory wear test methods. But to achieve a reliable and repeatable wear condition the wear tests should be controlled as close as possible to the field conditions [8, 157, 222]. Thus, there always remains a compromise between field and laboratory wear conditions which imparts a lack of correlation between the results. Field tests always have high degree of reality but lacks in control of tribo-conditions. The actual machines, variability within ore bodies, operating conditions, weather, working ground make the conditions real as well as difficult to control
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[223]. The model laboratory experiments simplify the working environment and make it easy to control the variables but at the cost of loss of “reality” [6, 222]. For example, two single scratch experiments cannot simulate the overlapping scratches occurred in the field [224]. The factors like work hardening, attack angles, surface roughness often remain unaddressed during the laboratory wear tests.

The difference in scaling [225] such as power and dimensions of real machines in field, bigger size of rocks (loose or adherent to the ground) become difficult to simulate in laboratory wear experiments. For the ease of work and safety matters the laboratory equipment are usually smaller and simpler and rock particles remain smaller in size. Thus, the loading effect on the test surface varies significantly, which is often responsible for the lack of correlation between the two results.

To design a simulative wear rig reliable field wear reference data is required. The representative data from the reference sample is always useful as it provides information of the nature of wear experienced during field operations [226]. Thus, comparing the field wear results with laboratory results, it is possible to relatively rank alternative wear resistant material [227]. However, the field results may also vary with the position of the reference sample attached during operation. For example, the excavator bucket may hold six digger teeth. The teeth at terminal ends wear differently than the teeth attached at middle [8, 223] which needs to be considered when positioning the reference sample.

During wear tests the specimens may be subjected to loose or fixed abrasives [227]. The weight before and after test of the test specimen is measured and the difference between them is reported as wear loss [228]. The weight loss may be converted to represent the wear in volume loss. If the test specimens are hard to remove from the testing equipment then dimensional changes compare to initial dimensions, can be used to measure wear loss [229, 230].
The size of the abrasive and the wearing materials may affect the test conditions. For example, the wearing materials may influence the abrasive movements [227]. The abrasive size, shape and comminution property affects the wear behaviour of the material. The abrasive particles with high comminution rate may lower the wear rate in a closed tribo-system because finer particles impart less loading effect. But if the abrasive particles are replenished with fresh particles the wear rate increases [12, 138].

However, to find out a suitable wear test rig that closely simulates digger teeth wear conditions, we must have a knowledge of the available wear rigs and their working principle. A brief discussion of several wear test methodologies is described below which will be helpful to choose the most appropriate wear test rig digger teeth wear;


2.1.4.1 Dry-sand, rubber-wheel wear test (DSRW)

This low-stress, three-body abrasive wear test is used to rank the materials using silica sand as abrasive particles, described in ASTM G65 [231]. A schematic diagram of a DSRW set-up is given in Figure 2.21 [184]. It is widely used in number of laboratories for many years [184]. Generally, the rounded silica sand particles 50-70 mesh flow at 250-350 g/minute between the specimen (25 × 75 × 12 mm) and a rotating (200 RPM) rubber rimmed steel wheel of 228 mm diameter and 12.7 mm wide. The specimen is held against the wheel with a contact force of 130 N [157]. After prescribed revolutions (may vary 2000–6000 as per the test design), the mass loss is calculated by weighing the specimen and represented as volume loss.
2.1.4.2 Pin-on-drum abrasive wear test (POD) and Pin on disc test

The Pin-on-drum and Pin on disc tests share common features in terms of their wear mode, hence they are discussed in same section.

The Pin-on-drum abrasive wear test simulates high-stress, two-body situation, described in ASTM G132 [232]. A cylindrical pin specimen of 6.35 mm diameter and 20-30 mm length is moved over abrasive cloth coated on a rotating drum of
500 mm diameter (Figure 2.22). Normally a load of 66.7 N is kept and an abrasive cloth of alumina, SiC or garnet with desired mesh size of abrasive grains are used. However, these parameters can be varied as per test requirements. The pin also rotates while traversing. This ensures that the pin always contacts fresh abrasive. This is a high-stress abrasion test, as the load is sufficient to fracture the abrasive particles. The test duration is selected to achieve at least 40 mg of specimen mass loss. The mass loss is then converted into a volume loss per unit distance description of the test apparatus (mm³/m) [184].

According to ASTM G99 – 05 (2016), two types of specimens are used in Pin-on-disk wear test [233]. 1) On a flat circular disk glued with desired abrasive paper and a pin is positioned perpendicularly. As the disc rotates, it abrades the pin and wear is measured by weight loss method. 2) A ball, rigidly held, is also used as the pin specimen. Load may be varied by using different dead weights to vary wear rate with load. Wear results are reported as volume loss in cubic millimetres for the pin. Wear results are usually obtained by conducting a test for a selected sliding distance and for selected values of load and speed. The wear loss is reported either in weight loss or volume loss. The test parameters for pin on disc are abrasive grain type and size, load, speed, sliding distance, temperature and humidity. The test is described in ASTM G99.
Figure 2.22. Schematic representations of Pin-on-drum (POD) abrasive wear test [184].

2.1.4.3 Jaw crusher gouging abrasion test

High stress type two-body or three-body wear condition is simulated by this test, described in ASTM G81 [234]. The arrangement of the jaw crusher test setup is shown in Figure 2.23. The jaw openings are 50 mm wide to provide a specimen width of 25 mm and it operates at 260 cycles/min. The system is motor driven with capacity of 3.7 kW. The test wear plates and reference plates have a 15° taper on each end for clamping to the jaws. In Jaw crushing test one set of
test specimen is clamped in stationary jaw and the other set in the movable jaw with minimum jaw opening around 3.2 mm. 11.35 kg pre-screened high silica quartzite (-20 mm sieve size) is passed through the jaw crusher which is repeated by replacing the specimens in the stationary and movable jaws. Finally the samples are cleaned, dried and weighed for mass loss and Thus, volume loss is calculated by dividing the mass loss with the density of the material [184].

![Diagram of Jaw Crusher Test](image-url)

Figure 2.23. Schematic representations of Jaw crusher test [184].

2.1.4.4 Pendulum grooving test

This is a modified Charpy impact tester, where a radially protruding cemented carbide tip is fixed at the terminal end of a pendulum hammer that forms groove on the test specimen of size $(10 \times 15 \times 100 \text{ mm}^3)$. It is placed in a horizontal specimen holder with normal and tangential force measurement capabilities. The groove size is varied by changing the radial position of the cemented carbide
tip and/or changing the vertical position of the specimen. The pendulum length is kept 830 mm and the tip entrance is 5.6 m/s. The pendulum entrance energy and momentum are 300 Nm and 107 Ns respectively. The energy consumed during each grooving event is measured. The tip face is kept normal to the grooving direction [235, 236]. Wear property is measured by two methods, either single pass or multi-pass grooving.

2.1.4.5 Impeller tumbler test

Swanson [237] compared the ploughshare field test results with dry and wet rubber wheel laboratory test results for tillage applications. The investigation of the wear surfaces obtained from field and laboratory test indicated a higher degree of disagreement. He attributed the limitation of the laboratory tests to their incapability of combining abrasion by loose smaller particles and repeated impacts by rocks. Tylczak et al. [157] argued that impeller in drum test can develop high stresses on the surface of the target materials by high impact velocity. In contrast to POD, DSRW and Jaw crusher tests, they claimed that impeller in drum test simulates more effectively the movement and handling of loose ores and rock those are common features of ground engaging applications.

Several impact abrasion tests were developed; MLD-10 (or somewhere MDL-10) [238, 239] and high temperature cyclic impact abrasion tester (HT-CIAT) [240], grooving abrasion resistance of steel by pendulum grooving [235, 236], Impeller in drum test [12, 184] to simulate field conditions precisely. Among these, the Impeller tumbler test rig provides most reliable test results (a critical analysis is described in Section 5.2). Impeller tumbler test is the modified impact pulveriser test rig used by Bond in 1952 [241, 242]. The rig simulates moderately high stress abrasion, used by research groups in USA [12, 184] Finland [9, 243-245], Austria [10, 246, 247] and Sweden [11]. The rig allows to use field ore particles as well. Figure 2.24a, depicts the schematic Impeller tumbler test arrangement and
Figure 2.24b represents the arrangement of the impeller inside the drum. Test specimens are used as metal plates. The plate dimension is $75 \times 25 \times 12.5$ mm.

During operation, the test samples rotate at 620 rpm (a velocity $\sim 6$ m/s at the tip of the plates) and engage with quartzite, granite, limestone or any desired
ore. The material loss occurs by combination of impact and abrasion [184]. Generally, Impeller tumbler test is conducted for one-hour. Other than one-hour tests a multi hour test is also conducted to achieve a steady state wear result. The first hour test shows a ‘break-in’ period where the wear rate is overestimated due to the initial high wear. Samples get work hardened maximum in this period whereas the multi hour test is the steady state period. The multi hour test produces more reliable results than one-hour test [12].

Based on the wear test methodologies and the failure analysis of the worn digger tooth (described in Section 4), a critical analysis for selection of the most appropriate wear test rig for this application is discussed in Section 5.2.

### 2.2 Excavator digger teeth: introduction

The digger tooth is a ground engaging tool (GET), mechanically clamped in front of a bucket to shovel soil, ore and rocks from the earth [6, 7, 76, 248]. Excavator buckets are fixed in front of a backhoe excavator machine used to load trucks in construction or mining sites. During excavation and lifting earth materials, digger teeth are used to protect buckets from high impact and abrasion while facilitating bucket entry into the aggregate [33, 248, 249]. The digger teeth are prone to high wear loss. Figure 2.25 below shows a new excavator digger tooth and Figure 2.26 shows its attachment to the excavator buckets. The tooth shown in Figure 2.25 was used to analyse surface to core hardness profile and generate CAD model to compare with a worn tooth, shown in Figure 4.1b, Section 4.2.
Figure 2.25. Excavator digger tooth.

Figure 2.26. Digger tooth attached to excavator bucket. Image received and used with permission from Keech Castings Ltd.

An excavator is a hydraulically operated digging machine. The mechanism of earth excavation is executed by forces applied to boom, arm and the bucket by
the hydraulic cylinders. Hence the critical parameters influence the digging forces are working mechanism, working pressure and diameter of hydraulic cylinders, although in general boom cylinders are used for bucket position adjustment, whereas arm and bucket cylinder are used for excavation. The maximum breakout or digging force exerted at the digger teeth tips depends upon whether the arm or bucket cylinder is the active cylinder, excluding weight of components and friction [250, 251]. A precise calculation of digging force produced by the actuators is necessary for effective excavation because the digging force must exceed the resistance forces provided by the ground.

The bucket digging or penetration force, exerted at the tip of the bucket teeth is calculated by the bucket curling force \( F_B \) and arm crowd force \( F_S \) in accordance with SAE J1179 standard “Hydraulic Excavator and Backhoe: Digging Forces” [252] (Figure 2.27).

![Figure 2.27. Digging forces: bucket curling force \( F_B \), arm crowd force \( F_S \), corresponding distances \( d_A, d_B, d_C, d_D, d_D1, d_E \), act as moments for the forces [252].](image-url)
According to SAE J1179, bucket curling force $F_B$ is the digging force generated by the bucket cylinder and tangent to the arc of radius $d_D$.

$$F_B = \left[\frac{d_A d_c}{d_B}\right] \left( p \cdot \frac{\pi}{4}\right) \cdot \frac{D_B^2}{d_D}$$  \quad \text{Equation 2.12}

Where $D_B$ is the end diameter of the bucket cylinder in (mm) and the working pressure is $p$ in MPa or N/mm².

Similarly, the arm crowd force $F_S$ is generated by the arm cylinder and tangent to arc of radius $d_F$.

$$F_S = \left( p \cdot \frac{\pi}{4}\right) \cdot \left( D_A^2\right) \cdot \frac{d_F}{d_F}$$  \quad \text{Equation 2.13}

Where, $d_F$ is the sum of bucket tip radius ($d_D$) and the arm link length in mm, and $D_A$ is the end diameter of the arm cylinder in mm.

**Figure 2.28**, displays the excavation trajectory, following its path as it penetrates the terrain and breaks material into fragments, followed by lifting for loading [253, 254].

The modelling of excavation involves describing soil-tool interaction that leads to failure of the tool. Gill and Vandenberg [255] proposed that the cutting and plastic deformation of the cutting tool resulted from a shear mechanism, offered by non-cohesive soil. The resistance force responsible for failure of a ground digging tool is a function of the shear strength of the soil and tool surface, which is generally considered flat rather than curved as shown in **Figure 2.29**. The influential parameters that characterize a flat surface are speed, shear plane angle, rake (or cutting) angle, operating depth, the blade width and submerged length of the blade [254].
Figure 2.28. The working range (trajectory) of a backacter [22].

Figure 2.29. A two-dimensional view of excavation [21].
2.2.1 Current digger teeth materials

A range of materials are used to manufacture digger teeth. The selection of the materials mainly depends on the local conditions of the application area.

- Mainly medium carbon, low alloy steels are used to manufacture digger teeth [6, 7, 76, 256]. The cast steels are quenched and tempered for martensitic microstructure which resists wear due to high hardness (~500 HV).
- Martensitic steels with retained austenite and finely dispersed carbides [257] are some of the wear resistant materials which are mainly used for Bucket liners for excavator, shovel, loader, dozer. Currently these materials are also used to cast digger teeth.
- Austenitic Mn steels [258, 259] are mainly used in ground engaging applications like dredging blades and wear parts for primary and secondary crushers. However, depending on the mine conditions sometimes this steel is used to cast digger teeth for high work hardening capacity.
- Other than alloy designing, hardfacing techniques are often used to coat the digger teeth surface for better wear resistance [6]. Generally, the hardfacing alloys are eutectic steels with Cr, Nb and V [8] or hypereutectic white irons with high Cr [6]. The hardfacing alloys form hard carbides on the digger teeth surface which resist wear.

2.2.2 Wear mechanisms of digger teeth

The excavation process of the particulates takes place by a combination of steps; penetration, breaking of material, scooping and lifting for loading into bucket. During these operations, the digger teeth undergo extensive abrasive wear and impact loads. This is very difficult to monitor and calculate the impingement
velocity, impingement angle and contact stresses experienced by the tooth surface during ground engagement without systematic field trials. Tupkar and Zaveri [260] calculated maximum stresses which may generate at the tooth tip due to the regular and maximum contact with the soil. They used analytical method and maximum shear stress theory and verified the results with finite element modelling. The maximum shear stress reported at the tooth tip using the former method was 96.39 MPa whereas the FEM modelling showed a shear stress value of 112.98 MPa. Similarly the FEM study by Dagwar and Telrandhe [261] shows a maximum shear stress acting on the tooth of 43.45 MPa. The data presented above may give some indication about the contact stresses acting on the tooth, however, the field operating conditions may very case to case resulting in a significant variation in the contact conditions and wear of tooth material. Unfortunately, in the present study neither any field operating conditions were monitored nor any such data had been provided by the industry other than the tooth position and weight loss data.

Limited literature is available on the metallurgical failure analysis of a worn digger tooth. Based on the specific mining environment, Mashloosh, Eyre and Bulpett [6, 76] investigated a digger tooth of martensitic steel and reported presence of surface white layers. The white layer was found to be a structurally and chemically homogeneous phase. This consisted of fine equiaxed grained martensite with homogenous distribution of very fine M₃C and M₇C₃ carbide particles. The white layer grain size was reported to be 200 nm with a hardness of 1200 ± 30 HV. No traces of Oxides or Nitrides were found that could be responsible for higher hardness of the white layer [76]. The subsurface was reported to be localized tempered martensite caused by the heat evolved during the deformation process. The white layer was etching resistant but the subsurface layer showed increased etching response. The results were in good agreement with the impact abrasive wear mechanisms, as discussed in Section
2.1.1.1. **Figure 2.30a** represents the worn tooth microstructure delineating three distinct regions, 1) white layer, 2) tempered martensite and 3) undeformed matrix. A microhardness profile measurement is shown in **Figure 2.30b**, displays the high hardness of white layer followed by a significant drop in hardness in the tempered region. The lower hardness value was attributed to the tempering occurred in that region by the heating effect during operation of the digger tooth. A similar thermal softening during impact wear is discussed in **Section 2.1.1.1.3.3**. The tempered region is followed by the undeformed matrix. Martensitic steels of hardness ~700 HV with good work hardening capacity was suggested for the digger teeth steels by Mashloosh [6].

![Figure 2.30](image)

**Figure 2.30.** a) Cross-section of worn digger tooth: Region 1 - white layer, Region 2 - tempered martensite and Region 3 - undeformed matrix, b) microhardness through white layer towards undeformed matrix [6].

Bryggman et al. [235, 236] investigated a martensitic digger tooth which was worn during loading of wet blast stone. They compared the abrasion of digger teeth with gouging abrasive wear. The cross-sectional microstructure of the worn tooth material was similar to the findings of Mashloosh [6], comprising of white layer at the surface followed by the soft tempered martensitic layer and
unaffected matrix. The material removal was attributed to the surface fatigue, chipping and fragmentation by the grooving action of the hard abrasives. The heavily deformed subsurface favoured the material removal, on-setting cracks at the boundary between hard and brittle martensite (white layer) and tempered martensite (soft layer). Quenched tempered steels (510 – 545 HV), tool steels (430 – 560 HV) and HSLA steel (505 HV) were used for field tests. The field test results showed a good correlation with the hardness of the materials. High-Cr tool steel (560 HV) displayed higher wear resistance. They [235] also conducted pin-on-disc, single pass pendulum grooving and multi pass pendulum grooving laboratory wear tests with the same steels. The pin-on-disc and single pass pendulum grooving provided a rational correlation with the field results and the High-Cr tool steel exhibited higher resistance to wear. Interestingly the multi pass pendulum grooving laboratory wear test showed a poor correlation with the field results and a higher wear rate was reported for the High-Cr tool steel in this test. However, the research does not provide detail about the discrepancy found in case of multi pass pendulum grooving wear test [235]. Expectedly, the High-Cr tool steel was recommended for digger teeth application in contrast to Mashloosh [6] where a material of high hardness with a considerable amount of workhardening capability was proposed.

Changming et al. [262] proposed the digger teeth wear mechanism of impact abrasion nature. According to them, under external force the tooth surface starts deforming elastically. With further load by the blunt edges of rock particles the material was extruded forward. Once the tooth material reached the yield point, plastic deformation occurred. The rock grain pushed the material ahead to form a trench and plough the material to both sides of the trench. The plastic deformation resulted work-hardening and stress concentration. Thus, the local tensile stress generated microcracks which on further deformation resulted in
wear loss by microchip formation. In contrast to Mashloosh [6] they recommended Hadfield grades for digger teeth applications due to the high workhardening capacity.

2.3 Summary/Gaps

The current literature review provides an overview of wear mechanisms in context of excavator digger teeth. These teeth are mechanically clamped in front of excavator buckets, used in mining, agricultural and material transportations. During excavation and lifting of soil, rock or ore particles the digger teeth undergoes severe wear and abrasion. Generally hard martensitic steels are used to manufacture digger teeth to resist wear. The major findings on digger teeth wear mechanisms and proposed materials are provided below;

1. Worn digger teeth failure analysis reveals different mechanisms in different applications. Thus, the nature of abrasive particles, machine loads, operating conditions, tool geometry and environmental factors are important. Without examining the wear mechanisms of a worn tooth, it is unrealistic to prescribe a wear resistant material.

2. There is no generally accepted wear test for ground engaging tools. The Impeller tumbler test displayed a rational correlation of the wear conditions to those encountered by digger tooth. But the test designs and the parameters given in the literature needed further improvement to achieve higher wear rate and with significant surface and subsurface deformations. Thus, an up-scaled tumbler test may be appropriate.

3. The grooving wear occurs during penetration of a hard particle on the softer surface. Three mechanisms are responsible for grooving wear; a) ploughing, b) wedging and c) cutting. The grooving wear is characterized by two parameters degree of wear $f$ and depth of penetration $\delta$. The $f$ plot as a
function of $\delta$ provides useful information about the low to high wear transitions. Grooving wear is simulated using scratch indenter test (Chapter 6) but limited tests are claimed out using near millimetre scale abrasive tips. The preconditioning of the scratch test surface is also an important factor. In reality, the workhardened surface of digger teeth encounters repetitive impact and rolling sliding actions by the abrasive particles. Thus, scratch tests on both virgin materials and prior workhardened surfaces may provide insights of grooving wear which is typical in field wear.
3 Research methodology

3.1 Research outline

The objective of the current research is to identify the operating wear mechanisms in context of excavator digger teeth to re-create similar mechanisms in the laboratory and explore candidate steels. The working framework is that a combination of post-mortem tooth analysis, tumbler testing and scratch testing can provide the insights required.

3.2 Materials and procedures

A brief overview of research materials and methodology is described in this Section. However, additional details are described in each Chapters separately. Worn digger tooth of tempered martensitic microstructure was provided by Keech Castings Ltd for forensic analysis. Several steel grades were chosen for wear tests in impact and grooving wear conditions (Table 3.1).

Table 3.1 Chemical composition and bulk hardness of the steels for wear tests.

<table>
<thead>
<tr>
<th>Steels</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Co</th>
<th>Al</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Cu</th>
<th>Hardness, HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>0.12</td>
<td>0.25</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>198</td>
</tr>
<tr>
<td>Current</td>
<td>0.32</td>
<td>1.4</td>
<td>1.2</td>
<td>0.02</td>
<td>-</td>
<td>-</td>
<td>1.7</td>
<td>0.35</td>
<td>0.12</td>
<td>0.25</td>
<td>475</td>
</tr>
<tr>
<td>tooth steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bainite</td>
<td>1.0</td>
<td>2.9</td>
<td>0.8</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>571</td>
</tr>
<tr>
<td>Martensite</td>
<td>1.0</td>
<td>2.9</td>
<td>0.8</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>677</td>
</tr>
<tr>
<td>Pearlite</td>
<td>1.0</td>
<td>2.9</td>
<td>0.8</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>323</td>
</tr>
<tr>
<td>Hadfield</td>
<td>1.26</td>
<td>0.65</td>
<td>12.08</td>
<td>-</td>
<td>-</td>
<td>0.13</td>
<td>0.0149</td>
<td>-</td>
<td>-</td>
<td>0.0114</td>
<td>214</td>
</tr>
</tbody>
</table>
Mild steel equivalent to AISI 1018 being softer material (190 HV) was used for initial trials. The current tooth steel (0.3% carbon, tempered martensitic microstructure, 475 HV)) similar to the digger tooth steel was used for comparison with other steels. A high carbon and silicon grade steel with three distinct microstructures: a) Carbide free bainite (570 HV) with finely distributed ferrite lath and 20-30% retained austenite being able to provide TRIP effect, b) tempered martensite with high hardness (677 HV) and c) fine pearlite (323 HV) were used for the wear tests. A Hadfield grade steel of ~12% Mn was also incorporated, to study the workhardening effect on such high impact wear conditions.

- **Impeller tumbler and Scratch tests:** An Impeller tumbler test rig was designed to simulate impact wear conditions with 10 kg basalt aggregates (size 50-80 mm), Impeller speed 800 RPM, drum speed 70 RPM per 10 minutes test cycle. The scratch test with spherical (~0.82 mm) indenter tip, made of cemented tungsten carbide (WC) + 10% cobalt was used to simulate grooving wear conditions with load range 500-2000 N.

- **3D Scan:** The new and worn teeth were scanned with a 3D scanning machine (Polygonia, Absolute Arm seven axis "SI" series) for dimensional comparison.

- **Optical profilometry:** Alicona infinite focus instrument, Austria made was used to analyse the surface impact craters, grooves and scratch events. The scanned profiles were superimposed on coordinate system with Alicona software, reference zero plane was set by aligning the ridges on a straight line. Surface roughness parameters were evaluated for further analysis.

- **Microscopy:** The cross-sectional microscopy was conducted, using Optical microscopy (Model - DP70, Olympus, Japan), JEOL Neoscope and scanning electron microscopy, Supra 55 VP, Carl Zeiss, Germany SEM machine. Samples were cleaned with ethanol in ultrasound bath, hot mounted, coarse ground by 80, 240, 600, 1200 grit SiC papers and fine polished by 15, 6, 3 and
1 μm diamond suspension. 3% Nital solution was used for etching for optical microscopy, Model - DP70, Olympus, Japan. Electron microscopy was conducted at an accelerated voltage 20 kV and SE2 and ASB detectors using Supra 55 VP, Carl Zeiss, Germany SEM machine. Samples were OPS polished and kept in vacuum 24 hours prior to electron microscopy. Most commonly occurring surface features like plastically deformed ridges, furrows, impact craters, delaminated layers, chipping and cracking were identified that represent the deformation mechanism.

- **Microhardness**: Struers make, DuraScan microhardness machine was used for microhardness measurements at 25 gf load, 10s dwell time. The bulk hardness of each material is an average of 10 measurements.

- **EBSD and EDX**: A Jeol JSM 7800F FEG-SEM with EBSD detector and Supra 55 VP, Carl Zeiss, Germany SEM with EDX detector were used for EBSD and EDX measurements. EBSD helped to map the grain structure of the surface white layer whereas entrapped ore particles at the surface layers were confirmed by EDX.

- **XRD**: It was necessary to confirm the phases present in the steel microstructures. X-ray diffraction technique confirms detection and quantification of phases. A Philips PW 1130 diffractometer with graphite monochromatic Co-ka radiation at 40 kV and 30 mA in the 2θ range of 40–105° at a rate of 0.02°/15s was used to perform X-ray measurements for qualitative and quantitative analysis of steel phases.
4 Analysis of worn tooth

4.1 Aim and scope of work

This chapter outlines a comprehensive 'forensic' examination of worn digger tooth which was used in an iron ore mining site in southern Australia. During excavation, the digger tooth experienced significant impact and penetration into the material surface resulting in a higher wear loss.

At first the worn tooth profile was superimposed with a new tooth profile to study the changes in geometrical shape. This comparison identified the location of high and low wear zones. A significant number (~60) of wear grooves were measured systematically to plot the degree of wear $f$ as a function of depth of penetration $\delta$ (see Section 2.1.1.2). These measurements were used to identify the wear modes.

Worn surface microscopy was conducted for damage evaluation at different locations of the tooth. The digger tooth was then sectioned for microstructural examination using optical and scanning electron microscopy (for EDX and EBSD). These results were used to gain an understanding of how the microstructure influences wear and also how it evolves during service. In summary, this is necessary to understand;

- the nature of the wear grooves,
- the role of the near surface microstructures,
- the main parameters that wear tests need to estimate.

These results are used in later chapters to validate that laboratory tests provide a useful simulation of service conditions.
4.2 Worn digger tooth background - mine site and gravel particles

A digger tooth of ~0.3% carbon steel, sand cast, homogenised and quenched-tempered was subjected to iron ore excavation in Southern Australian mine. Figure 4.1a displays the tooth before service. After 20 hours of service the same tooth was found to be significantly damaged (Figure 4.1b) and replaced.

![Figure 4.1a and 4.1b](image)

Figure 4.1. a) Excavator digger tooth as finish product before mining operation, b) the same tooth after 20 hours of service. The arrow marks display respective tooth lengths.

There were six digger teeth, mechanically clamped with the bucket clamping station (Figure 2.21), engaged in digging operation. The bucket digging force at a 40° penetration angle was calculated to be 1050 kN, or 175 kN per tooth. Figure 4.2 represents the mining site conditions.
The excavation operation was carried out to mine jasplite rock which is composed of dense crypto-crystalline silica traversed by fine quartz veins. The rocks are extremely hard and tough, breaking with a splintery fracture. These
Chapter 4. Analysis of worn tooth

Siliceous rocks contain irregular veins and nests of black manganese oxides and colours may vary from black through grey, green, red, and orange to white [263]. The gravel size varies extensively in mining site as shown in Figure 4.3.

Figure 4.3. a) View of jasplite gravel particles in mine site; b) size of ore particles. Images received and used with permission from Keech Castings Ltd.

The field study on material usage per hour was conducted by the Keech Castings Ltd. 17 sets of such teeth (Figure 4.1a) at 6 stations were in service for digging iron ore for a period of 2026 hours. The material consumption wear rate was estimated to be 2-4 kg.m$^{-2}$ hour$^{-1}$ for the digger teeth. The damaged tooth is shown in Figure 4.1b. The wear rate is specific for the mine site, rock particles, digger tooth geometry, excavation machine and other operating and environmental factors. But at the same mine site with similar conditions, the wear rate was consistent, as reported by Keech Castings. Thus, the present study is conducted based on the wear mechanism of the above stated wear conditions.
4.3 Experimental Methods

4.3.1 Material from Industry

The steel used for the digger teeth is a medium carbon steel (Table 4.1). The steel is sand cast, homogenised and heat treated in accordance with Figure 4.4 to achieve quench and tempered martensitic steel.

Table 4.1. Composition of the digger tooth steel.

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Cu</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.32</td>
<td>1.40</td>
<td>1.20</td>
<td>0.20</td>
<td>1.70</td>
<td>0.35</td>
<td>0.120</td>
<td>0.25</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

Figure 4.4. Heat treatment of the current tooth steel.

Samples were taken from both surface and core, and the microstructure was examined. The microstructure is shown in Figure 4.5a, which confirms a martensitic phase.

XRD analysis confirms the microscopic evaluation of the microstructure. The indexed peaks in Figure 4.5b confirms, presence of martensite and the Rietveld
refinement results indicate that the sample is 100% martensitic phase.

Figure 4.5. a) Quenched tempered martensitic digger tooth steel; b) XRD spectra of digger tooth quenched-tempered steel.

The mechanical data was supplied by the Keech Castings Ltd, summarised in Table 4.2.

Table 4.2. Mechanical properties of tooth steel supplied by Keech Castings Ltd.

<table>
<thead>
<tr>
<th>UTS, MPa</th>
<th>Yield, MPa</th>
<th>% Elongation</th>
<th>Hardness, HB</th>
<th>Impact, j @ room temp</th>
<th>Impact, j @ -40°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1618</td>
<td>1461</td>
<td>4.0</td>
<td>514</td>
<td>27</td>
<td>22</td>
</tr>
</tbody>
</table>

A cross-sectional Brinell hardness measurement was conducted by Keech Castings Ltd to verify the hardness profile from surface to the core. It was also cross-checked by the present author in Deakin University. Both results were found consistent. Figure 4.6 represents the hardness profile supplied by the
industry. Each hardness data comprises an average of at least three data points taken at appreciable distance to avoid nearby strain effect. The core structure is softer than the outer area. It has a significant effect in abrasive wear of material as soon as it reaches the softer part of the tooth core.

![Figure 4.6](image.png)

Figure 4.6. Digger tooth cross-sectional hardness to verify through hardening. Image received and used with permission from Keech Castings Ltd.

### 4.3.2 Wear and material characterization method

#### 4.3.2.1 3D scan of worn tooth

The new and worn teeth (Figure 4.1a and b) were scanned using a commercial 3D scanner machine (Polygonia, Absolute Arm seven axis "SI" series), see Figure
4.7. It has a portable measurement arm, designed for acquiring 3D measurements from points and surfaces within its workspace with a simple manual movement of the user. This is done by a non-contact technology for data acquisition, using a scan laser scanner.

![3D scanning machine](image)

Figure 4.7. 3D scanning machine.

Thus, CAD models of the teeth were developed to understand the change in shape and dimensions of the worn tooth during its service life. The scanned profiles were superimposed using Solidworks software to carry out shape assessment. This also allowed a close look at the surface of the worn tooth to identify the impact abrasion and grooving appearances. Figure 4.8a and b respectively show 3D models of the new and worn teeth. Due to different alignment and orientations, dimensional aspects of the teeth are not comparable based on these images.
4.3.2.2 Sample preparation techniques

A horizontal bandsaw (Figure 4.9a) was used to cut samples from the tooth from different sections and to the desired sizes. An abrasive cutter was used to cut the tooth samples to smaller sizes. Accutom (Figure 4.9b) was used for precision cutting to the final sizes to avoid the heat effect on sample metallurgy.
Chapter 4. Analysis of worn tooth

Samples were hot mounted, coarse ground by 80, 240, 600, 1200 grit SiC papers and fine polished by 15, 6, 3 and 1 μm diamond suspension. 3% Nital solution was used for etching for optical microscopy. The optical microscope was a Model - DP70, Olympus, Japan. Electron microscopy was conducted at 10KV voltage and SE2 detector using a Supra 55 VP, Carl Zeiss, Germany SEM machine. Samples were OPS polished and kept in vacuum 24 hours prior to microscopy. Light electron microscopy on worn surface was conducted using a JEOL Neoscope.

4.3.2.3 Surface optical profilometry

An Alicona infinite focus instrument shown in Figure 4.10 was used to measure wear grooves profiles.

![Alicona optical profilometry instrument.](image)

The desired area of the sample was scanned and superimposed on a global coordinate system. This excluded the ‘Form error’ that appears from presence of planar, parabolic or polynomial reference planes. Alicona software was used to
analyse the scanned surface for roughness and waviness profiles.

4.3.2.4 EBSD and EDX

A Jeol JSM 7800F FEG-SEM with EBSD detector and Supra 55 VP, Carl Zeiss, Germany SEM with EDX detector were used for EBSD and EDX measurements. For both cases, due care was taken in sample preparation to remove any surface scratches or impurities. EBSD Software – AZtecHKL and EDS Software – AztecEnergy were used to analyse the results.

4.4 Results

4.4.1 3D scan of worn tooth

Figure 4.11 displays a 3D scanned image of the worn digger tooth. Significant groove marks and plastic deformation are visible throughout the surface. The image also indicates a differential wear behaviour according to the tooth locations. The bottom surface which is not visible in this picture was worn significantly due to the sliding velocity at low angle. The nose area had undergone high angle impact wear and became blunt. Grooves are visible at the side faces which underwent a severe plastic deformation. The upper surface indicates a lower surface damage and corresponding wear loss compared to the nose and side faces. The observation is reasonable as the upper surface undergone predominantly rolling/sliding abrasion whereas the nose and side faces experienced significant impact abrasive wear. Samples for failure analysis were prepared from different locations to get representative results.
4.4.2 Shape wear assessment of worn tooth

In this Section, dimensional changes of the excavator tooth are examined. The shape assessment was done in orthogonal projections of the worn tooth which were then compared with a 3D model of the initial tooth. Figure 4.12 shows the orthogonal projections of the worn tooth, aligned using Solidworks software to eliminate positioning error. The wear is slightly asymmetric due to the off-centre location of the tooth on the bucket. Figure 4.13 compares the new tooth geometry with that of the worn tooth. A significant shortening of the tooth length within 20 hours of service indicates a harsh tribo-environment resulting in a higher wear loss. The apex of the tooth moved upward confirms that the
bottom face undergone severe wear loss compared to the upper face.

Figure 4.12. Orthogonal projections of worn tooth.

Figure 4.13. Dimensional comparison between new and worn tooth.

The top and bottom projections are shown below in Figure 4.14. The tip radius
became blunt and some signs of thickening indicate severe plastic deformation.

Figure 4.14. a) Top face projection and b) Bottom face projection.

### 4.4.3 Construction of f plot

A $f$ plot was constructed for the worn digger tooth surface, based on the grooving wear model [39, 41] to differentiate the dominant wear mechanism. Three stages of grooving wear were identified, i) ploughing mode manifested by plastic deformation ii) wedge formation and iii) the most severe cutting mode, characterized by higher penetration depth and removal of material by chip formation. The degree of wear and degree of penetration are given in Equation 2.9 and Equation 2.10. Based on the grooving wear schematic diagram (Figure 2.13), the degree of penetration $D$ is expressed as penetration depth normalised by radius of curvature $R$, instead of half groove width $a$. This is because $R$ directly
correlates the abrasive particle size in field than that of $a$. Since the expression of degree of penetration $D$ is changed, the notation of $D$ has been changed and should be read as $\delta$ in rest of the thesis. Thus, the expression of the degree of penetration $\delta$ becomes;

$$\delta = \frac{d}{R} \quad \text{Equation 4.1}$$

Where the relationship between $a$ and $R$ can be expressed as (Figure 2.13);

$$a \approx \sqrt{2Rd}, \text{ (for } R \gg d). \quad \text{Equation 4.2}$$

Thus, approximately ~60 grooves were chosen from upper, nose, side and bottom faces of the worn tooth. A wear mode assessment was carried out by examining the selected grooves. For example, a macroscopic view of a groove is displayed (Figure 4.15) which was scanned and analysed using optical profilometry. Figure 4.16 is the SEM image of wear grooves and adjacent material build up regions.

Figure 4.15. Wear groove on worn tooth surface.
Figure 4.16. Worn excavator tooth abraded surface showing grooving wear and ridge formation by plastic deformation.

After scanning, ‘Form’ errors were removed from the sample plane by using Alicona software and superimposed on a global coordinate. This helped to set the zero-reference level of the surface profile. The data were exported into a Microsoft excel file to measure the groove and ridge areas. Only those grooves were considered where the ridge profiles matched clearly on the zero-reference line. Therefore, grooves which were affected by the adjacent grooves or impacts were discarded in construction of the f plot. Profile length and width were kept sufficiently large to cover maximum groove area to achieve average profile data.

As an example, the groove profile in Figure 4.15 was measured in accordance with Figure 4.17a. The blue rectangular area on the groove represents the average profiling. The exported groove profile is shown in Figure 4.17b where the terminal points of the groove match with zero-reference line.
Figure 4.17. a) Wear groove profile measurement, b) Mean profile plot (Reference Figure 4.15).

Figure 4.18a, b and c exhibit examples of three groove profiles delineating three wear mechanisms. The ploughing profiles display larger ridge areas with lower groove depth whereas cutting profiles are the opposite. Profiles belong to wedge mode display intermediate depth and ridge area compared to cutting and ploughing profiles.
Figure 4.18. a) Cutting wear profile higher groove depth and lower ridge area, b) wedging profile manifests intermediate groove depth and ridge area, c) ploughing wear profile delineating lower groove depth and corresponding higher ridge area.

Similar profiles were used to construct the $f$ plot (degree of wear versus degree of penetration), see Figure 4.19. The $f$ plot displays a S type curve (reference Figure 2.14) where majority of the points belong to the cutting and wedging regions. Lower penetration depths are associated with plastic deformation. It is possible that in service the tooth displayed a greater degree of deformation than indicated due to ridge wear by fine particles.
Chapter 4. Analysis of worn tooth

Figure 4.19. Worn digger tooth \( f \) plot as a function of penetration depth normalized by groove radius of curvature \( \delta \). \( R \) was measured using Equation 4.2.

4.4.4 Worn surface characterization

The worn surface characterization was conducted with the samples collected from upper face, nose, side and bottom faces. Most of the worn tooth surface shows significant signs of damage, ploughing grooves, craters and delaminated wear debris. The upper face displays lower wear due to simple rolling over of the loose ore particles (Figure 4.20a and b). The nose part exhibits presence of craters and ploughing grooves (Figure 4.20e and f). However, this is difficult to distinguish whether these craters formed by percussive effect or those are high angle indentations. The side face (Figure 4.20c and d) represents the ridge areas formed by plastic deformation which is consistent with the worn tooth profile side face thickening observed in Figure 4.14. The bottom face (Figure 4.20g and h) is the highly worn area. Significant signs of material loss as delaminated flakes
by substantial grooving action are evident.

Figure 4.20. Worn surface; a) and b) upper face delineating rolling sliding abrasion, c) and d) side faces showing localized plastic deformation and material pile up, e) and f) nose area depicting signs of craters and ploughing, g) and h) bottom faces with significant material loss as high wear region.
4.4.5 Microstructural characterization

In this segment microstructures beneath the worn surface were examined. Samples were collected from the locations identified in Figure 4.11. Sections 1 and 2 at Figure 4.21 were cut along AB and CD lines respectively.

Figure 4.21. 3D view of sample drawn from nose part of the worn tooth, indicated in Figure 4.11 for metallography. Section 1 was cut along AB line to view microstructure at perpendicular to abrasion direction and Section 2 was cut along CD line to view microstructure at parallel to abrasion direction.

For metallographic Section 1 in Figure 4.22a, a white layer can be observed beneath a significant groove. Higher magnification view of Figure 4.22a reveals flow lines that may be formed by shear deformation caused by contact with ore particles, see Figure 4.22b. The brittle white layer at the surface with a thickness ranging from 20 µm to 100 µm was found (Figure 4.22). Figure 4.22c shows the presence of a fold in the white layer. Probable embedded particles are evident.
in Figure 4.22d. These were analysed using EDX, discussed in Section 4.4.6. A subsurface deformed zone beneath the white layer is evident in Figure 4.22f.

Figure 4.22. Microstructure perpendicular to abrasion direction; a) White layer formation along groove by shear deformation, b) flow lines beneath surface deformed zone by shear, c) fold inside white layer, d) possible embedded particles, e) brittle fracture of surface white layer, f) subsurface deformed zone.
Chapter 4. Analysis of worn tooth

The microstructures in metallographic Section 2 parallel to the abrasion direction illustrates adiabatic shear bands (ASB) beneath the white layer (Figure 4.23a). A similar white layer with an embedded particle is evident in Figure 4.23b. The presence of embedded particles was found quite often in the surface layers.

![Microstructure parallel to abrasion direction; a) Adiabatic shear bands (ASB), b) similar embedded particle.](image)

Figure 4.23. Microstructure parallel to abrasion direction; a) Adiabatic shear bands (ASB), b) similar embedded particle.

### 4.4.6 EDX analysis to confirm embedded ore

Figure 4.24 shows a SEM micrograph of a deformed matrix at the worn tooth surface where some of the material was plastically deformed. The underlying material between the plastically deformed region and the surface white layer contrasts with the deformed material. This underlying substance and surrounding region were chosen for Energy Dispersive X-Ray spectroscopy.
Figure 4.24. SEM micrograph showing organic mounting substance at upper part, steel matrix at lower part and probable embedded particle at middle.

An elemental chemical analysis was carried out which confirms that upper black region in Figure 4.25b is the carbon enriched resin material, used to mount the sample. Elemental presence of Oxygen (O), Silicon (Si) and Iron (Fe) were confirmed in respective Figure 4.25c, d and e. Thus, it may be concluded that the selected region appears to be primarily silica (SiO₂) and possibly traces of iron silicates, confirming a foreign embedded particle.
Chapter 4. Analysis of worn tooth

Figure 4.25. EDX analysis; a) C rich organic substance in blue region, b) O rich green region confirms oxides at middle, c) Si rich purple region at middle part evidences presence of silica material, d) Fe rich red region is the steel matrix with traces of Fe in the middle part.

4.4.7 Groove - white layer correlation

Literature suggests that there is a significant effect of load on groove depths [66]. But the relation between groove depth and the microstructure beneath the grooves is still not clear. Samples were prepared from different locations as shown in Figure 4.11. The maximum valley depth ($W_v$) at different locations were measured and plotted (Figure 4.26). The maximum valley depth ($W_v$)
provides a measure of the groove depth indicating severity of wear. The lower valley depth at upper surface indicates a low wear region occurred by rolling sliding abrasion. Moving from nose to side and bottom faces an increasing valley depth was obtained. This indicates an increasing trend in groove depth resulting in a higher wear rate.

![Graph](image)

Figure 4.26. Variation of maximum valley depth ($W_v$) at different locations as a wear severity index.

Metallography was performed for all the samples, used for valley depth measurements from different locations. For convenience, two microstructures from upper and side faces are represented here indicating low and high wear zones. Cross-sectional microstructure of the respective edges was superimposed with groove depth profiles. The superimposed images of the surface profile and corresponding underlying microstructure are displayed in Figure 4.27. This technique was found to measure the maximum depth of an individual groove.
and the average thickness of the underlying white layer beneath precisely. Investigation of the respective microstructural images reveals the presence of ~75% white layer along the edge in sample from upper face and ~85% in case of sample from side face. The percentage numbers of white layer at the respective samples indicate that most of the sample surfaces were covered with white layer. However, the thickness of the white layers varied significantly with the gouging events occurred in accord to tooth locations.

Figure 4.27. Superimposed images of surface profile with underlying microstructure. The Y axis represents surface profile depth corresponding to ‘zero’ reference line and X axis represents sample length; a) upper face representing low wear zone and b) represents side face high wear zone.

When the average thickness of underlying white layer was plotted as a function of the corresponding maximum groove depth, a linear relationship is evident in Figure 4.28. The result indicates that the loading effect governs the groove depth. The thick white layer formation might be resulted from a single gouging event which implies a direct correlation between the white layer thickness and the energy of the gouging event.
4.4.8 Work hardening from surface to matrix

Workhardening is a critical mechanism for a material during wear processes. Various literatures [18-23, 44, 59, 85, 88, 230] reported the presence of workhardening at the surface when subjected to impact and rolling or grooving abrasions. The white layer hardness depends on in-situ surface development [88]. The subsurface is strain hardened by the deformation and dislocation generation caused by the impacting particles [85, 88]. The plot below (Figure 4.29) refers the surface to matrix hardness profile using the locations described in Figure 4.30. The Y axis in Figure 4.29 depicts hardness values, starting from the surface white layer and moving into the matrix, see Figure 4.30. The X axis is the distance from the surface (0 µm) moving into the matrix along AB, CD, EF,
GH and IJ lines (Figure 4.30). The hardness values plotted are average values obtained from points on each of the AB, CD, EF, GH and IJ at the same distance from the surface. For example, the 1st point of the plot representing average hardness value of white layer, comprises measurements at data points A, C, E, G and I. The bulk hardness of the material was 510 HV. A significant ~31% increase in hardness was found at the surface white layer (average 670 HV) up to a depth of ~80 µm from surface. A softened layer was recorded just beneath the white layer. The average hardness of the soft layer was found to be 490 HV (~4% lower than bulk hardness) and extended up to ~200 µm from the white layer. The deformed subsurface layer had an average hardness of 585 HV, ~14% more than the bulk hardness and continued up to ~700 µm.

Figure 4.29. Average microhardness data along white layer, deformed subsurface and matrix.
Figure 4.30. Reference micrograph delineating microhardness data according to the lines AB, CD, EF, GH and IJ, used to construct the plot (Figure 4.29).

Microhardness was measured at various identified features of the deformed microstructure to verify repeatability. Figure 4.31a and b show hardness measurements through white layers, softened layers, adiabatic shear bands (ASB) and deformed subsurface regions at different samples.

Figure 4.31. Microhardness along white layer, soft layer, ASB and deformed subsurface regions at different samples.

The microhardness plot in Figure 4.32 demonstrates repeatable results at
respective locations. The average hardness of the adiabatic shear bands (ASB) was found to be quite similar to the hardness of surface white layer.

![Graph showing microhardness of white layer, soft layer, adiabatic shear bands and the deformed subsurface.]

Figure 4.32. Average microhardness of white layer, soft layer, adiabatic shear bands and the deformed subsurface.

### 4.4.9 EBSD analysis of white layer

A sample with a significant groove and white layer thickness was analysed with EBSD using Jeol JSM 7800F FEG-SEM with EBSD detector to determine the microstructure of the white layer. Figure 4.33a and b show the EBSD map sampling location. The microstructure was 60% indexed which was further improved to 80% with post acquisition software. Figure 4.34a is a SEM micrograph of the EBSD mapping area and Figure 4.34b is the respective EBSD map. The indexing was carried out using a cubic crystal structure. The microstructure of the white layer was found to be extremely fine grained and
the grain size estimated to be 600 nm.

Figure 4.33. Sample location for EBSD; a) on the white layer as shown in optical micrograph, b) SEM micrograph, c) EBSD map.

Figure 4.34. a) SEM micrograph, b) EBSD Map.
4.5 Discussion

The present study employs a ‘forensic’ analysis on abrasive wear of a digger tooth taken out of service. The motivation of the analysis was to understand; a) the wear mechanism considering surface grooves and subsurface deformation and b) to benchmark the important parameters which will guide the laboratory test requirements.

Interpretation of worn surface

The worn surface of the tooth was characterized with SEM. Sample surface from different locations reveals significant groove marks caused by the rolling sliding and scratching actions of the abrasive particles. The extent of plastic deformation and cutting wear were found to be varied according to the sample locations.

The nose area displays craters and ploughing grooves (Figure 4.20 e and f). Possibly those craters were formed by impacts or high angle indentations of the abrasive particles. Subsequent passage of the particles creates ploughing grooves. This part of the tooth shows a moderate plastic deformation and cutting wear. The shape wear assessment by 3D scan technique, described in Section 4.4.2, confirms that the apex of the tooth moved upward due to a severe underside wear as evident in Figure 4.13. The upper surface (Figure 4.20a and b) comparatively exhibits lower degree of wear scars caused by the rolling sliding abrasion of the loose ore particles.

The worn surface from side face of the tooth exhibits significant plastic deformation and wedge like formation, the lower tangential forces offered by the abrasive particles at the tooth sides are not enough to cause fracture of the plastically deformed ridges. Thus, materials remain adhered to the tooth surface causing higher plastic deformation and lower cutting. The top and bottom
Chapter 4. Analysis of worn tooth

projections in Figure 4.14 confirms a significant plastic deformation on the sides and there even some signs of thickening. However, there is a possibility of geometric variation for thickening in the castings.

The bottom face (Figure 4.20g and h) exhibits extreme wear with predominantly cutting. Perhaps, the bottom face experienced significant frictional resistance from the ground material against the low angle tangential sliding velocity. The micrographs represent heavily deformed wear surface with significant groove marks and delaminated flakes. The degree of deformation is lower in bottom face compared to the other faces rather material was found to be chipped off. Figure 4.13 supports the observation where the comparison with the new tooth profile displayed a higher wear loss at the bottom face of the worn tooth.

Wear mode

The worn tooth surface groove profiles may provide an insight of the operating wear mechanisms as discussed in Section 2.1.1.2. Several grooves were analysed to understand its nature and a $f$ plot (degree of wear as a function of degree of penetration) was constructed (Figure 4.19). The diagram implies that there exists certain critical value of degree of penetration $\delta$ that transforms the wear modes from ploughing to wedging and wedging to cutting. Hokkirigawa et al. [40] showed that the transition from ploughing to wedging is independent of hardness of the material. But increasing hardness decreases the wedge formation and increases cutting mode of wear. They also proposed [40] that degree of wear $f$ increases with increase in hardness resulting in higher cutting. Thus, the worn tooth $f$ plot demonstrates that the material surface became highly workhardened that lowered its deformation capability. The lower plastic deformation during groove formation led to higher material loss by microchipping depicting a dominant cutting wear mechanism [16, 31, 33]. Figure 4.18a displays a groove cutting profile defined by high penetration depth and
lower adjacent ridges. The bottom worn face (Figure 4.20g and h) exhibits higher cutting wear due to significant workhardening. Mezlini et al. [264, 265] correlated the operating parameters that influence the wear mechanisms in sliding abrasion. They proposed [264] that the particle geometry which determines the angle of attack and normal load have mutual effect on the wearing material microstructure. For aluminium alloys, they showed that increasing attack angles increases cutting wear, which is independent of normal load. But for nodular cast irons three wear mechanisms exist at attack angle < 30° and normal load < 15 N. Cutting dominates at attack angle > 45° which is independent of load. They also claimed [265] that workhardening decreases the wear rate for a spherical indenter but this cannot help the microstructure if the indenter is conical. They proposed that work hardening resists the wear only at the early stage and as wear progresses the work hardened layer are cut showing higher wear rate. Therefore, this is difficult to assess the effects of particle attack angle and loading conditions on the tooth surface in field. However, an alloy microstructure with high hardness, toughness and capable of crack propagation resistance can reduce wear for the digger tooth material [266]. In other words, if a material can shift the $f$ plot at the right side with lower steepness in Figure 4.19 may show a higher wear resistance. Hence an approach must be considered to conduct scratch tests on wear resistant steels at their virgin and workhardened conditions and compare the results with digger tooth $f$ plot. Work in Chapter 6 will explore the $f$ plot simulations in laboratory scratch tests.

**Interpreting surface and subsurface microstructures**

Microstructures and local mechanical properties have a significant influence on the response of a surface to impact and the subsequent wear processes. A detailed microstructural examination and evaluation of hardness throughout the worn tooth were carried out to gain insight into the changes in deformed region
than that of the undeformed matrix.

Cross-sectional microstructures beneath the worn surface were examined in perpendicular and parallel directions to the abrasion direction. The white layer was found to have a thickness ranging from 10–100 µm. Significant microstructural deformation features such as, flow lines formed by shear deformation beneath the grooves and folds in the white layer are evident. The presence of embedded particles in the surface white layer was confirmed by EDX analysis. This may have significant role to form recrystallized surface flakes which are detached during the process. However, this has not been investigated in the present study but the mechanism is discussed in Section 2.1.1.3.3.

The microhardness profile in Figure 4.29 reveals white layer hardness ~670 HV, less than the reported value 1200 ± 30 HV with grain size 200 nm [76]. The tooth analysis reported by Bulpett et al. [76] was a low alloy martensitic steel, replaced after extraction of 60000 t of gravel and reduced its mass from 10 kg to 6 kg. One of the reason for the difference between the hardness values may be due to the larger grain size of the white layer in the present digger tooth, 600 nm, confirmed by EBSD. However, there are several other contributing factors that can increase the white layer hardness, already discussed in Section 2.1.1.3.1.

The microhardness also depends on the material composition, microstructure and wear conditions. The white layer on the wearing surface is consistent with a microstructure arising in consequence of severe local deformation.

An attempt was made to illustrate the effect of loading on white layer thickness beneath the wear grooves. The technique described in Section 4.4.7 was found suitable for the study. The white layer thickness as a function of groove depth analysis (Figure 4.28) shows a clear correlation reflecting the geometry of the deformation zone. Thicker white layer was evidently common (Figure 4.27, Figure 4.30 and Figure 4.31) underlying deep grooves and in good agreement with Figure 4.28, where the white layer thickness has been plotted as a function
of maximum groove depth. The results indicate that the thick layer might have been formed by single gouging events and directly proportional to the energy of the gouging event.

The role of subsurface microstructure is critical in material removal process. The subsurface, shown in Figure 4.22f is associated with massive plastic strain. A softened layer just beneath the white layer and adiabatic shear bands (ASB) are evident in Figure 4.23a and Figure 4.31. The presence of softened layer was also reported in worn GETs [6] and attributed to the local tempering of the martensitic grains by heating caused by the impacting and sliding particles. Hutching [93, 94] proposed the mechanism of softening and its effect on material removal during impact wear, discussed in Section 2.1.1.1.3. Two important points about subsurface deformation are: i) it creates a work hardened layer and ii) it shows that there is enough plastic deformation with flow of material during wear, not just brittle material removal. Literature suggests [67, 88] that voids and cracks may nucleate in the subsurface which favours delamination. Another feature of the subsurface deformation was grain orientation towards the material flow direction defining the plastically deformed region and presence of adiabatic shear bands (ASB). The hardness plots in Figure 4.32 and Figure 4.31a and b show that ASBs have similar hardness values compared to the white layer. The formation mechanism of ASB and its effect in material removal is discussed in detail in Section 2.1.1.3.3. However, no voids or cracks were observed in ASB layers during the microstructural investigations in the present study.

Thus, the key features of the present analysis, where different mechanisms causing the wear, may be summarised as;

1. Plastic deformation as grooves are cut into the surface. Ore particles impact then slide across the surface white layer and chip forms at leading edge of contact and is eventually removed. The soft layer beneath the
white layer which was already created by severe impacts may facilitate the particle penetration effectively increasing the cutting wear.

2. Severe plastic deformation combined with heating/cooling from impacts forms a hard white layer on the surface. Beneath the surface a region of severe plastic deformation is formed. Further impacts damage the white layer, creating craters and chips as the particles slide over the surface. As the brittle white layer is removed, the next layer of material, already severely deformed, is exposed to the load and heat of the impact, converting to new white layer and so on. Along this process subsequently voids and cracks form in the subsurface and eventually join and the surface spalls.

In Chapter 5 tumbler test rig is used to simulate the impact wear conditions. Subsurface microstructures with similar features to those seen here are sought. Different steels of various hardness ranges are tested and ranked in accordance to their impact wear performance. The grooving wear on the workhardened surface was simulated on the steels in undeformed and deformed (Impeller tumbled) conditions (Chapter 6). Finally, a comparative study has been performed (Section 7) for all the steels both in impact wear and grooving wear conditions with reference to the wear features of the worn digger tooth.

4.6 Conclusion

A failure analysis of a worn digger tooth has been conducted in this Section. The low alloy martensitic steel displayed a significant wear loss during iron ore mining. A surface SEM characterization has been performed to understand the deformation mechanism. The surface groove profiles were analysed to construct a $f$ plot that displayed ploughing, wedging and cutting modes. A subsurface microstructural characterization and microhardness measurements from
surface to matrix were performed to understand the role of surface and subsurface during wear process.

- A simultaneous impact and grooving wear mechanism was found to be responsible for the material removal.

- The shape wear assessment was found to be consistent with the worn surface characterization. The upper surface profile of the worn tooth provides a decent match with the new tooth, exhibiting a low wear zone. The signs of thickening of the worn tooth side faces compared to the new tooth profile indicates a significant plastic deformation. The higher degree of material removal by the low angle tangential sliding velocity observed at the bottom face of the worn tooth evidently shown by the superimposed tooth profiles. The apex of the tooth nose moved upward delineating a higher underside wear.

- The \( f \) plot revealed that the major wear mode for digger tooth included the range from ploughing to cutting.

- The cross-sectional microstructure delineates formation of a brittle surface white layer (670HV) along with a work hardened subsurface zone (550HV) that remains in dynamic equilibrium. The white layer grain size was 600 nm.

- A linear relationship between the white layer thickness and groove depth was observed. Single gouging events probably being associated with both features. This implies that the white layer thickness is a strong function of the energy of the gouging event.

- An adiabatic shear band (ASB) resulting from localized thermal gradient and strain rates generated by impacting ores is also found at the subsurface. This region has a similar hardness to the white layer.

- Ore particles trapped in the surface of the worn tooth were common.
5 Impeller tumbler tests

5.1 Aim and scope of work

The current chapter deals with the development of a laboratory grade wear test rig and its application to rank different steels by wear resistance. The goal is to use this test to select materials that will offer improved wear resistance. The Impeller tumbler test rig was employed to replicate the extreme harsh field wear conditions. The current tooth martensitic steel grade (referred as current tooth steel in rest of the thesis) was subjected to Impeller tumbler testing and the wear features were compared with the field wear references obtained from worn tooth analysis. Different steels (mild steel, current tooth steel, Hadfield steel, high carbon: bainite, martensite and pearlite steels) with varying degree of hardness and work hardening levels were tested and ranked as per their wear performance. An effort has also been made to understand and explain the underlying mechanism of wear in impact conditions. Surface profilometry, worn surface and subsurface characterization by SEM and optical methods, hardness profiles by Vickers microhardness apparatus and XRD techniques were adopted to understand deformation mechanism.

5.2 Introduction

The ‘forensic’ analysis of worn digger tooth revealed significant surface damage (Figure 4.21), along with severe microstructural deformation (Figure 4.22). An approach was made to create similar surface and subsurface deformation with the current tooth steel in laboratory to replicate similar wear conditions. Field wear tests for material selection are time consuming and the cost of experiments is quite high. It is also highly dependent on the wear conditions that
may vary with environmental conditions (discussed in detail Section 2.1.4). Therefore, a controlled laboratory wear test rig was required to replicate digger teeth field wear conditions. Section 2.1.4 describes several different types of laboratory wear test methodologies. Those were developed to meet specific wear conditions and respective alloy development. Thus, it was necessary to design a wear rig that can simulate field particles (shape, size, hardness and abrasiveness) and impact abrasion features as impact force, velocity and impact angle. Brief descriptions have been provided on available wear test rigs in Section 2.1.4. The parameters which influence abrasive wear are difficult to simulate in a single wear test rig. Tylczak et al. [157] proposed that laboratory wear tests can only provide a reliable ranking of materials if the laboratory and field wear test mechanisms are similar. The wear ranking of materials based on hardness is worthy only if the wear mechanism is purely abrasion. If the wear mechanism is changed into impact or gouging then toughness and workhardenability control the wear rate [157]. The wear mechanism of the digger tooth suggests a high stress impact and significant grooving wear by ploughing and chipping, discussed in Section 4.5. Similar wear mechanisms of digger teeth were reported in [6, 76]. The Impact actions can be simulated in Pendulum grooving test and Impeller tumbler test, eliminating the other two/three body abrasion tests DSRW (Figure 2.21) and Pin-on-drum (POD) (Figure 2.22). But Pendulum grooving test only simulates impact conditions and neglects the abrasive wear offered by rolling sliding action by the ore particles [235, 236]. The POD and DSRW tests are unable to use field abrasive particles. Mostly these two tests rank materials on hardness and do not consider toughness and workhardenability of the materials. For example, High-Cr white cast iron provides higher wear resistance in POD and DSRW tests as the hard carbide phases resist penetration reducing the wear rate. But the wear rate of the same material is increased considerably in impact or gouging actions due to severe fragmentations of the hard carbide phases [157].
Chapter 5. Impeller tumbler test

Jaw crusher explicitly offers gouging behaviour but does not effectively simulate impact action. For example, the 13% Mn steel of Hadfield type combatted impact abrasive wear efficiently due to its workhardening capability. But the same material showed a reduced wear resistance in Jaw crusher test as the gouging action removed the material so rapidly that workhardening could not support the material [157]. The Impeller tumbler test rig (Figure 2.24) was chosen because this carries the best combination of impact and rolling/sliding interaction between the test surface and ore [9, 12]. The Impeller tumbler test was used previously [9-12, 184, 243-245] to test materials in moderate-stress abrasion. This test shows lower dependency on hardness indicating a dominant role of work hardening contrary to DSRW and POD test methods [184]. In contrast to DSRW test, white layer formation was reported by Xu, on quenched and tempered HSLA steels using Impeller tumbler test [13]. Impeller tumbler test also creates significant deformation [12, 184] compared to POD and DSRW tests.

5.3 Impeller tumbler wear rig

5.3.1 Design of rig

The dimensions of the Impeller tumbler machine were increased, compared to the literature [9-13, 184, 243-245, 247, 267] so as to achieve more severe wear using larger particles and higher speeds. The wear conditions can be altered either aggressive or mild by variation of test sample velocity and using larger or smaller aggregate size and quantity. The highest reported linear sample tip velocity in the literature was approximately ~8 m/s with an aggregate size of 19-20 mm and [9]. Thus, the limiting dimensions of the previous designs displayed an impact wear condition which is less aggressive resulting in lower wear loss. For example, Sundström et al. [11] carried out Impeller tumbler test with several steels among which the softer ferritic steel with limited amount of pearlite (HV
137) and fine grained martensitic steel (HV 501) displayed a wear loss of ~0.40 and ~0.28 kgm⁻²hour⁻¹ (normalized by sample area 50 × 25 mm²) respectively. The tests were conducted for one hour (4 tests in 15 minutes intervals), impeller RPM 600 with granite aggregate of 12-30 mm size and 400 g load per test cycle at high angle.

Impeller tumbler tests in the present test apparatus with mild steel (Ferrite-pearlitic microstructure, HV 198) and quenched and tempered martensitic steel (HV 475) displayed an approximately doubled wear loss of ~0.94 and ~0.42 kgm⁻²hour⁻¹ (normalized by exposed sample area 85 × 40 mm²) respectively. The tests were conducted for one hour (6 tests in 10 minutes intervals), impeller rotation 800 RPM (equivalent to sample tip velocity 12.5 m/s at 90⁰ angle) with Basalt aggregate of 50-80 mm size and 10 kg load per test at 90⁰ angle.

Wilson et al. [12] reported a wear loss of ~0.22 kgm⁻²hour⁻¹ (normalized by exposed sample area 38 × 25 mm²) for a 12% Mn steel of Hadfield grade (HV 208) in an Impeller tumbler test. This was also an hour test (4 tests in 15 minutes interval) with impeller velocity ~620 RPM (sample tip velocity 6 m/s) with granite of size -25 mm to +19 mm and 600 g load per test cycle at high angle.

A similar hadfield steel (12% Mn, HV 214) displayed a higher wear loss of ~0.38 kgm⁻²hour⁻¹ at our test conditions described previously. However, the same Hadfield steel at similar test conditions according to Wilson et al. [12] but with high silica quartzite aggregate exhibited a wear loss of ~0.57 kgm⁻²hour⁻¹. The higher wear rate due to change in abrasive particles is not unexpected and can be explained by the particle shape, hardness and abrasivity.

Ratia et al. [9] conducted Impeller tumbler tests on martensitic steel (HV 479) with granite rocks of size 10–12.5 mm and 900 g per load. The wear loss reported ~0.21 kgm⁻²hour⁻¹ at impeller speed 700 RPM (sample tip velocity 8 m/s) at 60⁰ angle. This is also a considerable lower wear loss compared to our Impeller tumbler rig. A summary of the above results is given in Table 5.1.
Table 5.1. Comparative summary of impeller tumbler test results from literature to the present wear test results.

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Steels</th>
<th>Impeller RPM</th>
<th>Linear tip velocity</th>
<th>Aggregate type and size</th>
<th>Quantity/ test cycle</th>
<th>Sample angle</th>
<th>Test duration</th>
<th>Wear rate kgm(^{-2})hour(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sundström et al. [11]</td>
<td>Ferritic with limited pearlite (HV 137)</td>
<td>620</td>
<td>-</td>
<td>Granite, 12-30 mm</td>
<td>400 g</td>
<td>High angle</td>
<td>4 tests in 15 minutes intervals, total one hour</td>
<td>0.4</td>
</tr>
<tr>
<td>Present case</td>
<td>Ferrite-pearlitic steel (HV 198)</td>
<td>800</td>
<td>12.5 m/s</td>
<td>Basalt, 50-80 mm</td>
<td>10 kg</td>
<td>90°</td>
<td>6 tests in 10 minutes intervals, total one hour</td>
<td>0.94</td>
</tr>
<tr>
<td>Sundström et al. [11]</td>
<td>Fine grained martensitic steel (HV 501)</td>
<td>620</td>
<td>-</td>
<td>Granite, 12-30 mm</td>
<td>400 g</td>
<td>High angle</td>
<td>4 tests in 15 minutes intervals, total one hour</td>
<td>0.28</td>
</tr>
<tr>
<td>Ratia [9]</td>
<td>Martensitic steel (HV 479)</td>
<td>700</td>
<td>8 m/s</td>
<td>Granite, 10–12.5 mm</td>
<td>900 g</td>
<td>60°</td>
<td>4 tests in 15 minutes intervals, total one hour</td>
<td>0.21</td>
</tr>
<tr>
<td>Present case</td>
<td>Martensitic steel (HV 475)</td>
<td>800</td>
<td>12.5 m/s</td>
<td>Basalt, 50-80 mm</td>
<td>10 kg</td>
<td>90°</td>
<td>6 tests in 10 minutes intervals, total one hour</td>
<td>0.42</td>
</tr>
<tr>
<td>Wilson et al. [12]</td>
<td>12% Mn steel of Hadfield grade (HV 208)</td>
<td>620</td>
<td>6 m/s</td>
<td>Granite, -25 mm to +19 mm</td>
<td>600 g</td>
<td>High angle</td>
<td>4 tests in 15 minutes intervals, total one hour</td>
<td>0.22</td>
</tr>
<tr>
<td>Present case</td>
<td>Hadfield steel (12% Mn, HV 214)</td>
<td>800</td>
<td>12.5 m/s</td>
<td>Basalt, 50-80 mm</td>
<td>10 kg</td>
<td>90°</td>
<td>6 tests in 10 minutes intervals, total one hour</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Thus, the lower wear loss in the previous designs is a direct outcome of the less aggressive wear conditions operating on the test samples which may not meet the similar aggressive digger tooth deformation (Figure 4.21 and Figure 4.22). Therefore, an up-scaled Impeller tumbler machine was designed in comparison to the designs available in literature to come up with a harsh wear conditions. The robust design of the present Impeller tumbler machine (Figure 5.1) allows ~12.5 m/s maximum linear speed at the sample tip with 50-80 mm aggregate.
size and up to 20 kg of aggregate loads.

![Figure 5.1. Up-scaled Impeller tumbler test rig.](image)

**Figure 5.1.** Up-scaled Impeller tumbler test rig.

Additionally, the design considers robustness, noise attenuation, dust suppression, and test flexibility. Some design features are:

The test apparatus consists of a steel drum of 760 mm diameter and 225 mm depth with a semi-circular door that allows loading and removal of aggregate. The drum can rotate both clockwise and anticlockwise. The inner wall of the drum is lined with rubber that allows sound dampening, aggregate attrition and enhances drum life. A 15 mm thick polycarbonate window allows viewing of testing.

There is a steel impeller hub fixed at the centre of the drum. The hub provides setting of two test samples at 90° and 45° angles. The impeller hub is designed to rotate at a maximum speed of 825 RPM which allows the sample tip to achieve a maximum linear speed of ~12.5 m/s.

The flexible nature of the equipment allows variation of parameters as follows:
countdown test duration, interrupted testing, drum speed, impeller speed, relative directions of drum and impeller, aggregate type, aggregate size 50-80 mm, impact angle, and test material. 

During commissioning, two concerns were associated with the design of the sample holder; a) to retain the holder on the impeller hub during the wear test and ii) to restrict bending of the samples by providing support with the holder. A considerable number of trial runs (~20) were made with two types of holder designs. Finally, a wedge-type holder (Figure 5.2a) was designed to accommodate a sample size of 40 mm width, 125 mm length and a thickness range of 6-9 mm (Figure 5.2b). Two notches in the one end of sample sides were required. This holds it with two locator pins into the wedge holder to retain the samples properly during testing.

![Figure 5.2. a) Wedge type sample holder accommodating a sample. The holder is fixed on the impeller hub, b) sample dimension 7 × 40 × 125 mm³.](image)

5.3.2 Selection of aggregate

The aggregate particles fluidisation refers to the free movement of individual particles in a drum to create impact events with the moving impeller test sample
Chapter 5. Impeller tumbler test

[12]. It was critical to achieve optimum fluidisation of the aggregate in the rotating drum. The lower drum speed reduces the fluidization which decreases the particle engagement with the rotating samples resulting in a lower wear rate. Higher drum speed also reduces the particle engagements as most of the particles remain at the drum periphery due to the centrifugal force. Trials were conducted to optimize the rotation speed of the outer drum. During trials the impeller speed was 800 RPM, aggregate load was 10 kg basalt of size 50-80 mm. The fluidisation was monitored using a Perspex semi-circle on the drum face plate. It was observed that at drum speed of 70 RPM maximum particles engaged with the rotating samples and considered an optimum fluidisation for 50-80 mm basalt.

Initial impact wear trials on mild steel samples were carried out with two types of aggregate: 40-50 mm granite and 50-80 mm size basalt at 800 RPM impeller speed. The aggregate was screened off for particles sizes greater than 80 mm, see Figure 5.3.

Figure 5.3. Basalt aggregate.
Chapter 5. Impeller tumbler test

The granite aggregate suffered a very high attrition rate relative to basalt. Based on the observation, it was decided that all the testings would be done using basalt only.

5.4 Materials and methodology

5.4.1 Materials selection and processing

Several grades of steel were chosen to study the wear behaviour in impact condition. The composition and bulk hardness of the steels are summarised in Table 3.1. The reason for selection of the steels in the present study, is discussed below;

- **Mild steel equivalent to AISI 1018:** All the initial trials were conducted with mild steel. The commercial steel was readily available and sample preparation was easy. The ferrite-pearlite microstructure of the steel is shown in Figure 5.4a. The poor wear resistance due to lower hardness and workhardenability of the mild steel was helpful to compare the wear performance with the other steels.

- **Current tooth steel:** This is the same material used for the manufacturing of the tooth, discussed in Chapter 4. Sand cast impact blocks of the steels were supplied by the industry partner, Keech Castings. The blocks were machined to prepare impeller samples (Figure 5.2b) and heat treated in Deakin University. The homogenisation, hardening and tempering parameters were similar to the standard industrial process of GET manufacture (Figure 4.4). The microstructure was similar to the digger tooth as tempered martensite, shown in Figure 5.4b.

- **High Carbon/High silicon Bainite:** A high carbon and silicon grade steel [196] was chosen to produce carbide free bainite of fine structure with a volume
fraction of retained austenite (~35%). The steel composition effectively reduces transformation time for bainite transformation which decreases cost and may be viable for the industry production [196]. The mechanical properties [196] of the bainitic steel are as follows; high yield (~1100 MPa) and tensile strength (~1500 MPa) owing to the highly refined structure, and good ductility (~10-15% total elongation) afforded by the transformation induced plasticity effect of the retained austenite. A similar carbide free fine grained bainitic steels with slightly different compositions depicted higher wear resistance compared to the harder martensitic steels when subjected to sliding abrasion due to TRIP effect [197, 198, 204, 205, 209].

A 20 kg Inductotherm® induction melter was used to pour melt into steel moulds producing two 10 kg ingot. For the bainitic steel sample the ingot was homogenised at 1200°C for 8 hours in Argon atmosphere, with a slow cooling rate 50°C/hour down to room temperature. The homogenised material was austenitised at 950°C for 30 minutes followed by direct transfer to a salt bath heated to 250°C for bainitic transformation over 16 hours. The wide process window for bainitic transformation allows through hardening on very large sections. This is attractive for accommodating the trend for increased machinery and GET sizes. It may be suggested that to achieving a through hardened digger tooth casting is a challenge on large cast sections of current industry grade. The bainitic transformation temperature is critical for coarsening of the microstructure and determining retained austenite volume fraction [268]. The literature suggests that similar heat treatment of the same grade of composition produces bainitic ferrite lath widths of 30-50 nm, separated by films of austenite of similar thickness. The quantity of retained austenite was expected to be ~20-30 volume percent. However, the bainitic microstructure in the present study (Figure 5.4c) shows a reasonably coarser grains compared to the literature [196]. The reported microstructure in the
literature consists of 34% retained austenite with matrix hardness \( \sim 613 \) HV whereas the present bainite consists of \( \sim 20\% \) of retained austenite confirmed by Rietveld analysis, XRD diagram shown in Figure 5.23a. The hardness of the current bainite is 571 HV.

- **High Carbon/High silicon Martensite:** Another high carbon/high silicon steel ingot was heat treated to achieve a martensitic microstructure. The high carbon martensite may provide an insight into the role of hardness in impact wear condition. The homogenised ingot was austenitised at 950°C and quenched in water. The quenched steel was tempered at 200°C for 2 hours. The tempering resulted homogenized structure, reduced internal stresses and less susceptible to quench cracks. In contrast to bainite (Figure 5.4c) the martensite plates illustrated in Figure 5.4d is coarse.

- **High Carbon/High silicon Pearlite:** To achieve fine structured pearlite, the homogenised ingot was austenitised at 950°C and cooled to 550°C over 1 hour, held for 4 hours and then air cooled as per [198]. The pearlitic microstructure depicted in Figure 5.4e was found to be slightly coarser (HV 323) than the literature [198]. The hardness reported in [198] was \( \sim 378 \) HV. However, the heat treatments are same but the compositions of the pearlitic steels in the present case and in the literature [198] are considerably different.

- **Hadfield steel:** A Hadfield grade steel of \( \sim 12\% \) Mn was introduced in the current study. It was heat treated to 1050°C for 15 minutes to allow the segregated carbides to dissolve completely in solution. Then it was water quenched and allowed to cool to room temperature. The final “retained” austenite microstructure with a large amount of carbon in solution allows these steels a high impact toughness and work-hardening rate and capacity. This is responsible for the superior wear resistance for these steels in impact wear conditions [269-272]. A comparative study in high impact abrasive
wear conditions of this steel with other steels may offer a deeper understanding of wear resistance behaviour. The microstructure of the steel is depicted in Figure 5.4f.

Figure 5.4. Microstructures of a) Mild steel, b) Current tooth steel, c) Bainitic steel, d) Martensitic steel, e) Pearlitic steel and f) 12% Mn - Hadfield steel.

### 5.4.2 Test procedure and result analysis

A standard operating procedure was prepared for the Impeller tumbler test, after optimization of process parameters. This includes impeller RPM, drum
RPM, and velocity of the test samples at the tip. Aggregate type, load, size and test intervals to replenish the drum with fresh ore were also some critical parameters which were optimized. For each process parameter, 5-10 trials were conducted with mild steel specimens. The major findings are reported below;

- **Aggregate quantity:** Sample weight was measured before and after each trial. The weight loss represents the wear rate of the specific sample at a particular set of test parameters. Higher wear loss of the test samples was found with higher amount and size of aggregate. The weight of the load for each test was optimized to 10 kg. Less than 10 kg load showed a lower wear loss. Load higher than 10 kg aggregate was creating anomalous RPM reading of the impeller hub, by offering higher resistance to the impeller rotation. It is well known that particle shape has significant effect on abrasive wear [47, 53, 273-276]. Since only basalt aggregate was used to carry out the wear tests, no trial was conducted to optimize the shape of the particles.

- **Aggregate replenish rate:** Basalt was preferred over granite due to its reduced attrition over the duration of the test, approximately half the rate. To minimize the attrition effect of the basalt aggregate, it was decided to replenish the drum completely with 10 kg of basalt for every test cycle. The attrition rate with current tooth steel was twice compared to the mild steel. So, the aggregate charge was changed in every 10 minutes for all materials.

- **Test speed:** Doubling of the impeller speed (400 to 800 RPM) results in 8-fold increase in wear rate on mild steel. It was decided to concentrate on the extreme abrasive wear condition (800 RPM) to determine the surface stress conditions and wear rates experienced by GETs could be approximated in this off-line test. The most severe wear occurs for a drum (70 RPM) and impeller rotation in the same direction. The highest rotation that the impeller could achieve is 825 RPM. It was calculated that at 800 RPM the sample tip reaches a linear speed \( \sim 12.5 \text{ m/s} \). The linear sample tip velocity
was calculated as;

The exposed sample length at $90^\circ$ angle becomes 85 mm for a 125 mm sample size. The impeller hub diameter is 200 mm. The linear distance traversed by the sample tip is $(200+90)\pi$. At 825 RPM the linear velocity becomes, $(290\pi*825)/60000 = 12.5$ m/s. A similar calculation for $45^\circ$ angle provides tip velocity 11 m/s. The high speed of the samples allows much frequent interaction at higher energy with the particles, enhancing the wear rate. Thus, the impeller rotation speed was optimized to 800 RPM.

- **Impact angle:** Sundström et al. [11] reported that high angle impacts form craters by plastic deformation and displacement of material and low angle impacts form grooves with lips at the rear ends. In contrast Impeller tumbler test of wear resistant steels at $90^\circ$ to $60^\circ$ exhibited similar wear surface excluding the edge part in the experiments of Ratia et al. [245]. The results indicate that smaller change in angle does not change significantly the operating wear mechanisms in Impeller tumbler test. However, it was decided to study the effect of sample angle, the impeller hub was designed to accommodate two samples at $90^\circ$ and $45^\circ$ angles.

- **Test duration:** It is reported in literature that during Impeller tumbler test cycle, the initial short time (break in period) overestimates the wear rate [12, 184]. Hence it is necessary to estimate the steady state wear rate. We decided to conduct total one-hour test at six 10 minutes cycles to achieve a steady state wear rate. Samples were cleaned and weighed (microbalance, 0.001g resolution) after every 10 minutes and up to 1 hour of testing.

### 5.4.3 Characterization techniques

- Optical profilometry was conducted to evaluate the surface damage and compared it with worn tooth surface features. Alicona infinite focus
instrument was used to measure the surface deformation and characterize
the profiles of impact craters of different steels. An area of \(~35 \times 20\) mm\(^2\)
section from tip was cut, cleaned with ethanol in an ultrasound bath and
subjected to scan.

- Benchtop SEM (JEOL Neoscope) was used to conduct surface
characterization of the worn surface. A sample area of \(~5 \times 10\) mm\(^2\) was
chosen from 5 mm away from the tip and 15 mm far from the widths of the
sample.

- The samples for subsurface characterization were selected from tip for
microscopy. Electron microscopy with Supra 55 VP, Carl Zeiss, Germany SEM
machine was used for the characterization at accelerated voltage 20 kV and
ASB detector. Samples were OPS polished and kept in vacuum 24 hours prior
to electron microscopy.

- Cross-sectional microhardness profile was carried out using Struers make,
DuraScan microhardness machine on the same sample, used for microscopy.

- A Philips PW 1130 diffractometer with graphite monochromatic Co-\(\kappa\)\)
radiation at 40 kV and 30 mA in the \(2\theta\) range of 40-105° at a rate of 0.02°/15
s was used to carry out X-ray measurements. The sample preparation
technique for the virgin materials was similar to the technique used in
electron microscopy. The worn samples were not polished as it may destroy
the transformed phases at the surface. It was only cleaned with ethanol,
followed by acetone in ultrasound bath.

5.5 Comparison: worn tooth and tumbler
results on similar steels

It was necessary to determine whether the impeller test could reproduce the key
features of the damage seen on the worn GET (Figure 4.21 and Figure 4.22).
These features include worn surface characteristics, formation of surface white layer, deformed subsurface and embedded aggregate at surface. The optical profilometry images and SEM micrographs were used to examine and compare the damage of the test specimens with GET microstructural features. EDX was used to confirm the presence of embedded aggregate particles at surface which was a common feature of the GET microstructure.

The current tooth steel (Figure 5.4b) described in Section 5.4.1 was cut and machined to prepare Impeller tumbler test samples. Before cutting, a cross-sectional hardness profile was measured through the thickness. A consistent hardness profile HV 480 ± 10, confirms a uniform microstructure (bulk hardness 475 HV, see Table 3.1). Two samples at 90° and 45° angles were tested under the high wear conditions described in Section 5.4.2. The impeller speed was 800 RPM for each 10 minutes cycle with 10 kg 50-80 mm basalt aggregate for an hour test period.

### 5.5.1 Worn surface comparison

Figure 5.5 delineates optical images of the worn tooth and the tumbled current tooth steel. The sampling location was nose area of the worn tooth and tip area of the tumbled current tooth steel. The images depict that the grooves on the tooth surface have wider dimensions (highest groove width was found to be approximately 1 mm, Figure 5.5a) with corresponding groove depth of >100 µm. In contrast, the tumbled specimen (Figure 5.5b) shows shallower grooves and depth that hardly crosses 20 µm. Significant crater is visible on the worn tooth surface in contrast to the tumbled specimen which indicates lower occurrence of craters.
Figure 5.5. Optical profilometry images; a) worn tooth surface from nose area, b) current tooth steel from tip area.

The SEM investigation of the Impeller tumbled worn surface (Figure 5.6) reveals formation of shallow craters by the oblique angle impact of an ore particle. Material is pushed as lips at the crater rims during impact. The crater lips are detached during repetitive impacts causing material removal. Shallow grooves are also evident which may be formed by low angle impacts and subsequent rolling of the particle. However, the surface damage exhibits lower degree of
deformation when compared to the worn tooth surface damage (Figure 4.20). The commercial worn tooth surface revealed significant plastic deformation, craters and larger grooves where material removed in flakes. Nevertheless, the Impeller tumbled specimens show a comparable damage mechanism where material was removed by the formation of craters and grooves.

Figure 5.6. Impeller tumbled current martensitic tooth steel damaged surface depicting craters of various sizes and the crater rims formed by displaced material, shallow grooves are also visible.

5.5.2 Deformed microstructural comparison

The SEM micrographs of the cross-section of an Impeller tumbled current tooth steel sample positioned at 90° are shown in Figure 5.7. Figure 5.7a reveals presence of a white layer and reasonably deformed subsurface similar to digger tooth (Figure 4.22b and f). However, the thickness of the white layer in the test sample was considerably lower (~2 μm) than that of the damaged digger tooth
ranging from 10-100 µm. A possible ore particle is adhered can be seen in the micrograph Figure 5.7b, subjected to EDX analysis in Section 5.5.3.

Figure 5.7. Impeller tumbled current tooth steel: a) white layer and subsurface deformation, b) adhering basalt aggregate at deformed surface. In both images, the black part is resin used for sample mounting.
5.5.3 **EDX analysis for embedded particle**

Entrapped ore particles at the surface was a common feature in the worn tooth (Figure 4.22f and Figure 4.23b). The same feature in the tumbled specimens may provide another similarity with tooth results. To confirm this EDX analysis (Figure 5.8) was employed on Impeller tumbled sample, location shown in Figure 5.7b.

Figure 5.8. EDX analysis at location Figure 5.7b showing resin for mounting at upper part and steel at lower part with probable adhered particle at middle, a) C rich organic substance in blue region confirms resin material for mounting, b) O rich green region confirms oxides at middle, c) Si rich purple region at middle part evidences presence of silica material, d) Fe rich red region is the steel matrix.
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A white appearance in Figure 5.7b represents basalt aggregate in-between the plastically deformed region of the steel and the thin surface deformed layer surrounded by resin. This location was chosen for Energy Dispersive X-Ray spectroscopy, to confirm the compositions of the layers. The elemental chemical analysis confirms that upper blue region in Figure 5.8a is the carbon enriched resin material, used for mounting. At the selected region, elemental presence of Oxygen (O), Silicon (Si) and Iron (Fe) were confirmed in respective Figure 5.8b, c and d. Tracer level of Fe, higher amount of Si and O, at the selected region, confirm basalt aggregate composition [277]. The result confirms that impeller tumble test entraps ore particles at surface layer. This is a typical wear characteristic qualitatively similar to GET results.

5.5.4 Wear loss in Impeller tumbler test compared to GET

The wear characteristics of the Impeller tumble test on current tooth steel and the worn digger tooth revealed a rational comparison in terms of surface damage and subsurface deformation. However, the Impeller tumbled specimens have shown a reduced degree of deformation compared to the tooth deformation. It is nonetheless interesting to compare the time rates of material loss.

The digger tooth wear rate was 2-4 kg.m\(^{-2}\) hour\(^{-1}\), described in Section 4.2. The current tooth steel was tested in the Impeller tumbler apparatus with an impeller speed of 800 RPM, drum speed of 70 RPM for one-hour at six 10 minute cycles. 10 kg of Basalt rock of 50-80 mm size was used for each test cycle. The total weight loss normalized by exposed sample area 85 × 40 mm\(^2\) after one-hour test was found to be \(~0.42\) kgm\(^{-2}\)hour\(^{-1}\). This wear loss was considerably lower than the digger teeth field wear rate. But the investigation of the tumbled
sample revealed that majority of the wear loss took place from the tip area of the specimen, evident in Figure 5.9. Ratia et al. [9] conducted impeller tumbler tests for a shorter period of 2 seconds and reported that 90% of the impacts occurred within a distance of 20 mm from the tip. However, the edges have significant effect in mass loss at initial stages of wear [9, 12] and the edges were not shielded in the present experiments.

![Image](Tip)

Figure 5.9. Impeller tumbled current tooth sample showing higher wear loss from the tip. Impeller speed 800 RPM, drum speed 70 RPM, one-hour test at six 10 minutes cycle. 10 kg Basalt rock of 50-80 mm size was used for each test cycle.

The observation was validated by performing thickness measurements of the sample area exposed during wear test. Figure 5.10 exhibits the thickness of the current tooth steel subjected to tumble test displayed in Figure 5.9. The original average thickness of the specimen before tumbler test was 7.13 mm. The 85 mm sample length exposed during wear test confirms that the wear loss occurred predominantly from the tip area, effectively 25 mm of the sample length. The observation was also similar to the other materials where majority of the wear loss occurred from the tip area. Therefore, this is more rational to calculate the wear loss with respect to the area 25 × 40 mm² rather than the full 85 × 40 mm². The reevaluated wear rate is 1.43 kg.m⁻²hour⁻¹ than the previous value 0.42 kg.m⁻¹
However, the wear rate 1.43 kg.m$^{-2}$hour$^{-1}$ of the tumbled specimen is still lower than the magnitude of the worn tooth wear loss of 2-4 kg.m$^{-2}$hour$^{-1}$.

Figure 5.10. Thickness variation along the sample length exposed to Impeller tumbler test delineating higher wear loss at the 25 mm zone towards tip. Exposed sample length 85 mm. Average thickness of the specimen before tumbler test was 7.13 mm.

5.6 Results

5.6.1 Wear behaviour of various steels

Initially Impeller tumbler tests were performed on mild steel and current tooth steels to examine the repeatability of the results. The wear loss of the steels normalized by the test area 25 × 40 mm$^2$ are plotted as a function of time in
**Figure 5.11** for 90° and 45° angles. The weight loss was measured at each 10 minutes intervals. The Impeller speed was 800 RPM and 10 kg basalt of size 50-80 mm was used per cycle. The wear test results were highly repeatable for both steels. The plot in **Figure 5.11** also indicates that samples at 90° angle exhibits higher wear loss than that of 45° angle but the difference in wear loss was not significant. The higher wear loss at 90° angle was consistent with the findings of the other research groups [9, 11, 12]. Impact craters were formed by the normal loads exerted by the particles impinging at oblique angles leading to higher wear loss. Low angle impacts form grooves [11] due to easy sliding of the abrasive particles [9]. However, the lower difference in wear results between the two angles indicates a similar material behaviour. A similar observation was reported by Ratia et al. [9] in Impeller tumbler testing of martensitic steels. They reported that samples at 90° exhibited slightly higher wear loss than the sample at 60° angle with 10-12.5 mm granite rocks. They proposed that high impact energy operating at both angles suppressed the relative effect of the abrasive movements. Thus, the wear of same material at different angles displayed a linear dependence of hardness on the impact energy. Sheldon observed [278] that erosion rate of a hardened steel with larger particles is independent of impact angles but the rate is dependent on the impact angles for smaller particles. It was claimed [278] that the erosion behaviour with larger particles are predominantly brittle but smaller particles induce ductile behaviour that varies the erosion rate with impact angles.

In the present case, the impact energy of a single basalt particle was estimated to be ~5 J and ~4 J at 90° and 45° angles, considering single particle mass 0.064 kg (10 kg aggregate contains ~155 number of particles) and sample velocities of 12.5 and 11 m/s respectively. Therefore, the similar wear behaviour at two angles occurred predominantly by the high impact energy that suppressed the effect of relative abrasive movements caused by the change in angles.
Figure 5.11. Wear loss normalised by test area 25 × 40 mm² for mild steel and current tooth steels as a function of time, Impeller speed 800 RPM, drum speed 70 RPM, 10 kg basalt (50-80 mm) for 10 minutes test cycle. Wear loss shows repeatable results and no significant difference between two different sample angles.

Two inferences can be drawn from Figure 5.11:

a) The Impeller tumbler machine produces highly reliable data which allowed us to exempt the repeat tests for other steels.

b) The materials displayed an approximately similar wear behaviour at 90° and 45° angles. The outcome attracted us to focus especially on the wear results at 90° angle. The aim of the research was to create extreme wear conditions. The wear results at 90° angle differentiates the wear performance more clearly. Hence all the following analysis have been performed on wear results at 90° angle.
Figure 5.12 represents cumulative wear loss of different steels as a function of time. The wear loss of the steels was normalized by the test area $25 \times 40 \text{ mm}^2$ and plotted in log scale to differentiate the wear performances more clearly in impact wear conditions. The tests conditions were one-hour test, impeller speed 800 RPM, drum speed 70 RPM, 10 kg basalt aggregate of 50-80 mm size per 10 minutes test cycle and sample angle $90^\circ$.

![Figure 5.12. Wear rate of the steels for one-hour test, Impeller speed 800 RPM, drum speed 70 RPM, 10 kg Basalt of size 50-80 mm at 90\(^\circ\) angle.](image)

The soft mild steel shows higher wear rate of approximately an order of magnitude than that of the bainite which exhibits lowest wear rate compared to the other steels. This is evident from the plot Figure 5.12 that initial stage of wear occurs within 30 minutes of period and after that the steels display a steady
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state wear. The slopes look fairly close once they reach steady state. The total wear loss of the steels normalised by the test area $25 \times 40 \text{ mm}^2$ in one-hour has been summarised in Table 5.2.

The current tooth steel provides a ~65% reduction in wear rate relative to the mild steel as evident in Table 5.2. The bainitic microstructure shows further reduction in wear rate by ~40% compare to the current tooth steel. The wear resistance of Hadfield steel (bulk hardness ~214 HV) was promising and similar to the current tooth steel, though the latter had a bulk hardness of 475 HV (Table 5.3). Bainite shows a comparative wear rate with martensitic grade instead of lower bulk hardness (bainite 571 HV, martensite 677 HV, see Table 5.3). This may be due to the effect of work hardening by the mechanically induced transformation (TRIP) of retained austenite to martensite.

Table 5.2. Wear rate of the steels at 90$^\circ$ orientation normalized to that of the current tooth steel.

<table>
<thead>
<tr>
<th>Steels</th>
<th>Wear rate, kg.m$^{-2}$hour$^{-1}$ Tip area (25 $\times$ 40 mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>2.88</td>
</tr>
<tr>
<td>Current tooth steel</td>
<td>1.00</td>
</tr>
<tr>
<td>Bainite</td>
<td>0.63</td>
</tr>
<tr>
<td>Martensite</td>
<td>0.68</td>
</tr>
<tr>
<td>Pearlite</td>
<td>1.82</td>
</tr>
<tr>
<td>Hadfield steel</td>
<td>0.92</td>
</tr>
</tbody>
</table>

The next Section 5.6.2 describes the wear rates shown in Figure 5.12, with the help of surface profile data, workhardening, characterizations of impact craters, worn surface and subsurface characterizations.
5.6.2 Effect of work hardening on wear rate

A cross-sectional microhardness test from surface to matrix was conducted using Vickers apparatus for all the steels. The sample was prepared from the heavily worn cross-section of the tip area, shown in Figure 5.13. The tests comprised of three parallel indentations, 20 µm apart to avoid strain effects. All measurements commenced at 5 µm away from the surface. Up to 100 µm the readings were taken 10 µm apart and after that 50 µm apart up to 800 µm.

Figure 5.13. Schematic diagram of an Impeller tumbled sample at 90° angle. Sample for metallographic analysis and microhardness was prepared from the heavily worn cross-section of the tip area shown in blue textured region. The tip surface area was used for optical profilometry, impact and worn surface analysis.

Figure 5.14 depicts average hardness as a function of distance from hardened surface to the unaffected matrix. The bulk hardness and the surface hardness of the Impeller tumbled steels are summarized in Table 5.3 (the bulk hardness is same as in Table 3.1).

Martensite shows the highest surface hardness of ~700 HV from bulk hardness 677 HV. The hardness increased up to 4.4% and depth of the work hardened zone was found up to ~40 µm from the surface. The result is consistent with
typical martensitic properties of high hardness and low workhardening.
Bainite displayed appreciable workhardening from 571 HV to ~643 HV. A 12.5% increase in hardness at the surface with a hardened zone extending to ~130 μm depth is evident in Figure 5.14. The workhardening can be attributed to the presence of softer retained austenite (i.e. TRIP effect) [196, 198, 209, 279, 280].

Figure 5.14. Surface to matrix hardness profile of the steels. Point ‘0’ indicates microhardness reading commenced at 5 μm away from the surface of the tip area (Figure 5.13). Readings were taken 10 μm apart up to a depth of 100 μm and after that 50 μm apart up to a depth of 800 μm.

The bulk hardness and surface hardness of the current tooth steel were 475 HV and 595 HV respectively. This enhancement in hardness was due to the transformed white layer at the surface and the deformed subsurface.

Hadfield steel reveals excellent work hardening where the hardness increased
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from 214 HV to 615 HV (an increase of 187%). The depth of work hardened zone was found to be ~700 µm.

The pearlitic microstructure shows a work hardened zone of ~70 µm towards matrix. The surface hardness of pearlite was measured 430 HV with relative to the bulk hardness 323 HV. It is interesting to note that pearlitic microstructure had undergone a considerable surface hardening of ~33%, higher than the bainitic steel, however it exhibited higher wear rate than bainite.

The mild steel microstructure displays a work hardened zone of ~150 µm towards matrix. Mild steel surface hardness was ~300 HV than that of the bulk hardness 190 HV.

Table 5.3. Hardness and extent of workhardening table of different steels.

<table>
<thead>
<tr>
<th>Steels</th>
<th>Bulk hardness, HV</th>
<th>Surface hardness, HV</th>
<th>Workhardening depth, µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>198</td>
<td>299</td>
<td>150 ± 10</td>
</tr>
<tr>
<td>Pearlite</td>
<td>323</td>
<td>430</td>
<td>70 ± 5</td>
</tr>
<tr>
<td>Current tooth steel</td>
<td>475</td>
<td>595</td>
<td>300 ± 10</td>
</tr>
<tr>
<td>Hadfield</td>
<td>214</td>
<td>615</td>
<td>700 ± 20</td>
</tr>
<tr>
<td>Bainite</td>
<td>571</td>
<td>643</td>
<td>130 ± 10</td>
</tr>
<tr>
<td>Martensite</td>
<td>677</td>
<td>707</td>
<td>40 ± 5</td>
</tr>
</tbody>
</table>

5.6.3 Optical profilometry

5.6.3.1 Surface appearance

Surface topography was analysed for all the Impeller tumbled steels. The most severely affected surface tip area (~25 × 40 mm²) ~5 mm away from the tip (Figure 5.13) was chosen for the topographic analysis. A differential colour profile portrays the impact depth and subsequent ridge formation at adjacent
sides of the impact craters. The microstructure of the respective steels displays significant influence on the impact characteristics (Figure 5.15).

Figure 5.15. Surface profilometry of different steels at 90°; a) mild steel, b) current tooth steel, c) Hadfield, d) pearlite, e) bainite and f) martensite.

Significant deep impacts are evident for the mild steel and Hadfield steels (Figure 5.15a and c). The bainite and martensite show shallow impacts, Figure 5.15e and f. The current tooth and pearlitic steel reveal the impact characteristics midway between the two extreme cases (Figure 5.15b and d).
5.6.3.1 Interpretation of profilometry

Definition and physical interpretation of surface parameters

The surface roughness profiles were measured on the worn surfaces, data presented in Table 5.5. $S_a$, $S_q$, $S_v$ and $S_p$ represent average surface roughness, RMS surface roughness, maximum valley depth and maximum peak height of the selected area in $\mu m$ respectively. The definitions are summarized in Table 5.4.

The literature suggests that smoother surfaces are typical of lower wear and irregular surfaces indicate higher wear. But this is not necessarily true because it depends on the exact wear mechanisms operating and an interplay between the mechanical conditions and a range of material properties [197, 198].

Table 5.4. Definition of surface parameters.

<table>
<thead>
<tr>
<th>Surface parameters</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_a$</td>
<td>Average height of the selected 3D surface</td>
</tr>
<tr>
<td>$S_q$</td>
<td>RMS height of the selected 3D surface</td>
</tr>
<tr>
<td>$S_v$</td>
<td>Maximum valley depth of the selected 3D surface</td>
</tr>
<tr>
<td>$S_p$</td>
<td>Maximum peak height of the selected 3D surface</td>
</tr>
</tbody>
</table>

Table 5.5. Surface roughness data of worn steels.

<table>
<thead>
<tr>
<th>Steels</th>
<th>$S_a$</th>
<th>$S_q$</th>
<th>$S_v$</th>
<th>$S_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>58.80</td>
<td>81.76</td>
<td>564.50</td>
<td>359</td>
</tr>
<tr>
<td>Hadfield</td>
<td>19.97</td>
<td>25.39</td>
<td>120.40</td>
<td>84.72</td>
</tr>
<tr>
<td>Pearlite</td>
<td>13.60</td>
<td>18.37</td>
<td>141.50</td>
<td>63.83</td>
</tr>
<tr>
<td>Current tooth steel</td>
<td>7.73</td>
<td>10.11</td>
<td>70.70</td>
<td>49.46</td>
</tr>
<tr>
<td>Bainite</td>
<td>5.87</td>
<td>7.88</td>
<td>67.70</td>
<td>44.23</td>
</tr>
<tr>
<td>Martensite</td>
<td>4.24</td>
<td>5.88</td>
<td>72.68</td>
<td>41.07</td>
</tr>
</tbody>
</table>
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The $S_a$ and $S_q$ represent average height and Root-Mean-Square height over the complete 3D surface of the selected area. $S_q$ is more sensitive to the local irregularities, making it a valuable complement to $S_a$. The main difference in the two scales is that $S_q$ offers weighted average of micro peaks and valleys, while $S_a$ simply averages them [281]. The higher value of $S_q$ represents higher surface roughness. The maximum valley depth ($S_v$) and maximum peak height ($S_p$) of a selected area have a relatively combined effect on the worn surface. For example, higher value of $S_v$ with corresponding lower value of $S_p$ denotes higher area depth with lower plastically deformed region. This indicates that material was removed from the surface, showing higher wear rate. But at lower value of $S_v$ with higher value of $S_p$ indicates a higher tendency of plastic deformation or lower wear rate. Roughness is about the change in shape of the surface whereas wear rate is a measure of material loss. For the samples tested, the surface roughness parameters broadly correlate the wear rates.

**Interpretation of wear performance of steels with surface parameters**

A log scale plot demonstrating wear rate as a function of surface hardness of the steels is displayed in Figure 5.16. This is interesting to note that the Hadfield steel (bulk hardness 214 HV) exhibits lower wear rate than the current tooth steel (bulk hardness 475 HV). A significant workhardening of ~400 HV is evidently contributed for the higher wear resistance of Hadfield steel. A similar mechanism can be seen in case of bainite (bulk hardness 571 HV) which shows marginally higher wear resistance than martensite (bulk hardness 677 HV). The average and root mean square surface roughness values of the steels obtained from Figure 5.15 were plotted as a function of surface hardness in log scale (Figure 5.17).
Figure 5.16. Log plot of wear rate as a function of surface hardness of the Impeller tumbled steels. Hadfield steel depicts lower wear rate than current tooth steel and bainite shows marginally higher wear resistance than martensite.

The plot in Figure 5.17 broadly correlates the wear rate plot in Figure 5.16. The roughest surface corresponds to the mild steel that shows higher wear rate. Smoothest surfaces are related to bainitic and martensitic steels delineating lowest wear rates. But Figure 5.17 fails to explain the higher wear performance of Hadfield steel compared to the current tooth steel and bainite compared to the martensite despite their lower bulk hardness.
Figure 5.17. Log plot of average and root mean square surface roughness as a function of surface hardness of the Impeller tumbled steels. The plot broadly correlates the wear results in Figure 5.16 but insufficient to address the wear behaviours of Hadfield and bainitic steels.

Figure 5.18 illustrates a log plot of maximum valley depth and maximum peak heights of the craters with surface hardness. The plot more explicitly correlates the surface features with the wear rates of the steels shown in Figure 5.16. This is interesting to note that the maximum valley depths of the steels ($S_v$) in Figure 5.18 closely correlate the wear rate depicted in Figure 5.16. Bainite exhibits lower valley depth resulting in a reduced wear rate compared to the martensite (Figure 5.18) despite its lower hardness. The lower valley depth may be due to the TRIP effect of the microstructure which resisted the penetration of the impacting particle. The marginally higher peak height ($S_p$) of bainite also
indicates that bainite has higher tendency of plastic deformation than that of the martensite. The plastic ridges in bainite contributed for higher peak height and remain adhered to the surface reducing the wear rate. The higher hardness and lower deformation capability of martensite reduces the formation of plastic ridges. Even if the ridges are formed, they immediately fractured by the subsequent impacts increasing the wear rate. Pearlite shows a higher valley depth \((S_v)\) than Hadfield steel (Figure 5.18) with a corresponding lower value of peak height \((S_p)\) in Figure 5.18. This may have occurred due to the lower deformation of cementite layers in pearlite resulting in a higher wear loss (Figure 5.16). A similar explanation applies to the wear rate of Hadfield steel when compared to the current tooth steel.

Figure 5.18. Log plot of surface peak and valley depths as a function of surface hardness of the Impeller tumbled steels. The blue markers represent maximum valley depth and red markers represent maximum peak height of the surface.
5.6.4 Characterization of impacts

The profilometry in Section 5.6.3 showed that different steels have different worn surface morphologies and these can be correlated with hardness and wear rate. Impact craters are also a characteristic feature of the wear surfaces. This segment explores whether impact crater dimensions can be correlated with the wear rate of the surface.

The length and width of a crater provide an idea of plastic deformation of a crater whereas the maximum depth signifies the volume of material removed. Higher value of crater length or width with corresponding lower magnitude of crater depth indicates that much of the material was deformed plastically with lower material removal. Microploughing is typically the wear mechanism involved in this type of deformation [16, 30, 39, 40, 125, 282, 283]. If the impact craters show higher depth with respect to the length or width value, it is more likely that a microcutting mechanism was operating and material was removed by microchip formation.

Figure 5.19a and b show the variation of maximum crater depth as a function of crater length or major axis and width or minor axis respectively. Thus, the plots display a wear regime of the steels at high impact wear conditions. No significant difference is noticed between the graphs when the crater depths were plotted against crater length or width other than a little shifting towards left for crater width.
Figure 5.19. Impact characteristics of test steels. Larger sizes craters were chosen randomly from the tip area of the respective steels (Figure 5.15); a) Maximum crater depth as a function of crater length or major axis and b) Maximum crater depth as a function of crater width or minor axis.
The results are consistent with the wear rate diagram shown in Figure 5.12. The map also discriminates more clearly between the different steels. The pearlite and Hadfield are in their own spaces. This is really interesting especially with the current tooth steel being in the middle of the harder steels and Hadfield steels. At similar crater lengths and widths bainite shows slightly lower impact depth than martensite which is consistent with Figure 5.18. The two are the best performers and have similar wear rates over time (Figure 5.12). This map of impact crater dimensions actually discriminates more clearly between the two steels than measuring wear rates. Mild steel and pearlite show higher material removal than current tooth steel at similar crater length. This corresponds with the higher wear rates observed for both (Figure 5.12). For the pearlitic steel, hardness plays the key role to minimize wear loss than that of the softer mild steel.

Being softer material (214 HV) Hadfield steel exhibits higher crater lengths and widths, comparable with mild steel. But the excellent workhardening resists the impact simultaneously, resulting into lower crater depth. Thus, the material shows a higher tendency to plastic deformation than removal. This is consistent with the wear rate (Figure 5.12).

Mapping the impact crater dimensions is therefore a useful tool in evaluating wear performance of steels under impact conditions. The map may also provide insight into the types of wear damage mechanisms operating.

### 5.6.5 Worn surface characterization

Investigation of the worn surface provides a critical information about the process and mode of wear for different microstructures under a specified set of conditions.

The mild steel surface in Figure 5.20a, presents banded plastically deformed
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ridges. Furrows of larger dimensions are also evident. These observations are consistent with the surface topography image in Figure 5.15a. Repetitive impingements of aggregate particles at 90° angle caused severe plastic deformation. The lower hardness and workhardening properties of mild steel are not enough to withstand such large impact energy of ~5 J. Concurrently, the abrasive particles glide along the wear surface and form furrows. As wear progresses, the ridges finally break down and leave the material surface as wear debris.

The worn surface of the current tooth martensitic steel shows shallower impacts. This may be due to the hardness of the material (bulk hardness 475 HV, Table 5.3). Moderate evidence of plastically deformed zones may be observed. Displacement and finally removal of material occurred by microchip formation from the adjacent sides (Figure 5.20b).

In Figure 5.15c, Hadfield steel exhibited higher number of impact craters of larger size. In contrast, a reduced number of furrows are apparent. Figure 5.20c shows an impact crater with plastically deformed ridges. The soft austenitic microstructure workhardened (~187%) significantly by the impact energy of impinging particles and surface craters are formed. Subsequent impacts make the crater and plastic ridges larger in size. A considerable increase in dislocation density at the deformed ridges lowers the toughness in these areas. As wear progresses, micro-cracking takes place at the interface of the hardened areas finally results in fracture. Furrows then become shorter due to the exposure of fresh surface by the spalling of the plastically deformed ridges.

The surface profile image of pearlitic steel in Figure 5.15d, shows impact craters which are larger in size than those on the martensite but significantly shorter than the impact craters on the Hadfield steel. The hardness of pearlitic steel shown in Table 5.3 evidences a surface hardening up to 33%, which explains the crater size. However, the plastic deformation could not support the
microstructure when subjected to the particles with an impact energy of ~5 J. Probably the cementite layers undergone severe brittle cracking due to such high impingement energy resulting in a higher wear loss. The worn surface in Figure 5.20d evidences the presence of several craters and a lower degree of deformation.

The bainitic steel has a smoother worn surface with an occasional presence of loosely bound surface layers (Figure 5.20e). The delaminated layer is next to an impact crater and may be part of its plastically deformed ridge area. The combination of soft and brittle phases in this microstructure enables the material to absorb a significant amount of impact energy. During impact loading the deformation layer work hardens. Detaching the deformed delaminated area would require more impact events, e.g. by running the test for longer. This explains a comparatively better wear resistance of the bainitic microstructure than that of the other steels.

The worn surface of the martensitic steel (Figure 5.20f) reveals signs of fragmentation of the surface layer by microchip formation. The impacting particles damage the material by a microcutting action. Due to extreme hardness of the microstructure there is a very little evidence of plastic deformation. The harder phase undergoes severe brittle fracture at high loading and material loses the surface as microchips. However, the lower wear rate may be directly attributed to the hardness of the microstructure.
Figure 5.20. Worn surface of Impeller tumbled steels: a) mild steel, b) current tooth steel, c) Hadfield steel, d) pearlite, e) bainite and f) martensite.
5.6.6 Deformed subsurface characterization

The subsurface characterization of the steels reveals a significantly deformed microstructure compared to their bulk matrix after wear testing. Substantial material flow along impact direction, surface white layer formation, workhardened subsurface were the features that determined the wear behaviour of the steels.

The mild steel (Figure 5.21a) suffered severe plastic deformation on the surface with significant material flow. The plastic flow was found to a depth of ~150 µm (Table 5.3) at high wear regions. No white layer was observed in this material.

The current tooth steel shows a limited amount of plastically deformed region. A thin white layer (~2 µm) can be observed at the surface, Figure 5.21b. The deformation features are comparable to those of the GET used in a high abrasion application Figure 4.22f. A white layer is common in both cases; however, the white layer is much thicker in worn GET, ranging between 10 and 100 µm. Both samples show cracks in the white layer and a deformed subsurface.

The bainitic and martensitic steel samples exhibit a thicker white layer (5-6 µm) in contrast to the current tooth steel (~2 µm) (Figure 5.21c and d). Fragmentation of the white layer is evident in the martensite specimen, whereas the white layer on the bainitic sample appears to be more intact, suggesting it is better supported by the matrix. Fragmentation of the martensite as evident in Figure 5.21d attributes its higher wear rate than the bainite.

A very thin white layer with complete detachment of the surface layer is apparent in the pearlitic microstructure, see Figure 5.21f. Under high impact conditions, the ferrite might have accommodated strain. However, this needs further specific characterization to confirm which was not carried out in the present study. It is reported [284] that the dislocations during deformation can generate at the interface between ferrite and cementite which likely contributed
the increase in surface hardness. Minor plastic deformation of the harder cementite lamellae may be observed (Figure 5.21e) but the significant loading condition breaks the cementite lamellae rapidly. Eventually the microcracking of the harder cementite lamellae causes the surface to detach and results in the higher wear rate. There also may have a possibility of the presence of porous basalt rock at the surface. However, this was not investigated.

A similar white layer with a significant plastically deformed subsurface is evident in the Hadfield steel (Figure 5.21f). It is necessary for Hadfield steels to face significant impact loading conditions, so that it can workharden and resist the wear loss [285-287]. For example, Tylczak et al. [157] conducted Jaw crusher test with 13% Mn Hadfield grade steel and reported higher wear rate for the said material. They argued that at high stress gouging abrasion condition the material’s surface worn away because its surface was unable to achieve sufficient workhardening to resist wear. However, the effect of prior workhardening on wear resistance of materials is still a matter of discussion [16, 128]. The white layer in the Hadfield steel appears to be ductile in nature and remains attached to the surface at highest deformation resulting in a lower wear loss.
Figure 5.21. Subsurface characterization: a) mild steel, b) Current tooth steel, c) bainitic steel, d) martensitic steel, e) pearlitic steel and f) Hadfield steel.
5.7 Discussion

The “failure” analysis of worn digger tooth in Chapter 4 revealed that impact and rolling sliding action by the abrasive particles resulted in material removal. The present Chapter 5 deals with recreating the similar impact wear condition in laboratory using Impeller tumbler machine. Different steels with varying degree of hardness and workhardening propensities were subjected to the tumbler test to study their impact wear behaviour.

The results indicate that different microstructural steels responded in different manner when exposed to impact wear condition [11, 184, 198, 267, 288]. Previous studies claim [11, 184, 243] that Impeller tumbler test results broadly correlate with materials hardness, perhaps more sensitive to the workhardening behaviour of the materials. The wear test results depicted in Figure 5.12 and Figure 5.16 exhibit a trend of reduced wear rate with increasing hardness, however, this was not true for ductile Hadfield steel and bainite.

The impact wear response of mild steel, presented in this study is relatively similar to that found in previously published works [11, 245, 267]. Being a softer material (198 HV) mild steel shows extensive plastically deformed surface as evident in Figure 5.20a. A higher value of surface roughness ~82 µm (Table 5.5) confirms the observation. The hardness profile of mild steel in Figure 5.14 illustrates a work hardened layer up to a depth of ~150 µm revealing a severe plastic deformation. Similar work hardening profiles were observed for ferrite-pearlitic steel under impact wear conditions [11, 245]. The severely deformed subsurface in Figure 5.21a, shows deformed grains along the impact direction whereas Figure 5.22 confirms a cell structure.
The rolling sliding wear resistance increases with increase in hardness of the pearlitic microstructure as a consequence of decreasing distance between ferrite and cementite [289-291]. Fine pearlite exhibits higher flow stress and workhardening rate in rolling sliding wear resulting in a reduced wear [284, 291, 292]. The flow stress and workhardening properties of the pearlitic steels were studied by Takahashi and Nagumo [284]. They demonstrated that during deformation the dislocations are generated at the interface between cementite and ferrite. Hence, deformation of cementite hardly affects the workhardening of pearlite. Even it was also found that fine cementite can accommodate an appreciable amount of deformation prior to fracture at the wear surface [149, 293]. A significant workhardening about 1 GPa was reported during rolling sliding wear test of fine pearlites [294]. Similar workhardening of pearlitic structure is reported elsewhere in [295]. The hardness of pearlitic steel in the present study (Table 5.3) exhibits an increase in surface hardness up to ~33%, even higher than bainite (~12.5% increase relative to the bulk hardness). In contrast, the wear rate
significantly higher for pearlite than that of the bainite. Bakshi et al. [198] and Narayanswami et al. [197] claimed that fine pearlite exhibits lower wear rate than martensite and similar wear rate compared to fine grained bainite in DSRW and pin-on-disc tests. Bakshi et al. [198] found a relatively softer white layer on the abraded surface of fine pearlite and proposed that the white layer was relatively ductile which was adhered to the surface resulting in lower wear loss. Narayanswami et al. [197] attributed the lower wear rate of pearlite to the plastic deformation of the cementite lamellae and accommodation of strain by the softer ferrite phase during the abrasion process. However, a significant increase in surface hardness was reported by Narayanswami et al. [197] in contrast to the work of [198] where the white layer correspond to fine pearlite was soft. In the present case, the pearlitic steel displayed a wear rate just beneath the mild steel (Figure 5.12 and Figure 5.16). The lower wear resistance of pearlite is not surprising and can be attributed to the change in wear condition. A moderate hardness and presence of brittle cementite layers (Figure 5.14) could not resist wear at high impact loads. The impact crater characterisation curve in Figure 5.19, confirms the domain of the steel in the map by the type of its damage. At similar crater length pearlite shows higher crater depth compared to the current tooth steel, which translates to a higher wear loss. Figure 5.21e depicts a brittle fragmented material along the impact groove and some slightly realigned pearlitic lamellae. Repeated impact loading changed the surface microstructure to a brittle white layer. The high hardness at the surface (430 HV, Table 5.3) is consistent with [197], which facilitates the rapid break-down of the harder cementite lamellae during impact events increasing the wear rate. Nevertheless, the softer ferrite phase that played a significant role in reducing the wear rate [197] may not applicable for an impact event where a single particle impinges on a specimen with ~5 J impact energy. Aminul et al. [296] studied the erosion behaviour of AISI 1080 (pearlite) steel
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with the abrasive particles (Al$_2$O$_3$, size ~57 µm) velocities 36-81 m/s and reported a higher erosion rate with increasing particle velocity. The material removal was attributed to the flattening, ridge formation and fragmentation of the cementite lamellae by the subsequent impacts. The materials and the experiments are markedly different than that of the present case however, this provides an indication that similar microstructural constituents behave differently when wear conditions are changed.

The current tooth martensitic steel exhibits a moderate wear response to the impact wear conditions. A workhardened subsurface and a thin white layer at the surface are evident in Figure 5.21b. The high bulk hardness of 475 HV appreciably resists the impact loading and results in a moderate wear rate. The impact crater characterisation curve in Figure 5.19 confirms the wear behaviour of this steel. It is worth comparing the wear rate of the current tooth steel (Figure 5.4b) with martensitic microstructure (Figure 5.4d). The higher hardness of the latter (677 HV) due to high carbon content resists wear more effectively. A similar result was reported in [11] where the high carbon martensite outperformed the low carbon martensite in impact wear conditions representing the role of hardness for similar microstructures.

The bainite of lower hardness (571 HV) exhibits a marginally higher wear performance than martensite (677 HV), see Figure 5.12 and Figure 5.16. The impact characterization curve Figure 5.19 also confirms the ranking as at similar crater length, martensite displays higher crater depth, indicating marginally higher wear loss. Figure 5.14 evidences that bainite is capable of higher work hardening than martensite. The marginally better wear performance of bainite is probably due to the transformation of retained austenite in stress induced martensite, i.e. TRIP effect. The finding is consistent with early reports [197, 198], however the wear tests were conducted on Pin-on-disk and DSRW methods. But in both cases fine pearlite and bainite showed a significant wear
resistance over martensitic microstructures.

In martensite, the high impact loading produced significant strain to the microstructure and severely fragmented the brittle surface (Figure 5.21d). Martensite gets little chance to accommodate the strain through any retained austenite transformation. This may be due to the morphology of the retained austenite. For example, the effect of retained austenite was studied in Quenched-Partitioned martensitic steel with Nanobainitic steel under stirring wear experiments [208]. The wear performance of the Quenched-Partitioned martensitic steel was higher and attributed to the higher stability of retained austenite which effectively contributed during the wear process. The blocky structure of austenite was less stable and transformed into martensite at an early stage of wear process [208]. However, the morphological investigation of the microstructure was not the aim of the present study.

To examine the effect of retained austenite during impact wear, XRD experiments were carried out on both microstructures before and after wear. As evident, in Figure 5.23a, the diminishing peaks of retained austenite after wear in bainite confirms the phase transformation which accommodates strain and reduces damage. The XRD analysis of the martensite (Figure 5.23b), clearly shows the presence of austenitic peaks after wear. Evidently the retained austenite did not undergo strain-induced transformation to austenite. Further investigations are required to characterize the surface white layers for both microstructures to understand the surface tribo-layer and its effect on wear behaviour.
Figure 5.23. XRD spectra: a) bainite before and after wear, b) martensite before and after wear.

With a significantly lower bulk hardness of \(~214\) HV (Table 5.3) the Hadfield steel shows a closer wear rate to the current tooth steel, Figure 5.12 and Figure 5.16. It is well known that Hadfield steels exhibit better wear performance at impact conditions in contrast to gouging abrasion condition due to its exceptional
workhardening propensity [155, 157, 271, 272]. Figure 5.14 demonstrates the workhardening depth of ~700 µm from the surface to matrix. The surface hardness was increased by ~187%. The surface profilometry in Figure 5.15c shows significant impact events with corresponding plastically deformed ridges. The Impact crater plot in Figure 5.19, demonstrates that instead of higher crater width the depth is appreciably low, which was opposite to the mild steel. From microstructural point of view, the Hadfield steels have ductile and resilient austenitic grains. Since impact wear can only be combatted by absorbing the impact energy, the toughness allows the microstructure to resist impact wear more effectively. The subsurface microstructure in Figure 5.24 depicts the presence of twinned structures in the deformed region and a harder white layer at the surface. As the tumbling continues, the ore particles are impacted on the specimen surface and slide across it. The impact energy causes rapid cold workhardening. Several mechanisms have been proposed to explain the strengthening process of Hadfield steels.

One reason proposed is strain-induced γ → ε martensitic transformation [297, 298]. Segregation [299], precipitation [300] and even fragmentation of grains was associated with martensitic transformation which anticipated in work hardening [301]. However, low temperature (4 K) deformation of Hadfield steels did not yield martensite and the workhardening was suggested to be due to the lowering of stacking fault energy by Mn atoms [271, 302] and pinning up dislocations and stacking faults by interstitial carbon atoms [271]. The contribution of twinning and slip were put forwarded to be associated with the deformation mechanisms depending on the crystallographic orientation [303]. It was reported that deformed austenite grains display primary and secondary twin systems with slip lines as slip - twinning interaction is another mode of hardening of such steels [304]. The formation of nanocrystals and partial amorphization were reported in the surface of Hadfield steel under high impact
energy [305]. Since Figure 5.24 illustrates the presence of both white layer and twin systems, accordingly, it can be suggested that several mechanisms discussed above could have contributed to the wear of Hadfield steel and is a matter of further detailed investigation.

Figure 5.24. Deformed subsurface of Hadfield steel; a) white layer, b) twin hardening at deformed substructure.
Thus, the current study suggests that the higher wear rate of soft mild steel is due to the moderate workhardening and removal of material due to lower hardness value. Pearlite wears in a brittle manner despite of appreciable hardening. Current tooth steel shows higher wear resistance than the pearlite due to its higher hardness value. Due to the lack of toughness, current tooth steel gets less opportunity for plastic deformation that explains its higher wear rate than bainitic steel. Bainite with lower hardness value shows marginally higher wear resistance than harder martensite. The TRIP effect of bainitic microstructure favours the wear performance. The hardness of the martensitic steel played the key role for the wear performance. However, the brittle fragmentation of martensite is evident on the surface resulting in wear loss, even at high hardness (677 HV).

5.8 Conclusion

The impact wear behaviour of different steels was studied in this chapter using Impeller tumbler test. The plate specimens were subjected to one-hour test consisting of each 10 minutes cycles. The impeller speed was 800 RPM, drum speed was 70 RPM and basalt aggregate of 10 kg, size 50-80 mm were the test parameters for each 10 minutes cycles. Similar wear loss was found for the samples positioned at 90° and 45° angles and we decided to focus mainly on the wear results of 90° angle. Wear tests were conducted on mild steel, current tooth steel of martensitic microstructure, carbide free fine bainite, tempered martensite and fine pearlite of same composition (1% C and 3% Si) and 12% Mn steel of Hadfield grade. The current tooth steel wear results exhibited a reasonable correlation with digger teeth failure analysis. The tumbled specimens were further examined using optical profilometry, microhardness measurements and SEM investigation to analyse the surface and subsurface
deformation. The following conclusions are drawn from the present study;

- The Impeller tumbler test provides qualitatively comparable wear conditions as experienced by GET. White layers are evident but lower in thickness compared to GET. Embedded ore particles at the surface also denotes severity of wear. By varying test conditions, microstructural changes and damage comparable to the worn GET could be achieved. This makes the test useful for comparing and ranking materials for use in a GET.

- The wear rates of the materials display a broad correlation with the bulk hardness. However, the results are largely influenced by the work hardening as indicated by the surface hardness plots and microstructural properties. Addressing the workhardening property in a laboratory wear test makes this test most appropriate than the others because impact wear was one of the major wear mechanisms for digger tooth and impact wear is governed by workhardening propensity of a material.

- The characteristic impact craters can be used to develop a wear regime plot, which may help to select material for certain wear conditions.

- Among several steels bainite and high Mn austenitic steels showed better wear resistance due to presence of ductile and tough austenitic phase. Other than better wear resistance, heat treatment of bainite makes this less prone to quench cracks.

- Among both martensitic microstructures, the martensite with higher level of carbon showed better wear resistance due to high hardness.
Chapter 6. Scratch test

6 Scratch tests

6.1 Aim and scope of work

The ‘forensic analysis’ of worn digger tooth in Chapter 4 depicted two types of abrasive wear, a) impact and b) grooving. During excavation of iron ore, the digger tooth had undergone severe workhardening by the impact actions as well as grooving wear on the workhardened surface.

The impact wear was replicated using impeller tumble test, described in Chapter 5. However, the wear rig was not sufficient to address the grooving behaviour. The one-hour impeller wear test of the steels illustrated a steady state wear behaviour which involved workhardened surface with respect to the impact actions by the basalt aggregates. But the grooving wear, evident on the workhardened tooth surface (Figure 4.15) was not addressed adequately by the test method. Therefore, scratch test was devised to conduct single scratch experiments on the steel surfaces to replicate the field grooving wear condition.

The steels described in Section 5.4.1, were employed for scratch experiments on undeformed and worn tumbled surfaces. The groove dimensions analysed on the tooth surface were sufficiently large (groove depth ~20-300 µm and groove width ~500-3000 µm, Figure 4.18). It was necessary to recreate grooves of similar dimensions. Higher loads up to a range of 1000 N and an indenter of spherical tip (radius’ 0.82 mm) were used to generate coarser wear grooves. However, the scratch tests conducted in the present study with the indenter tip radius 0.82 mm allowed groove width ranging from 200-1400 µm and a groove depth ranging from 3-200 µm depending on the steel microstructure, load and surface condition.

The present study seeks to gain insight into grooving wear by single scratch
experiments. The critical normalized depth or ‘scratch ductility’ [306] was evaluated for each test steel at virgin (undeformed) and worn tumbled regions. The scratch ductility is a material property which determines the proclivity for material removal during a scratch event.

6.2 Introduction

It was necessary to address the grooving wear behaviour which played a vital role in wear of digger tooth. A scratch test rig was developed to conduct controlled grooving wear on the steels. Substantial work is reported in literature, on scratch and frictional behaviour of surface coatings using a scratch test rig [265, 307-324]. Scratch testing was also used to study the abrasive wear behaviour of steels as a function of loading, indenter size, scratch speed, length and steel surface conditions [30, 39, 40, 282, 325-332].

During abrasive wear the material surface and subsurface are workhardened that contribute significantly in material removal [65, 67, 88, 126, 149, 333-335]. However, the effect of prior working on the abrasive wear behaviour is a matter of debate. The prior working mainly increases the hardness of the material which is thought to increase the wear resistance. But models of Zum Gahr [16] and experiments of Misra et al. [128] reported that prior working is detrimental for the wear behaviour of a material (Figure 2.16), discussed in Section 2.1.1.2.

Limited work is reported on the effect of prior working on wear resistance [9, 245, 270, 287, 336-338]. Venkataraman et al. [338] found that presence of cracks in deformed subsurface enhances wear rates of Aluminium alloys. Ratia et al. [9, 245] conducted Impeller tumbler tests with martensitic steels of different hardness and proposed that material was detached more easily from the previously deformed impact craters. A similar wear behaviour of martensitic steels was found by Lindroos et al. [224] in scratch tests. Shot peening on
Chapter 6. Scratch test

Hadfield steels was used to increase hardness by Yan [337]. But the abrasive wear resistance was not improved when the steel was subjected to harder abrasives. This was attributed to the loss of ductility of the surface hardened layer.

Mathematical Modelling

Zum Gahr’s [16] grooving wear model was discussed above in Section 2.1.1.2. Two variables were introduced to describe the grooving wear of a material. Degree of wear \(f\) and degree of penetration \(D\) (Figure 2.13). The degree of wear \(f\) represents cutting to ploughing ratio, determined in Equation 2.9 and degree of penetration \(D\) which was replaced by \(\delta\) represents depth of penetration normalized by curvature radius (Equation 4.1). The variation of \(f\) with \(\delta\) provides a S - type curve [16, 31, 125], see Figure 2.14, discussed in Section 2.1.1.2.

The present research work outlines influence of ‘scratch ductility’ on abrasive wear of workhardened and virgin materials by single scratch test measurements. The ‘scratch ductility’ is the critical normalized depth specific to a material, proposed previously in an unpublished work by Ghaderi et al. [306]. They expressed the degree of wear \(f\) as;

\[
\begin{align*}
\delta_c & = 1 - e^{-\left(\frac{1.3\delta}{\delta_c}\right)^2} \\
\text{Equation 6.1}
\end{align*}
\]

Where \(\delta_c\) is a fitting parameter that characterizes the scratch ductility. Thus, we have two material parameters to describe the propensity for abrasive wear: hardness and scratch ductility.

During digging the teeth experience impact and grooving wear. Due to significant strain accumulation, the surface and the near surface zone get workhardened. Subsequently the hard-abrasive particles continue repetitive impacts and grooving actions on the hardened surface. Thus, the single scratch experiments help to understand the variation of the depth of penetration at workhardened
surface and its influence on the wear resistant property. The study also provides a comparative wear response of the steels (described in Section 5.4.1) at similar working conditions.

6.3 Experiments

6.3.1 Materials

Steels for scratch test

The same steels (Section 5.4.1), subjected to Impeller tumbler tests were used for scratch tests. A list of the materials is provided below for the convenience;

- Mild steel equivalent to AISI 1018,
- Current tooth steel (0.3% C, martensitic microstructure)
- A high carbon and silicon grade steel with three distinct microstructures: a) Carbide free bainite with finely distributed ferrite lath and retained austenite, b) Tempered martensite with high hardness and c) fine pearlite.
- A Hadfield grade steel of ~12% Mn.

The reason for choosing the steels and their composition and hardness (Table 3.1), casting, heat treatment, microstructure (Figure 5.4) and mechanical properties are discussed in detail in Section 5.4.1.

Surface and loading conditions of the steels during scratch test

The present study employs scratch testing of the steels in two surface conditions; a) scratch test in virgin condition (undeformed part) and b) On work hardened region (worn Impeller tumbled part).

The tests on the virgin material were carried out by Dr Alireza Ghaderi on the same steel microstructures described in Section 5.4.1. The test conditions were similar to the present work exercised with an indenter of spherical tip radius of
0.82 mm at different loads ranging between 500 N and 2000 N. We have used the results of Dr. Ghaderi’s work [306] with his permission to compare the results on worn surface. Dr. Ghaderi’s research work is yet to be published. The scratch tests on the worn surface and analysis of data for both the undeformed and deformed steel surfaces were conducted by the present author.

Impeller tumbled samples positioned at 90° angles were chosen as worn samples. The tip area was severely deformed than that of the back part (Figure 5.13). A microhardness profile was measured from tip towards back of the samples to confirm the existing hardness gradient. A schematic diagram of an Impeller tumbled sample is provided in Figure 6.1. The sample length of 26 mm was used for scratch test and 8 mm sample lengths at adjacent sides were used for clamping. The hardness measurement was commenced 10 mm away from the tip (shown in red dotted line in Figure 6.1) as ~8 mm section was used for clamping and 2 mm distance was kept for safe operating condition during scratch test. The hardness tests were performed on the surface and up to 90 mm distance from the tip. 85 mm sample length was exposed to the tumbler test and the hardness between 85-90 mm represents undeformed regions which was consistent with Dr. Ghaderi’s hardness values on undeformed surface.

Figure 6.1. Schematic diagram of an Impeller tumbled specimen delineating the scratch test area and clamping area.
The hardness plot in Figure 6.2 confirms that a reasonable hardness variation exists up-to a sample length of 42 mm. The hardness data is an average of three consecutive readings conducted between 25 to 30 µm distances from the surface. The depth chosen for the hardness measurements was optimized to represent the actual hardness profile. The hardness profile just beneath the surface (from surface to 20 µm) showed higher scatter due to the occasional presence of the thin white layers and surface irregularities. The hardness profile measured at depth > 30 µm was closer to the matrix and misrepresenting the actual hardness profile. Hardness values after 42 mm do not show appreciable difference from the bulk hardness (Table 5.3) performed at 90 mm position except for Hadfield steel. The sample length exposed to Impeller tumbler testing was 85 mm. Hence it was decided to perform scratch test from tip to 42 mm section. However, 26 mm section was used for scratch testing because adjacent 8 mm sections were consumed for clamping of the samples.
Chapter 6. Scratch test

Figure 6.2. Microhardness profile on the surface of the Impeller tumbled samples from tip towards back. The hardness measurements were performed 10 mm away from the tip towards back of the sample. A reasonable hardness gradient is apparent from 10 mm up to the 42 mm of the sample length. The hardness at undeformed regions were consistent with Dr. Ghaderi’s [306] hardness values on undeformed region.

Figure 6.3 represents the 42 mm sample length area (shown in Figure 6.1) used for scratch testing and adjacent clamping areas. The scratches are designated as S1, S2, S3, S4, S5 and S6 which represent first to sixth scratch. The undeformed scratch results were taken from the previous work [306] on the same material at similar working conditions. The scratch at undeformed region is designated as
S7. Initially the hardened region was subdivided into six separated regions, indicated as H1, H2 up to H6. H7 denotes the undeformed region, however, this is not shown in the diagram. Scratch test was performed at 10 mm distance from the tip at 500 and 1000 N loads towards back. Thus, alternatively 6 scratch tests were conducted at 500 and 1000 N loads, total 12 scratches. Each hardened region consists of two scratches at 500 and 1000 N loads. The H1 region consists of two scratches S1-500 N and S1-1000 N and this is similar for all other hardened regions, for example H6 consists of two scratches S6-500 N and S6-1000 N.

Figure 6.3. Schematic view of the hardened regions containing two scratches at loads 500 and 1000 N. Undeformed region is not shown here. For example, region H1 consists of scratches conducted at 500 and 1000 N loads (S1-500 N and S1-1000 N).
The average hardness of the regions where the scratch events were conducted have been extracted from Figure 6.2 and Figure 6.3 are represented in Figure 6.4.

Figure 6.4. Hardness of the regions where the scratch events were conducted for all the steels.

Trials were conducted to decide loading conditions during scratch tests. 500 N, 1000 N, 1500 N and 2000 N loads were used to conduct trials on workhardened current tooth steel surface. Only at 500 N load a workhardening effect was observed from tip to back in terms of scratch depth profiles. At the tip, the scratch depth was less and towards back the scratch depth was increasing. The scratch tests with higher loads displayed similar scratch depth profiles from tip to back. This may be due to the penetration reached undeformed matrix at higher loads. Thus, it was decided to carry out scratch tests with 500 N and 1000 N loads.
6.3.2 Scratch test

Equipment

A high stress abrasion scratch testing machine equipped with a conical stylus indenter (Figure 6.5a) was used for scratch tests.

Figure 6.5. Scratch testing machine.
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The servo controlled single axis driven scratch test rig can apply a vertical load ranging from 100-4000 N. The scratch test rig is placed on the lower jaw of a 100 kN servo-hydraulic Instron test machine while the upper jaw holds a compression platen that offers load through the sliding plate. The conical stylus (30° cone) has a spherical tip of radius ~0.82 mm. The indenter is made of cemented tungsten carbide (WC) + 10% cobalt. During testing the 100 kN Instron machine applies desired loads to the samples through upper jaw whereas a load cell arrangement records the loading data. Samples of size 5 × 40 × 45 mm³ are clamped by screw arrangements shown in Figure 6.5b.

Testing methodology

The single scratch test cycle consists of certain steps described in Figure 6.6a. At first, the indenter makes an indentation on the sample surface at 150 N preload. As the indent is made the load starts to rise till it reaches the desired load. 20 seconds holding time is kept to stabilize the system at the target load before the onset of scratch. After 20 seconds of holding the scratch machine is run manually to start the scratch event at 40th second. All scratch events were conducted at 1 mm/s scratch speed that produces a consistent scratch profile. Usually, the scratch test length was kept 35 mm for all the samples except mild steel (25 mm) and bainite samples (20 mm). The extreme rough surface and significant rounding of sample edges for mild steel during Impeller tumbler tests restricted the scratch event to continue smoothly. Scarcity of sample lead to short scratch events for bainite. The scratch event ends at 75th second then another 10 seconds holding time is given to stabilize the system. At the finishing of the total time the sample is unloaded and the lower jaw is returned to its unloading condition. The handle system shown in Figure 6.5b is used to move the sample to start the next test at new desired position.
Figure 6.6. Scratch test on pearlite sample: a) Load as a function of time plot obtained from Instron machine, b) Load variation during a scratch event at 500 and 1000 N loads. Scratch indenter radius 0.82 mm.
The scratch test events conducted on pearlite sample at 500 and 1000 N loads are shown in Figure 6.6b separately. The scratch events commenced at 40th second and finished at 75th second. The load shows a reasonable consistency of ± 5 N fluctuation over the scratch period. The scratch at 500 N load is rougher compared to the 1000 N load, the reason is discussed in Section 6.4.1. The loading behaviour was consistent for all the other materials presented in this study.

### 6.3.2.1 Consistency of scratch profiles between Instron and optical profilometry

Figure 6.7, compares the scratch profiles obtained from Instron machine and optical profilometry for current tooth steel. The comparative profiles are represented for both loading conditions 500 N and 1000 N. In case of Instron machine the vertical axis represents the depth of the scratches and the horizontal axis shows the scratch length. The scratch length was extracted from load versus time data obtained from the Instron machine. As the scratch speed was 1 mm/s the corresponding time was translated in scratch length of 35 mm for the current tooth steel. The scratch commenced on 40th second of the test and finished on 75th second. The zero position corresponds the indenter position which was at 150 N preload. For the optical profilometry Alicona software was used to draw an average profile along the middle portion of the scratches which provides the vertical displacement from the reference zero surface.

For both loading conditions the scratch Instron machine exhibited reasonable consistency with the profiles obtained from optical profilometry. The outcome was same for all the other steels. However, the presence of wear debris may have incorporated an error in the profile measurement of Instron data. Therefore, all the following calculations were performed with profilometry data.
Figure 6.7. Comparative scratch profiles of current tooth steel, data obtained from Instron machine and Optical profilometry; a) 500 N load, b) 1000 N load. Scratch indenter radius 0.82 mm.
6.3.2.2 Longitudinal scratch profiles of steels

Figure 6.8 demonstrates longitudinal scratch profiles of the steels at 500 N and 1000 N loads. The tip profiles (S1) for the steels are represented in this segment. Expectedly, martensite represents the lowest depth of scratch whereas mild steel shows highest scratch depth. A significant roughness (peak and valleys) in the scratch profiles may be observed in case of mild steel, pearlite and Hadfield steels due to the formation of microcracks, chipping and delamination of wear debris. The profiles of the martensite and bainite microstructures were smooth and free from debris.

A transient region exists at the beginning of the test. It depends on the material property and loading conditions and can be attributed to the reduction in contact area between indenter and grooving material during onset of steady state scratching from an initial period of indentation [134, 306, 307, 321, 339]. A similar transient region was recorded in case of softer steels at 1000 N load. However, the transient behaviour was less prominent in this case, may be due to the presence of workhardened surface. No transient behaviour was observed at 500 N load which is consistent with the previous report [306].
Figure 6.8. Longitudinal scratch profiles on worn surface (tip region) by optical profilometry of steels; a) 500 N load and b) 1000 N load. Scratch indenter radius 0.82 mm.

### 6.3.3 Surface characterization

Scratch tested samples were cleaned with alcohol in an ultrasound bath to remove wear debris and dried. The surface scratches were scanned with a 3D optical profilometry (Alicona™ Infinite Focus, Figure 4.10) to evaluate groove depth profiles and measure wear rate.
6.4 Results

6.4.1 Scratch profiles of steels

The scratch depths of the individual scratches from tip towards back (S1 to S6) and undeformed (S7) are shown in Figure 6.9a and b at 500 N and 1000 N loads respectively.

An increase in scratch depth is noticeable for all the steels on progress towards back at 500 N load. The variation in scratch depth can be attributed to the hardness profile (Figure 6.2). This may be inferred that a thin workhardened layer was created on all the steel specimen surfaces after Impeller tumbler test. The indenter penetrated the workhardened layer at 500 N load.

No significant scratch depth variation was observed at 1000 N load scratch tests, except for Hadfield steel (Figure 6.9b). Similar scratch depths at 1000 N load towards back indicate that the indenter penetrated the unaffected matrix beyond thin workhardened layer.

In both cases the mild steel exhibited some noise that may be due to the entrainment of delaminated wear debris during scratches. This was examined by the optical images and discussed in Section 6.4.6. The significant workhardening of Hadfield steel up to a depth of ~700 μm (Table 5.3) correlates the depth profile observed at 1000 N load. The other steels showed an increase in scratch depth towards the back which is consistent with the lower hardness of the back part of the samples. The scratch depths of the other steels at 1000 N load do not show appreciable variation.
Figure 6.9. Scratch depth of individual scratches from tip towards back of all the steels at loads; a) 500 N and b) 1000 N. Scales are different for two plots. Scratch indenter radius 0.82 mm.
Figure 6.10 and Figure 6.11 respectively represent the scratch profiles at 500 N and 1000 N loads. For ease of distinguishing in all cases the scratch profile at tip (S1) was marked with ‘orange’ colour and the scratch at undeformed region (S7) was marked with ‘black’ colour. To maintain experimental similarity, each scratch graph was extracted by averaging the profile length excluding 5 mm distance both from starting and finishing points of the scratches. The justification for average profiling is discussed in Section 6.4.2.

The depth profiles shown above in Figure 6.9 were extracted from the scratch profiles (Figure 6.10 and Figure 6.11) respectively for 500 and 1000 N loads. The plots in Figure 6.10 and Figure 6.11 have same scales for all the steels except mild steel. The mild steel, Hadfield and pearlite showed higher scratch depths compared to bainite and martensite which resisted the indenter penetration most.
Figure 6.10. Scratch depth profile of the steels at 500 N load; a) mild steel, b) pearlite steel, c) Hadfield steel, d) current tooth steel, e) bainite and f) martensite. Scales are same except mild steel. Scratch indenter radius 0.82 mm. Scratch profile at worn tip (S1) was marked with ‘orange’ colour and the scratch at undeformed region (S7) was marked with ‘black’ colour.
Figure 6.11. Scratch depth profile of test steels at 1000 N load; a) mild steel, b) pearlite steel, c) Hadfield steel, d) current tooth steel, e) bainite and f) martensite. Scales are same except mild steel. Scratch indenter radius 0.82 mm. Scratch profile at worn tip (S1) was marked with ‘orange’ colour and the scratch at undeformed region (S7) was marked with ‘black’ colour.
6.4.2 Justification of average profiling

Figure 6.12 demonstrates a comparative plot of 10 scratch profiles of worn mild steel sample at worn tip (S1) under 1000 N load. The optical profilometry image of mild steel S1 scratch at the tip with 1000 N load is displayed in Figure 6.16c. The separate brown profile in Figure 6.12 has been shifted intentionally to the right for better clarity. The brown profile exhibits the single profile, taken by averaging the whole scratch. The average profile reveals approximately similar groove depth and height of the ridges compared to the average representation of 10 profiles throughout the scratch length. Figure 6.12 evidences that averaging of the profiles allows more approximate representation of the scratch depths and plastic ridges than that of the line profiles.

Figure 6.12. Profiles of 10 scratches along the scratch of a worn mild steel (S1), 1000 N load and the average single profile shown separately in brown colour (intentionally shifted to the right for better clarity). Indenter radius 0.82 mm.
6.4.3 Scratch profiles comparison of steels

The scratch depths of the steels for three positions have been compared. Three positions were selected for the analysis; a) worn tip region (S1), b) worn 4th scratch region (S4) and c) the undeformed region (S7). The comparative scratch profiles are shown in Figure 6.13. Mild steel showed highest depth at the tip among other steels that increases towards undeformed region at 500 N load. An increasing scratch depth of mild steel at 500 N load indicates that the tip is workhardened compared to the back. However, at 1000 N load no appreciable change in scratch depth was observed that confirms a deeper groove. At 500 N load pearlite shows marginally better resistance to indenter penetration than Hadfield steel at hardened regions (Figure 6.13a and c) instead of higher hardness of Hadfield steel (Figure 6.4). This may be due to the underneath soft matrix of Hadfield steel that surrounded the indenter. The inherently lower hardness of the matrix and lower opportunity to workharden at 500 N load resulted in higher penetration depth. However, the higher depth did not translate to higher wear rather material was pushed as ridges resulting in lower wear loss compared to pearlite, evidenced in volume wear plot in Figure 6.15a. The depth is high for Hadfield steel at undeformed region (S7-500 N, Figure 6.13e) than pearlite. This is reasonable and can be correlated to the lower hardness of Hadfield steel. However, the 1000 N load reveals increase in scratch depth for pearlite than Hadfield steel (Figure 6.13b, d and f). The better resistance to penetration is attributed to the sufficient workhardening effect at higher load. It was discussed earlier (Section 5.7) that Hadfield steels require requisite loading to workharden effectively and resist wear [285-287]. Thus, at high load the workhardening plays the key role. The scratch depths of martensite and bainite display a direct correlation with the hardness of the materials. Thus, the scratch depth comparison provides an insight of the loading effect on the...
prior worked steels of different workhardening propensity.

Figure 6.13. Scratch profiles; a) S1 – 500 N, c) S4 – 500 N, e) S7 – 500 N and b) S1-1000 N, d) S4 – 1000 N, f) S7 – 1000 N. Scales are different at different loads. Indenter radius 0.82 mm.
6.4.4 \( f \) plots as a function of \( \delta \)

The degree of wear \( f \) was plotted as a function of depth of penetration \( \delta \) in log scale, see Figure 6.14a and b respectively for 500 N and 1000 N loads. The \( f \) and \( \delta \) values were evaluated using Equation 2.9 and Equation 4.1 respectively. The average of \( f \) and \( \delta \) values of the scratch events S1, S2 and S3 represent the hardened worn tip, worn middle location is an average of S4, S5 and S6 scratches and the scratch S7 represents undeformed surface. For each steel the red, green and blue markers represent the worn tip, worn middle section and undeformed surfaces respectively.

Since the tip regions were hardened a distinct transformation from ploughing to cutting is evidenced for all the steels. The plots Figure 6.14a and b also clearly discriminate the domain of the steels. Mild steel having higher depth of penetration under both loading conditions situates at extreme right. Pearlite and Hadfield steels show similar depth of penetration and retain their positions between mild steels and current tooth steel. Bainite shows lower depth of penetration due to higher hardness than current tooth steel. Martensite (1\% C) positions at extreme left offering higher wear resistance due to high hardness. The lower scatter of the \( f \) values in Figure 6.14b indicates deeper grooves under 1000 N load. These plots have been used to study the effect of deformation on the steels, discussed in later section.
Figure 6.14. Degree of wear \( f \) as a function of degree of penetration \( \delta \) in log scale plots; a) 500 N load and b) 1000 N load. For each steel the red, green and blue markers represent nearby average \( f \) and \( \delta \) values at worn tip, worn middle section and undeformed surfaces respectively.
6.4.5 Wear volume of scratches

The wear volume was measured for each steel at the respective scratch events S1, S4 and S7 for both loads. For individual scratches, the ridge areas were subtracted from the groove area \( A_v - (A_1 + A_2) \), Figure 2.13 which was multiplied by the respective scratch length. The wear volume per unit scratch length was plotted for the corresponding scratch (Figure 6.15).

In general, mild steel had the highest wear volume and bainite and martensite the lowest. Under 500 N load Hadfield steel exhibited a lower wear loss due to the dominant effect of workhardening at low scratch depths (Figure 6.15a). The wear volume plot (Figure 6.15a) under 500 N load reveals an increase in wear volume at the hardened tip for the softer steels. This reflects the effect of \( f \) on wear. The 1000 N load plot (Figure 6.15b) confirms that the effect of prior working is marginal for deeper scratches.
Figure 6.15. Wear volume of the scratch events: a) at 500 N and b) 1000 N load.
6.4.6 Optical profilometry

A comparative optical colour images are provided below which support the above results in terms of scratch depth and plastically deformed ridges. All the images correspond to the range of 7 to 9 mm length collected from the similar section of scratches to maintain experimental similarity. For all the steels, the worn tip (S1) and undeformed (S7) scratches are displayed side by side at respective loads. Figure 6.16 represents mild steel and Hadfield steel. Figure 6.17 shows pearlite and current tooth steels. Figure 6.18 corresponds to bainite and martensite scratch images. The scratch profile images are consistent with the optical profilometry profiles shown in Figure 6.10 and Figure 6.11. The scratch surface of the steels at worn tip (S1) are rougher compared to the smoother undeformed (S7) scratches. The adjacent plastic ridges are uniform and distinguishable for undeformed scratches (S7) than that of the tip scratches. This is consistent with the brittle nature of the hardened tips of the steels. Significant cracks, delaminated flakes and chipping may be observed in case of mild steel that imparted noise in profile measurement shown in Figure 6.9. The side ridges of Hadfield steel are even and thick at undeformed surfaces perhaps a degradation in ridge formation on the hardened tip may be observed in Figure 6.16. Bainite and martensite steels show smoothest wear tracks with uniform ridges and lowest scratch depth which is consistent with the above results.
Figure 6.16. Mild steel: a) S1-500 N, b) S7-500 N, c) S1-1000 N, d) S7-1000 N. Hadfield: e) S1-500 N, f) S7-500 N, g) S1-1000 N, h) S7-1000 N.
Figure 6.17. Pearlite: a) S1-500 N, b) S7-500 N, c) S1-1000 N, d) S7-1000 N. Current tooth steel: e) S1-500 N, f) S7-500 N, g) S1-1000 N, h) S7-1000 N.
Figure 6.18. Bainite: a) S1-500 N, b) S7-500 N, c) S1-1000 N, d) S7-1000 N. Martensite: e) S1-500 N, f) S7-500 N, g) S1-1000 N, h) S7-1000 N.
6.5 Discussion

A scratch test was employed to understand the grooving wear behaviour of different microstructural steels to complement the previous two Chapters. Two loads (500 N and 1000 N) were applied to execute single scratch experiments on the samples subjected to tumbler testing.

The grooving wear behaviour of the steels was found to be consistent with the respective undeformed microstructures. Mild steel and pearlite offered lowest abrasive resistance, characterized by significant chipping and delaminated debris for mild steel as evident in Figure 6.16a, b, c and d. Hadfield steel, bainite, current tooth steel and martensite showed appreciable wear resistance with smoothened grooves and plastic ridges (Figure 6.16, Figure 6.17 and Figure 6.18).

However, the effect of prior deformation needs to be investigated more explicitly. To address this, the $f$ and $\delta$ values obtained from Figure 6.14 were averaged for nearby locations. Using Equation 6.1, fitted curves were constructed for the hardened worn tip, worn middle and undeformed regions in combination of 500 and 1000 N loads (Figure 6.19). For the undeformed part Dr. Ghaderi’s scratch data on the undeformed steels under 500 and 1000 N loads were used, indicated by blue lines in Figure 6.19 for each plot. The transition from ploughing to cutting was assumed to have occurred at $f = 0.90$. It is interesting to note that the prior deformation shifted the $f$ plot towards left compared to the undeformed surface in Figure 6.19. This indicates a lower penetration depth due to the presence of thin workhardened surface layer.
Figure 6.19. Fitted $f$ versus $\delta$ curves. Blue line indicates undeformed surface, orange hardened middle and red line hardened tip. Each plot contains scratch data under 500 and 1000 N loads; a) mild steel, b) Hadfield, c) pearlite, d) current tooth steel, e) bainite and f) martensite. Scales are same for all the steels.
The critical normalized depths or ‘scratch ductility’ ($\delta_c$) were extracted for the hardened worn tip, worn middle and undeformed regions, summarized in Table 6.1.

Table 6.1. $\delta_c$ values of different steels at undeformed and other two different hardened regions.

<table>
<thead>
<tr>
<th>Steels</th>
<th>Undeformed</th>
<th>Middle</th>
<th>Tip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>0.16</td>
<td>0.08</td>
<td>0.049</td>
</tr>
<tr>
<td>Pearlite</td>
<td>0.04</td>
<td>0.015</td>
<td>0.012</td>
</tr>
<tr>
<td>Current tooth steel</td>
<td>0.016</td>
<td>0.0065</td>
<td>0.0035</td>
</tr>
<tr>
<td>Hadfield</td>
<td>0.1</td>
<td>0.02</td>
<td>0.0165</td>
</tr>
<tr>
<td>Bainite</td>
<td>0.04</td>
<td>0.0053</td>
<td>0.0037</td>
</tr>
<tr>
<td>Martensite</td>
<td>0.03</td>
<td>0.0016</td>
<td>0.0012</td>
</tr>
</tbody>
</table>

Figure 6.20 demonstrates a degradation of scratch ductility on the worn surface compared to the unworn surface. The surface working has two effects; a) increasing surface hardness and b) decreasing ductility. These effects may cancel each other and leave the wear rate same. The prior working increases surface roughness that might make material removal easier. The deep grooves on the thin workhardened skin layer indicate that the skin has little effect on wear.
H7 (Undeformed) H4 (Middle) H1 (Tip)

Figure 6.20. Degradation of scratch ductility ($\delta_c$) in log scale at undeformed and hardened middle and tip sections.

The $\delta_c$ values at the worn tip and undeformed regions were further plotted as a function of hardness, see Figure 6.21. Bainite and martensite steels can be seen situated at the top right of the plot exhibiting higher wear resistance at undeformed conditions. This is because wear mechanisms at the undeformed surfaces are cutting and ploughing. However, the microstructures display a high susceptibility to scratch ductility. The critical depth or scratch ductility that transforms the wear mode for bainite and martensitic microstructures from ploughing to cutting is highly dependent on the surface hardening as evidenced by the respective slopes in Figure 6.21. The decrease in scratch ductility deteriorates the surface and the dominant wear mechanism becomes cutting and fracture which enhances the wear rates of bainite and martensite at hardened conditions. Lower decrease in scratch ductility for a wider range of surface hardness indicates that higher critical depth is required for wear mode
transition from ploughing to cutting. In other words, ploughing mode of wear dominates for a wider range of groove depth resulting in a reduced wear. Thus higher workhardening capacity of Hadfield steel allows a little drop in scratch ductility from unworn to the worn surface, consequently a low wear is evident. Mild steel exhibited that a critical depth for ploughing to cutting wear may be achieved within a very lower increase in surface hardness, expressing its high vulnerability to wear. Pearlite and current tooth steels revealed parallel slopes but higher hardness of the latter helped to resist wear more. The results are consistent with the wear volume of the steels (Figure 6.15).

Figure 6.21. Drop in scratch ductility due to prior work by tumbling. Filled markers for mild steel, current tooth steel, bainite and martensite represent $\delta_c$ at undeformed regions and the unfilled markers correspond to worn tip regions. The undeformed and tip regions of pearlite are indicated by horizontal and vertical red lines. For Hadfield steel, the magenta coloured plus sign indicates undeformed region and cross sign indicates the tip region.
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6.6 Conclusion

The current study describes a high stress grooving behaviour of the steels at deformed and undeformed conditions by single scratch experiments. The scratch tests on the deformed surface represents a typical digger tooth grooving wear on workhardened condition. Following are the conclusions;

- The scratch depth of the alloys correlates with hardness of the materials.
- The depth of penetration is critical for the grooving wear. The critical normalized depth or scratch ductility that transforms wear mode from ploughing to cutting explains the grooving wear of steels.
- Prior working degrades the scratch ductility, evident at the hardened worn tip.
- Increase in surface roughness due to prior deformation facilitates material removal. Deeper grooves evidently demonstrate that thin layer of workhardened skin has little effect on wear.
- At undeformed region martensite and bainite show comparatively similar wear behaviour, however the wear resistance deteriorates for both materials at prior deformed condition.
- Hadfield steel displayed a lower drop in scratch ductility for a wider range of surface hardness indicating dominance of ploughing mode of wear resulting in a reduced wear.
7 General discussion

The current project began with an investigation of the failure mechanisms of a worn digger tooth which was in operation in an iron ore mine. The Impeller tumbler test machine was used to conduct impact wear tests and found to be effectively addressing the workhardening behaviour of the steels. However, the white layer formed on the tumbled steels revealed lower in thickness compared to the worn tooth. There was also a reduced appearance of grooves on the tumbled specimens. Thus, scratch test was conducted to investigate the grooving wear.

Scratch test was performed on the Impeller tumbled samples and the fitted curves were compared with Dr. Ghaderi’s scratch test results conducted on undeformed surfaces of the steels at similar working conditions. The scratch tests on the deformed surface replicates the real field conditions and help in ranking of the materials as per their grooving wear performance. This is reasonable to compare the wear results of the steels with the digger tooth steel to prescribe the suitable alloy for this application.

7.1 Comparison: Impeller tumbler and scratch test results

A comparative wear ranking of the materials is presented in Figure 7.1 for Impeller tumbler and scratch test methodologies. The normalized wear rate of the steels is plotted as a function of surface hardness. The wear rates obtained from the tumbler tests (Table 5.2) were normalized by the mild steel wear rate. Similarly, for scratch tests, the wear volumes at 500 N load of the materials were scaled with mild steel wear volume at hardened tip region (Figure 6.15a). The
surfaces of the materials were significantly work hardened after tumbling, further used for the scratch testing. Thus, this is more realistic to plot the wear rates as a function of surface hardness in contrast to bulk hardness.

Figure 7.1. Comparative wear results of the steels in Impeller tumbler and scratch tests as a function of surface hardness. Wear rates obtained from tumbler testing, normalized by the mild steel wear rate and the volume wear obtained from scratch tests with 500 N load at the hardened tip of the steels, normalized by the mild steel volume wear.

Generally, both normalized wear rates display an approximate correlation with hardness of the materials. Hadfield steel resists wear most than the current tooth steel in both wear conditions due to its dominant workhardening property. However, bainite exhibits higher wear resistance compared to the martensite in
impact wear condition but its wear rate increases in scratch test at hardened region compared to the martensite. It was demonstrated that retained austenite in bainite had undergone strain induced transformation to martensite (Figure 5.23a). Perhaps, during scratch test the thin workhardened layer on bainite surface had no retained austenite that could resist wear. Thus, hardness played the predominant role and bainite worn off rapidly than that of the martensite which had higher hardness than the bainite. Thus, Impeller tumbler test results are evidently more inclined towards workhardening of a material in contrast to the scratch test where hardness governs the wear behaviour. Similar results were reported by Ratia et al. [243] and Hawk et al. [184].

Figure 7.1 also demonstrates that scratching shows a clear difference in wear performance of the steels whereas impact tends to reduce the differences. However, in both wear tests the worse and best two steels are approximately same. The key observation is that high C martensite offers higher wear resistance in scratching but bainite might be preferred when the wear process involves impact. The reason for this might be that in impact dominated deformation we don’t have much of a groove; so material removal is different than the scratching. Hence for the GETs, harder martensitic steel can be used in coal mines but bainite is preferred for digging of iron ore.

Finally, this can be inferred that scratch test is the preferred method for the GETs used in mining of soft materials like coal and tumbler test is more likely for mining of harder iron ore materials.

7.2 Comparison: laboratory and digger tooth grooving wear

It is interesting to compare the digger tooth surface grooves with the scratches conducted in laboratory. The comparison may provide significant insights into
the changes in surface conditions of the digger tooth during operation. Therefore, the digger tooth \( f \) plot (Figure 4.19) was compared with the \( f \) plots of the undeformed and hardened tip of the current tooth steel obtained from the fitted curves considering \( f = 0.90 \), shown in Figure 6.19d. The comparative plot in Figure 7.2 depicts that the \( f \) plot of the commercial worn digger tooth is positioned at the right side followed by the unworn material despite of significantly workhardened surface. The \( f \) plot obtained from the scratch test on the worn hardened tip was found to be located at the extreme left.

![Figure 7.2](image-url)

Figure 7.2. Comparative \( f \) plots of the commercial worn digger tooth steel (obtained from Figure 4.19) and fitted curve of the current tooth steel at undeformed surface and hardened tip under 500 and 1000 N loads.

The \( f \) plot of the worn digger tooth positions further right of the scratch test \( f \)
plots for both undeformed region and hardened tip of the impeller specimen. This suggests a lower propensity for material removal in the industrial environment.

Frictional effects may play a role in the difference between the scratch tests and the grooves, found on the worn tooth. Significant impacts in the field may also cause thermal softening of the surface. A soft layer beneath the white layer, adiabatic shear bands and entrapment of ore particles were evidently common in worn digger tooth microstructure. Thus, frictional effects and thermal softening at the interface might have increased the propensity for material removal in the field.
8 Final conclusion and future work

Conclusion

- Long grooves are evident on the worn tooth surface. The $f$ plot and white layer thickness as a function of groove depth are useful characteristics which can be extracted from the worn components.
- Impeller tumbler tests show qualitatively similar microstructures compared to the worn tooth but thickness of white layer was lower and grooves were shorter in the former. Bainite showed promising wear resistance in tumbler test.
- Scratch tests provide a good steel differentiation in terms of $f$ plots as a function of $\delta$. Small and complex effect of prior work revealed a notable shift in $f$ curve.
- The $f$ plots comparison between the worn digger tooth and the tumbled current tooth steel indicates that the linear scratch test over-constrains the stylus with respect to the rock asperities in the industrial environment.
- Wear rate comparison shows high C hard martensite is preferred for scratching but bainite is more likely if the wear process involves impact.
- Scratch test methodology is favoured for the wear performance of GETs used for the mining of softer materials and tumbler test for harder materials.
- The worn tooth $f$ plot shows significant deeper grooves compared to the laboratory scratched current tooth steel. This was attributed to the loading, particle shape and size and thermal softening effects.
Future work

- Since the hardened surface of the tumbled samples was not controlled, it was difficult to correlate the scratch test results with prior worked conditions. It is required to carry out controlled cold working either by rolling or shot peening and then to conduct scratch tests. The effect of prestrain on the scratch test of the steels may convey deeper knowledge on the combined effect of hardness and toughness on the wear property.

- Multiple scratches at high loads can also be conducted to quantify the effect of scratch ductility on the hardened surface by the previous scratches. This may also be helpful for GETs where grooving wear is dominant.

- The effect of thermal softening is debatable and needs further investigations to examine the depth of penetration in presence of soften zones.

- During Impeller tumble tests the retained austenite in the martensitic microstructure did not undergo martensitic transformation in contrast to bainitic steel. However, more specific experiment is required to confirm its beneficial effect in context of wear resistance. The morphology of the retained austenite needs to be investigated to understand the conditions that causes retained austenite to take part in the wear process.
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