

50 Years of Oilsands Operation: Comprehensive Review of Wear Materials

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ABSTRACT

Wear plays a major role in the mining and extraction operations, and the industry has been continually developing materials to extend reliability of equipment since the Oilsands industry started 50 years ago. With the continuing challenges the Oilsands industry faces to date, it has become more crucial to focus on cutting costs in the open-pit mining operations to recover bitumen. This paper provides a summary of the factors and parameters affecting wear, the various forms of degradation at every stage of the mining and extraction operation, qualification and testing of materials, the key features, benefits, and limitations of the various material technologies. The material groups reviewed include weld overlays, metallic claddings and inserts, non-metallic liners, ceramics, and various cast and wrought alloys used for piping and equipment.

Key words: Wear, Oilsands, CCO, WC, CWI, hardfacing, non-metallic liners, ceramics

INTRODUCTION

The Athabasca oil sands deposits located in northern Alberta Canada are primarily near-surface deposits and are recoverable by open-pit mining. Open-pit mining operations recover oil-soaked sand down to 75 meters from the surface, using large shovels and trucks. The oil sands ores are then transported to the ore preparation plant where the ore is mixed with warm water and other additives to make the oil sands slurry. The oil sands slurry is then transported to the extraction plant to recover the bitumen for further treatment. The reject tailings, with high amount of solids, is separated and pumped to the tailing pond via long pipelines. Due to the abrasive nature of these solids, the open-pit mining equipment, process facilities, and piping experience severe wear, erosion, and erosion-corrosion, and have short service life. The Canadian oil sands industry demands wear materials to better manage the wear problem and relieve the associated high operation, maintenance and inspection cost.

An oil sand is essentially a grain of quartz sand encapsulated by a layer of water, silt, clay, and surrounded by bitumen. Typically, an oil sand has 3-18 % wt bitumen, 50-75 % wt sand, 10-30 % wt clay, and 2-10 % wt water. From the solids, more than 90 % is the mineral quartz (SiO_2), and is the main reason for wear. It is to be noted that wear resistance' is NOT a physical material property, but is a system response of a material. Wear in the Oilsands could be categorized into five main categories:

- (1) Low Stress Abrasion, or scratching abrasion, is the most common and predominant wear degradation mechanism. It is characterized by the absence of abradant fracture. The particles tend to retain their size and shape, while the material thins out by micro-cutting. Generally, higher hardness material will have higher resistance to surface indentation, abrasion, and micro-cutting. Examples include slurry and tailings pipelines, truck beds, hoppers and chutes
- (2) High Stress abrasion, or grinding abrasion, is a more severe form of abrasion in that the abradants fracture into smaller, usually sharp and angular pieces. Higher contact stresses leads to a different form of wear, with a combination of indentation, scratching, or micro-ploughing. Wear resistance is improved by increasing hardness of the base material so it is higher than the abradant hardness. Yield strength and toughness of the base material also needs to be considered. Examples include shovel ground engaging tools (GETs) and crushers.
- (3) Gouging Wear is a more severe form of high stress abrasion leading to macroscopic grooves, gouges, and deformation or deep scratches on the surface. It is due to high stresses driving abradants (e.g. lumps) into a material, plowing out the material by plastic flow. Important base material properties to consider are hardness (resistance of a material from indentation and penetration), toughness (resistance of a material from fracture) and yield strength (resistance to deformation from the large load stresses). Examples are shovel ground engaging tools (GETs), crushers, breakers, chute liners, pump casings
- (4) Impact wear is a result of repeated collisions between two solid bodies. It results in a gross material deformation, cracking, fracturing, fatigue, and/or spalling. Impact strength (toughness), a measure of the resiliency or toughness of a solid, is an important material property. Examples are shovel ground engaging tools (GETs), crushers, breakers, sizing screen, and pump impellers.
- (5) Erosion is a broad term used to describe various wear mechanisms, such as liquid impingement erosion, solid impingement erosion, and cavitation erosion. In the Oilsands context, erosion refers to the progressive loss of material due to the mechanical interaction with an impinging fluid or multi-component fluid (with entrained solid particles, such as Oilsands slurry). Low impingement angles cause micro-cutting while high impingement angles cause micro-fracturing. The important material property for low impact angles is hardness, and for high impact angles is fracture toughness.

- (6) Erosion-Corrosion is different from erosion in that there is a synergistic process involving both erosion and corrosion. Corrosion is the deterioration of a metal due to electrochemical reactions taking place on the surface in an aqueous environment. In erosion-corrosion, there is repeated removal and reformation of the corrosion product layer/scale. In most cases, the damage is more amplified than the sum of these two processes acting independently.

Knowing these wear mechanisms enable operators to identify the dominant mechanisms and the mitigation measures at the various stages in the Oilsands operations.

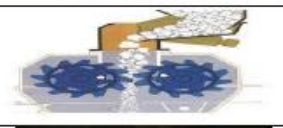
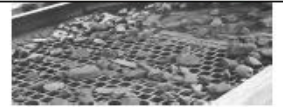
Operation		Material Degradation Mechanisms
Mining		Impact, Gouging, Low and High Stress Abrasion
Hauling/Conveying		Low Stress Abrasion
Crushing		Gouging, Low and High Stress Abrasion, Impact
Breaking		Low and High Stress Abrasion, Gouging, Impact, Erosion-Corrosion
Screening		Impact, Low Stress Abrasion, Erosion-Corrosion
Pumping/Piping		Erosion-Corrosion, Low Stress Abrasion, Aqueous Corrosion
Classifying		Low Stress Abrasion, Erosion-Corrosion, Aqueous Corrosion
Separation		Erosion-Corrosion, Aqueous Corrosion

Figure #1: Degradation Mechanisms at various stages of Oilsands Mining and Extraction Operations

It is to be noted that there are other parameters and factors affecting wear, and some of these are tabulated below.

Table #1: Some parameters and factors affecting wear of materials

Parameter	Factors	Effect on Wear
Abradant Material	Size/density	Larger/ heavier particles generate higher impact forces increasing wear
	Shape	Angular particles are more aggressive increasing wear
	Hardness	Higher hardness ratio with base material (H_a/H_m) leads to higher wear
	Yield strength	Higher strength particles are more abrasive increasing wear
	Fracture properties	Tougher particles have greater abrasivity increasing wear
	Concentration	Increasing abrasant flux/concentration leads to higher wear
Process and Contact Conditions	Force/impact level	Larger forces cause more damage increasing wear
	Velocity	Slurry velocity has a very pronounced influence on erosion rates. Higher speeds increase wear particularly by micro-fracture.
	Impingement angle	Higher impact angle increases wear for brittle materials due to micro-fracture. Lower impact angle increases wear for ductile materials due to micro-cutting.
	Sliding	Promotes wear due to scouring and adhesion
	Rolling	Promotes wear due to fatigue and spalling
	Temperature	Elastomers/polymers soften at high temp. Depending on the specific elastomer/polymer, some have shown increased wear resistance with temperature
	Wet/dry	Wear is usually more severe in wet conditions
	Liquid Media	Lower pH, high chlorides and/or high dissolved oxygen in the liquid increases corrosion rate, and enhances erosion-corrosion rates
Wear (Base) Material	Hardness	Keeping $H_a/H_m < 1.0$ will keep wear rates at low levels
	Yield strength	Stronger material resists higher stresses leading to lower wear
	Elastic modulus	Higher modulus materials absorb more energy elastically lowering wear
	Ductility	Ductile materials can withstand more plastic flow before fracture
	Toughness	Tougher materials have greater impact resistance
	Work-hardening capacity	Keeping $H_a/H_m < 1.0$ will keep wear rates at low levels
	Microstructure	Finer structures are usually tougher
	Corrosion resistance	Will inhibit chemical attack and reduce erosion-corrosion rates

There have been some 'rules of thumb' established in the wear industry for improving wear resistance. Some of these are:

- (i) Keeping the ratio of $H_a/H_m \leq 1.2$ for homogenous metallic materials, where H_a =hardness of abrasive, H_m = hardness of base material for low-stress abrasion, low-impact angle, or scouring erosion applications. Hardness values of some relevant materials are tabulated below:

Table #2: Some Relevant Materials and their Corresponding Hardness Ranges ^[1]

Material	Hardness (Hv)
Alumina (corundum)	1800-2000
Quartz (silica)	750-1200
Ferrite, α -Fe	70-200
Pearlite (plain C)	250-320
Austenite (high Cr)	300-600
Martensite	500-1000
Cementite, Fe_3C	840-1100
Chromium Carbide, $(Fe,Cr)_7C_3$	1200-1600
Iron	70-200
Chromium Carbide, Cr_7C_3	1600
Chromium Carbide, Cr_3C_2	1300
Niobium Carbide	2400-2850
Titanium Carbide	2000-3200
Tungsten Carbide, WC	2000-2400
Vanadium Carbide	2460-3150

- (ii) Engineering a composite for a specific application, such as metal matrix composite (MMC). It takes advantage of hard carbides that arrest abrasion and scouring, combined with a soft matrix that holds carbide intact and provide impact resistance.

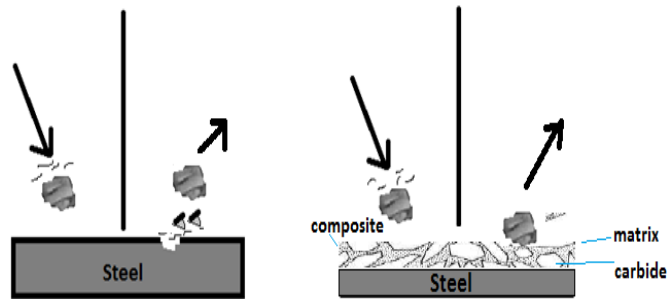


Figure #2: Wear on steel and on a metal matrix composite

- (iii) Selection of non-metallic materials with sufficient resilience, that absorb particle impact forces through elastic deformation (i.e. elastomers). It is to be noted that the material thickness has to be more than the maximum depth of elastic compression to avoid tearing or cutting of the material. The frictional stress has to be low, to avoid tensile tearing. The material has to have good cut and tear-resistance against large, angular particles. The material has to have good compatibility to the process media (i.e. hydrocarbon swelling, cold wall effect due to water diffusion). The bond (adhesion) strength to the equipment or pipe is also important to avoid delamination.

Some commonly used materials in the Oilsands are:

- 1) Carbon steel: a mild steel of specification ASTM A106 Gr B, ASTM A53 Gr B (Type S), ASTM A333 Gr 6, and API 5L grades of steel with yield stress less than or equal to 52 ksi. Depending on the grade, it typically has a hardness less than 200 BHN (212 Hv).
- 2) Chromium Carbide Overlay (CCO): a weld surfacing over carbon steel containing high amount of chromium (20-25% Cr) and high Carbon (3.5-4.5% C) in accordance with EFeCr-A1A classification in AWS A5.21 and ASME SFA 5.13. The wear surface typically has hardness between 510 Hv-900 Hv.
- 3) Hardened steel (e.g. Fedur 40 and 90): composed of two metallic layers bonded by hot rolling. The base layer is a weldable micro-alloyed carbon steel with composition in accordance with ASTM A283 Grade D, and the inner layer is a hardened high Carbon-12% chrome alloy. The wear surface typically has a hardness of 580Hv-615Hv. Another variety is a hardened high carbon alloy and the wear surface has a hardness of 700Hv-860 Hv.
- 4) Specialty Stainless Steels: Solid, dual phase stainless steels made of tempered martensite and ferrite engineered/optimized for erosion corrosion applications. Dual phase is stabilized with Ti/Nb or Mo for weldability and good matrix toughness. Hardness is typically 170-260 BHN (178-280 Hv).
- 5) Abrasion Resistant (AR) cast-irons: the most commonly used group is the high chrome white iron (CWI) in accordance with ASTM A532 Class II or III. The extensive distributions of hard micro-constituents in the alloy result in widespread application for severe low and high stress abrasion, gouging and low to moderate impact situations. Depending on the chemistry, could also offer outstanding resistance to severe sliding abrasion and corrosion. Typical hardness of 1200-1800 Hv (carbides), 400-750 HBN (matrix + carbide).