The Use of Protective Weld Overlays in Oil Sands Mining

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Alberta’s oil sands are the second largest reserve of oil in the world, after Saudi Arabia [1], with an estimated 170 billion barrels recoverable using current technologies [2]. The oil sands are processed primarily by surface mining; a schematic of the open pit process is shown in Figure 1. Oil sand deposits are removed via truck-and-shovel operations and transported to a crusher/conveyor system where the sands are sized. The processed sands are mixed with water and other additives to form slurry, which is piped to the extraction plant for subsequent processing to extract the bitumen. Approximately two tonnes of oil sand ore has to be processed to produce one barrel of synthetic crude. The sands in the ore are mainly composed of quartz sand, silt, clay, water and bitumen [3]. Quartz particles typically comprise of between 80 to 95% of the total solids, and are generally less than 150 µm in size with a semi-angular shape. This scale of processing has produced unique challenges as the hard particles within the oil sands are responsible for severe wear of equipment and components.

In the Fort McMurray, Alberta region, the four commercial oil sands mining and processing operations encounter high maintenance costs and significant production losses due to material degradation through wear and corrosion. These costs include both the replacement of the equipment and the associated labour and lost production. In 2011, the annual operating budget for Syncrude Canada Ltd. was estimated at $1.3 billion [4]. Operating costs across the four commercial mine sites can be estimated at approximately $5 billion. A major portion of this budget is due to wear damage to machinery and equipment [5].

The main wear mechanisms encountered when extracting the oil sands are abrasion, impact and erosive wear. Low stress abrasion is prominent where sands are sliding over a surface with a relatively low contact force (e.g. a hopper wall) [6]. High stress abrasion (and gouging) tends to result in higher levels of material loss as abrasives are driven under high load into the contacting surfaces of equipment (e.g. bucket teeth) [7]. Rocks and boulders present in deposits cause impact-related damage to equipment; the degree of which is somewhat governed by climatic conditions. During winter months the sand and bitumen can consolidate into larger lumps, increasing the level of impact damage [8]. The addition of water in the hydrotransport operations has introduced wear-corrosion issues. The main corrosive species present are chloride-containing compounds in the sands and dissolved oxygen in the water [9]. Increased wear rates of separating screens, slurry pumps and tailings lines have been observed and attributed to the synergistic effects of wear and corrosion producing an amplified rate of material removal [10].
There has been a wide adoption of wear resistant weld overlays in an effort to combat these repair and maintenance issues. By employing weld overlays it is possible to retain the desired properties of the bulk material used to produce a component while vastly improving the protective qualities of surfaces in contact with the wear- and corrosive-media. The two main categories of weld overlays used for wear protection are chromium carbide-based alloys and tungsten carbide metal matrix composites.

The compositions of chromium carbide-based hardfacing alloys are essentially based on high chromium cast irons. Typically, the grades of alloy will contain in the range of 25 to 32 w% chromium and up to 5% of carbon. Their microstructures tend to contain large amounts of M₇C₃ carbides, where M can represent metals such as chromium, iron or manganese (Figure 2) [11]. The carbides are contained within an iron-based austenitic or martensitic matrix, and have the microstructure of acicular, hollow rods. These are aligned parallel to the heat flow direction of the weld deposition, i.e. roughly perpendicular to the surface of the substrate material [12]. The M₇C₃ carbides have a reported hardness of approximately 1700 Hv, whilst the matrix of the alloys tends to be softer (approximately 350 Hv) [13].

Chromium carbide-based overlays (CCOs) are usually applied using arc welding processes [14]. These can be either manual, or for larger components automated processes are used. Compared to other wear-resistant materials (tungsten carbide-based overlays and certain polymer liners), CCOs are relatively inexpensive. As such, they are utilised for larger scale, high volume applications such as wear-plate for truck beds and piping in hydrotransport applications [15]. The overlays are generally deposited in two passes, with the second pass having a larger thickness. This is to compensate for the dilution of the hardfacing alloy with the base material, and allows the second pass to nucleate and grow the large, acicular carbides necessary for wear resistance. The overlays tend to contain transverse cracking resulting from the contraction of the weld pool upon cooling (i.e., often called ‘relief’ or ‘check’ cracking).

CCOs are commonly employed to protect against abrasive wear in wet or dry environments. There is a general consensus that having a high proportion of M₇C₃ carbides in the overlay is beneficial to protect against abrasion. However, there is a lack of available information correlating the effects of carbide size or populations with the performance in specific, abrasive oil sands mining applications. CCOs are generally less suitable for protection from impact wear. If the impact loading is high enough to produce plastic deformation, the brittle nature of the carbide-rich alloy can act in tandem with the pre-existing transverse cracks in the hardfacing, resulting in the spallation of the overlay.

To extend the service life of production-critical components it has been found necessary to use tungsten carbide-based metal matrix composites (MMCs) [16]. These tend to be deposited by plasma transferred arc welding (PTAW); however for specific components or in-field repairs gas metal arc welding (GMAW) techniques are employed.

The MMCs contain distributions of hard tungsten carbide particles suspended in a tough, ductile metal matrix alloy (Figure 3). PTAW is the most common method for depositing
MMC overlays. The PTAW process involves an arc being established between a non-consumable tungsten electrode and the work piece, typically with argon gas shielding and powder feeding through the welding torch (Figure 4). This process can produce relatively thick deposits (between 3 to 6 mm in a single pass), with low dilution rates while maintaining the integrity of the composite materials [17].

Commercial MMCs usually combine tungsten carbide particles with a Ni-based matrix alloy. The carbide particles can be either angular or spherical, with the angular particles being sub-divided between monocristalline tungsten carbide (WC) and eutectic (WC/W_2C) (Figure 5). The heat produced by the PTAW deposition can promote the dissolution of the tungsten carbide particles into the metal matrix. This dissolution effect can embrittle and reduce the overall corrosion and wear resistance performance of the MMC. WC is more chemically stable than W_2C and less prone to this effect [18]. WC-bearing MMCs are more widely used in the oil sands industry as they allow for a wider window of production welding parameters and improved material consistency compared to WC/W_2C particles, since spherical carbides generally have a eutectic WC/W_2C composition, making them more prone to dissolution. However, due to the fine lamellar structure of WC/W_2C, these tend to be harder than WC carbides, with measured hardness in excess of 2,200 Hv (while WC has a range of hardness from approximately 1,100 to 2,100 Hv [19]).

Commercial MMC overlay powders tend to contain a blend of between 60 to 65 w% tungsten carbide combined with a Ni-based matrix alloy. The Ni-alloys are based on NiBSi or NiCrBSi, and contain typically 2 to 5w% B and Si to suppress the melting point of the alloy to around 1050ºC, and act as self-fluxing agents. The matrix microstructure typically consists of primary nickel dendrites, with interdendritic eutectics composed of Ni+Ni_3B or Ni+Ni_3Si. These boride and silicide phases are harder than the Ni phase, however the hardness of the tungsten carbide is far superior [20].

The addition of up to 15wt% Cr to the alloy can augment the hard precipitate phases in the matrix due to the formation of Cr-borides and Cr-carbides, however this may not necessarily improve the wear or corrosion resistance of the MMC overlay. The issue is that the presence of Cr will accelerate the dissolution of tungsten carbide particles [21]. This not only reduces the volume fraction of primary tungsten carbide, but may also promote other secondary carbides to precipitate in the matrix during cooling. These secondary carbides are often very fine in size/shape, and may be too brittle to provide significant improvements in wear resistance.

The PTAW process is generally limited to shop production environments, and is impractical for most field welding applications since the gravity fed powder requires deposition in the flat position. In-field repair welding tends to be conducted using techniques such as GMAW using tungsten carbide-based wire consumables. However, due to the increased WC dissolution caused by the high droplet temperatures during deposition and limitations in the composition of the consumables, the performance of overlays deposited by GMAW are currently significantly lower than those deposited by PTAW [22].
The extreme wear-conditions in oil sands processing has led to a wide adoption of tungsten carbide-MMC overlays deposited by PTAW, especially for production-critical components. To be economically feasible, PTAW overlays should at least double the service life of a component. Field experience of overlays used to protect equipment such as bucket teeth, hydrotransport screens and crushers report improved service lives of up to 600%, with the associated economic savings [23].

Research and development is on-going in an effort to build on the performance exhibited by current, commercial composite weld overlays. Key areas of work include the design of MMCs with improved corrosion resistance and the tailoring of overlay compositions to combat specific types of wear. Research is also being conducted on developing processes (such as advanced complex-waveform modes of GMAW and GTAW welding) for the effective deposition of MMC materials for the demanding wear and corrosions application encountered in Oil Sands operations.

References


Figure 1: Schematic diagram of the open pit process used for oil sands mining.

Figure 2: Micrograph of a chromium carbide-based overlay, etched, showing the acicular carbides in an iron-based matrix. Magnification x50.
Figure 3: Micrograph of a tungsten carbide-based MMC overlay, showing the tungsten carbide particles distributed in a nickel-based matrix alloy. Magnification x50.

Figure 4: Photograph showing PTA welding apparatus
Figure 5: SEM Micrograph of a typical angular tungsten carbide powder. Magnification x100.