

APPLICATION OF FeNbC AS A HARDFACING MATERIAL USING LASER CLADDING

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Abstract

The sugar-cane and mining sectors experience substantial losses due to shut-downs and repair or replacement of worn out or obsolete components. Surface engineering studies have been widely developed aiming at optimizing the coating processes and, mainly, increasing the portfolio of higher wear resistant materials. HRC Metalização® (a joint venture between Höganäs and Oxipira), in partnership with CBMM, has been working on the development of niobium carbide (NbC) in iron matrix (FeNbC) hardfacing coatings, applied by laser cladding on wear components for mining. Field trials were conducted on the coated teeth of a Volvo wheel loader operating at CBMM's mine in Araxá, Brazil. The metallographic analysis of the coated teeth showed an excellent adhesion of the FeNbC coating layer, as well as a homogeneous dispersion of the hard NbCs. The loader's coated teeth achieved an increase of approximately 64% in service life above best performance, and 80% above the average service life of the regular uncoated, low alloy carbon steel teeth, demonstrating the significant potential of FeNbC as a hardfacing coating applied by laser cladding.

Introduction

Wear in industrial components and equipment for agriculture and mining activities is a key factor in capital depreciation and expenses related to maintenance, and to restoring and replacement of parts. It is often necessary to oversize components to avoid production stoppage due to the wear of those particular parts that directly influence production losses. Thus, the development of new wear resistant materials for coatings would be a way to increase productivity in the industry, particularly in Brazil's mining sector, which has expanded significantly in recent years. Therefore, the challenge is to develop new materials and processes that provide outstanding wear resistance and high toughness for use as a technological coating solution [1].

The laser cladding process is a deposition welding technique applied for the addition of a material or a mixture of materials on to the surface of a substrate, under controlled conditions. In this process, a stream of a coating powder is fed into a laser beam that is focused and scanned throughout the target area, leaving behind a fully fused layer of the desired material. Laser cladding can be used for many purposes, including the application of wear resistant or corrosion-resistant coatings, the restoring of worn out components and deposition welding of shaped parts.

Conventional deposition methods, such as plasma transferred arc welding, flame spray and high velocity oxy-fuel spraying are also used for situations where materials with high wear resistance are desired [2]. The intrinsic characteristics of the application method generally determine the coating quality, and these conventional methods usually result in low compliance, a high degree of porosity, high dilution and severe distortion of the material [3]. Materials clad by laser are attractive and advantageous since this method enables an extremely localized treatment area, overcoming problems described for conventional coating processes [3]. The low power input required by the laser coating technology results in less extensive heat-affected zones, low distortion and a minimum degree of substrate dilution. Additionally, high heating rates combined with fast cooling of localized areas promote the formation of fine-grained microstructures [3].

The mining and ore moving operations of pyrochlore at CBMM's open pit mine in Araxá, Brazil, are carried out by means of bulldozers, graders, excavators, wheel loaders and trucks. The weathered ore is soft enough that it does not require any blasting and there are no water inflows. One of the main causes for stoppages of the mining and ore moving equipment is downtime for replacing their ground engaging tools (GETs), such as bulldozer cutting edges, side cutters, grader blades, excavator and loader buckets, teeth or tip adaptors and bucket teeth or tips. Choosing the right GET material and design can result in reduced labor costs and reduced downtime required for change outs.

Regular laser cladding of materials comprises nickel- and cobalt-based alloys, carbide and hard metal blends for wear applications and carbide matrix materials for customized blends. The carbide based blends provide high toughness protection for components that are exposed to severe wear conditions. Tungsten carbide (WC) plus titanium composite coatings are normally used to protect drilling and mining components.

NbC possesses similar hardness to that of WC, but only half its density, and it has a higher melting point and higher oxidation resistance. Thus, it exhibits many outstanding properties that can make it an attractive option for most of the already consolidated industrial applications. NbC also presents lower solubility in iron than WC and has a similar density to materials like cast iron and steel, opening the possibility of using NbC as a raw material for hard metals, as well as of developing new wear resistant materials for castings and hard facing coatings with high levels of hard primary NbC homogeneously distributed in the microstructure [4].

Based on these scenarios, HRC Metalização® (a joint venture between Höganäs and Oxipira), in partnership with Companhia Brasileira de Metalurgia e Mineração (CBMM), conducted several field trials on the application of FeNbC as a new hardfacing material applied by laser cladding on wear parts for mining, earth moving and agricultural equipment. The present work reports the results of the characterization and performance in field trials of the FeNbC applied as a hardfacing coating by laser cladding on the bucket teeth of an ore wheel loader operating regularly at CBMM's mine in Araxá, Brazil.

Wear in Mining and Minerals Processing

In view of the extremely abrasive characteristics of the ore and overburden handled in mining, it is expected that abrasive wear represents an important percentage of the maintenance costs of mining operations. Therefore, increases in service life generally result in net cost reductions and as a consequence, economic earnings. The correct materials selection of abrasive resistant consumables may result in substantial increases in service life [5]. Wear resistant materials include metals like high alloyed steels and cast irons, ceramics, polymers and composites. Metallic components can be classified in four groups: castings, forgings, rolled plates and hardfacing or fusion-clad plates [5].

The wear behavior of materials used in mining and minerals processing depends on a number of factors that fall into three main groups: (1) the properties of the wear resistant material, (2) the characteristics of the abrasive material and (3) the nature and severity of the interaction between the abrasive and the wear resistant materials [6].

Depending on the nature of the interaction between the abrasive particle and the wear resistant material, abrasive wear can be classified in the following categories [5,6]:

- Low-stress abrasion: the abrasive particle remains intact as it moves freely across the wear surface, as occurs in chutes, excavation and general handling of loose granular minerals;
- High-stress abrasion: the abrasive particle is crushed during the wear interaction, occurring in crushing and grinding, as well as in hard rock excavation;
- Gouging abrasion: the removal of a large volume of material per event from the wear surface occurs as the result of deep individual wear grooves, as in primary crushers and impacts from very large rocks;
- Solid particle erosion: abrasive particles move in a fluid medium, as occurs in pumps, slurry pipelines and hydrocyclones;
- Impact abrasion: particles are coarse and the impact velocities of the particle are greater than 10 m/s, as in high-speed hammer mills and impact crushers.

In general, three conditions are required for abrasion to occur: an abrasive particle harder than the wear part, a contact force to press the abrasive particle into the wear part surface, and a sliding velocity sufficient to cut a groove in the surface of the wear part.

Function and design also influence the wear of earthmoving, mining and mineral processing components. In earthmoving operations, the abrasive wear from scraping operations is less severe than operations requiring earth penetration and removal, as in the wear of digger teeth on bucket excavators. Wear rates in crushing and grinding equipment are much higher than wear seen in chute linings, screens and classifiers. In fact, crushing and grinding operations account for about 95% of the material wear in general ore processing [6].

According to Gates [5] and the abrasive wear model of Rabinovicz [7] for single phase materials, hardness is a primary property for wear resistant parts. Abrasive particles will only penetrate the wear part surface if they are harder than the wear part material. If wear material can be found that is greater than 2/3 the hardness of the abrasive material, wear rates can be reduced substantially, staying in the mild wear regime. For instance, very hard quartzitic rocks can have hardness greater than 900 HV, so wear part materials with hardness higher than 600 HV would be necessary to reduce wear rates to acceptable values. Most commercial martensitic wear resistant steels exhibit hardness levels between 540 HV and 700 HV. Alternative materials reinforced by hard particles can be used, including NiHard and high-chromium white cast iron and hardfacing alloys with high contents of chromium carbide particles with an approximate hardness of 1400 HV. Although the bulk hardness of the composite may not be greater than 600 HV, the hard reinforcing particles can be very helpful in the prevention of abrasion from most minerals. Also, other hardfacing alloys, with tungsten and titanium carbides as reinforcing particles, are available for wear applications. Particle-reinforced materials or composites can be effective in increasing the service life of wear parts when working in low-stress abrasion conditions [5].

Castings are very appropriate for thick walled wear parts, but the volume fraction of reinforcing particles is limited to a maximum of approximately 35%. The mismatch in density between common hard phases and alloys, as well as their solubility in these alloys, limit cast metal matrix composites. Higher hard phase contents decrease toughness and can lead to breakage in service or during assembly. Higher percentages of hard particles are possible in hardfacing and clad coatings that are deposited on tough steel substrates for structural support [5]. For this reason, an area of recent and continuous development is the field of fusion-clad products applying modern weld-deposition and thermal spray technologies, including the laser cladding deposition process.

FeNbC Laser Cladding Process for the Wheel Loader Bucket Teeth

FeNbC was developed by CBMM for applications where very high NbC contents are sought. This material constitutes a source of hard primary NbCs and it can be applied as an alloying addition for castings and hardfacing products for surface protection of wear parts, such as crusher hammers and rolls, conveyor screws, chute liners and GETs. As shown in Figure 1, FeNbC is a natural composite that contains hard NbC, homogeneously distributed in an iron based matrix with residual elements, such as aluminum, silicon, titanium and manganese. The main phases are NbC, Fe₃Al and Fe₃AlC. The microhardness of the intermetallic Fe₃Al ranged from 360 to 470 HV 0.05 and of Fe₃AlC from 630 to 670 HV 0.05, which indicates that the metallic matrix itself is a very tough and wear resistant material [4]. These characteristics raised the possibility of applying FeNbC as a hardfacing material, even without using any other coating additives.

FeNbC is produced in a wide range of NbC contents (typically between 40 wt.% and 80 wt.%NbC) and granule sizes between 0 and 50 mm, Figure 2.

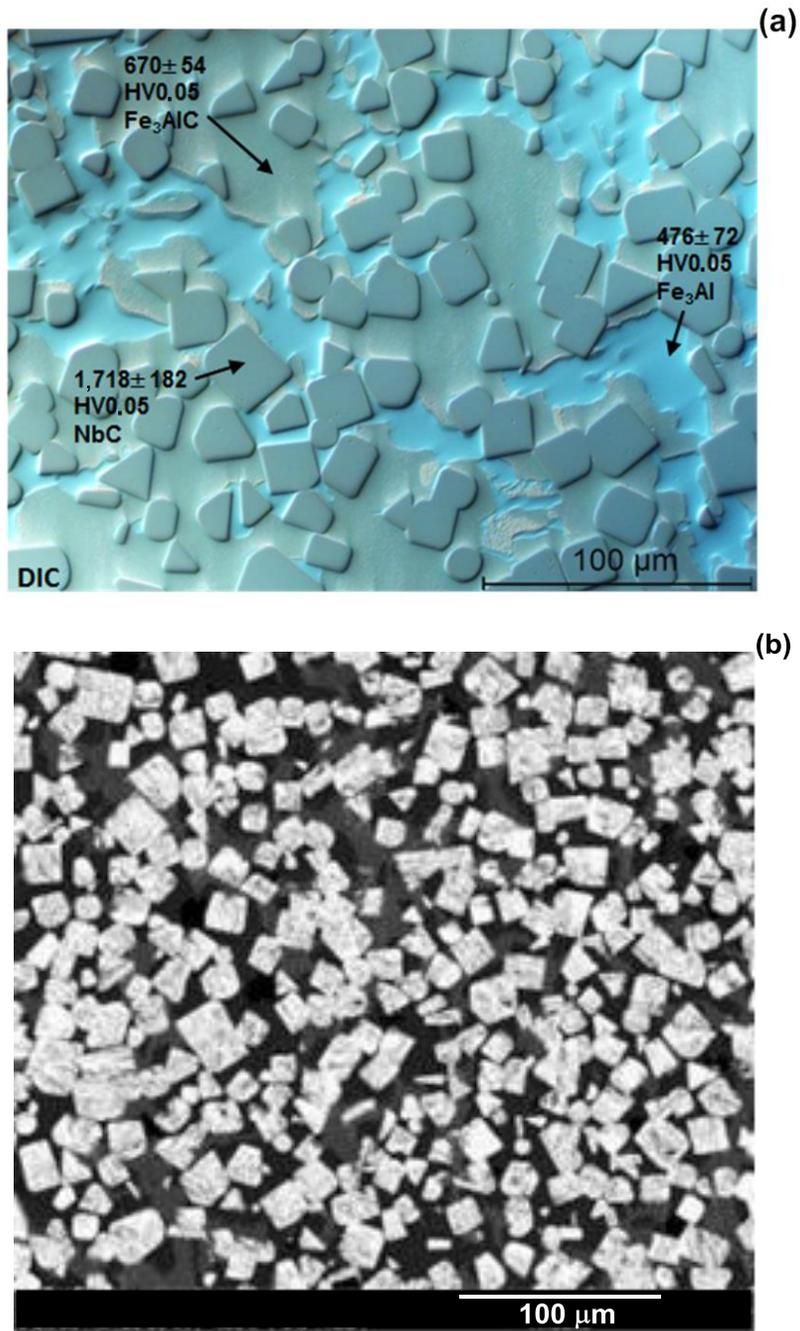


Figure 1. Typical microstructure of FeNbC observed using optical microscopy with differential interference contrast (DIC) (a) and mapping of niobium by SEM/EDS (b).

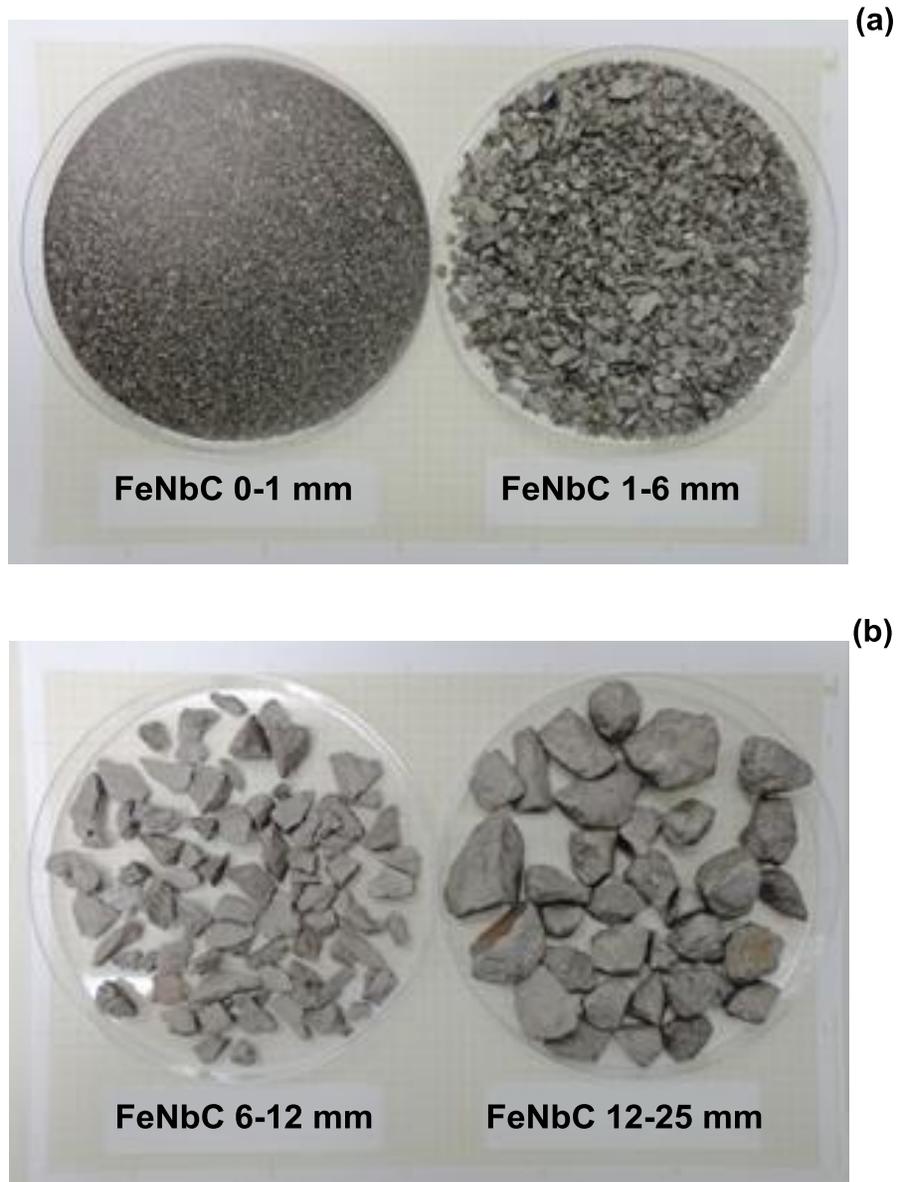


Figure 2. Appearance of different granules of FeNbC: <1 mm and 1-6 mm (a) and 6-12 mm and 12-25 mm (b).

The FeNbC powders used in the laser cladding trials of the loader bucket teeth were prepared from the <1 mm fraction. The chemical analysis of the FeNbC powder was approximately 35 wt.%Nb, 5 wt.%C, 7 wt.%Al and 2.5 wt.%Ti.

In order to evaluate the performance of the FeNbC powder as a hardfacing material for bucket teeth, a Volvo ore wheel loader was chosen for field trials, Figure 3.



Figure 3. Views of the Volvo wheel loader (a) and bucket teeth (b) at CBMM's mine.

The pyrochlore wheel loader bucket operates regularly with eight teeth or tips of low alloy carbon steel weighing approximately 11 kg each. The average service life of these conventional bucket teeth is 1,220 hours with best performance reaching approximately 1,340 hours.

In order to increase the lifetime and performance of the conventional low alloy carbon steel tips by using FeNbC as a hardfacing material, some teeth were coated at HRC Metalização® via High Power Direct Diode Laser technology in a Coherent High Light 8000D system, Figure 4.



(a)



(b)

Figure 4. Coherent High Light 8000D laser system (a) and FeNbC laser cladding (b).

Figure 5 shows the low alloy carbon steel tips before and after coating with FeNbC by laser cladding. As can be observed, the tips used in the field trials were coated with FeNbC on the top, left and right faces but not the bottom. The total weight of the deposited FeNbC was about 200 grams per steel tip. The FeNbC was deposited in layers along the ore flow except on the front face where the deposit was transversal to the ore flow. Some of the tips showed small filling defects and cracks on the fused layers. As usual in similar hardfacing processes some of the tips showed small filling defects and cracks on the fused layers which, however, did not affect their good performance in service.

(a)



(b)



(c)

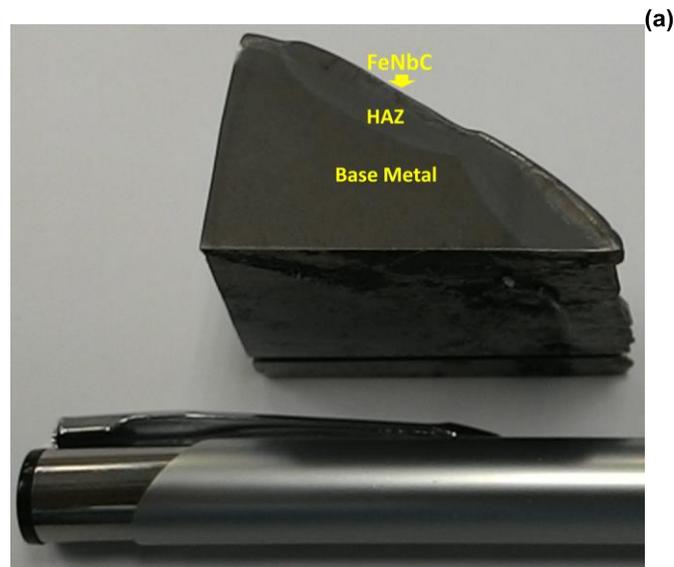




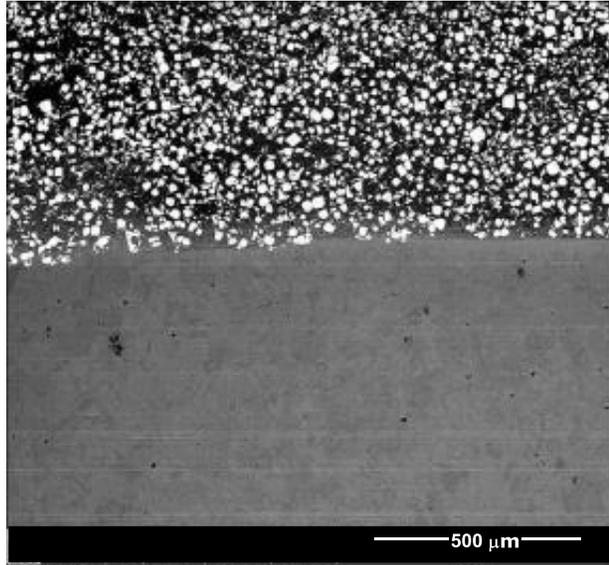
Figure 5. Volvo wheel loader steel teeth before (a) and after (b), (c) and (d) coating with FeNbC.

Figure 6 shows the macro and microstructural aspects of the interface between the carbon steel tip and the FeNbC coating deposited by laser cladding as revealed by SEM/EDS. There are three main regions: the base metal (low alloy carbon steel), the heat affected zone (HAZ) and the FeNbC hardfacing layer.

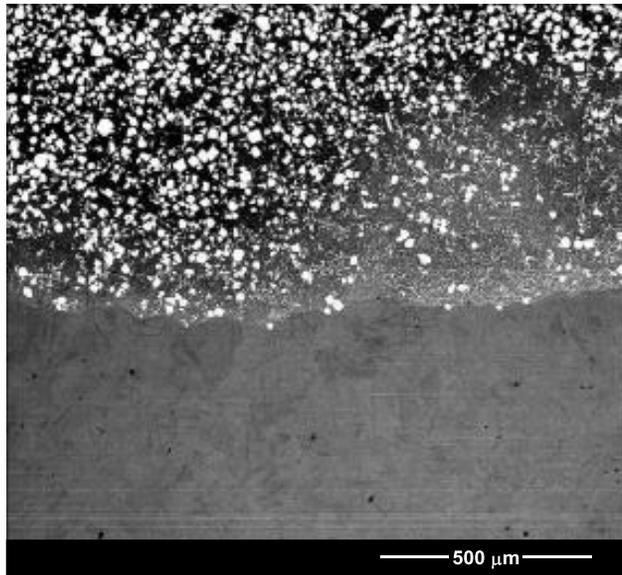
The FeNbC coating layer presented quite good adhesion to the base metal or substrate. It is possible to note that most of the deposited coating layer showed a similar appearance and presented the same phases found in the original particles of the FeNbC, Figure 1. Additionally, it can be seen that some NbC particles in the hardfacing layer suffered partial dissolution in the metal base areas closest to the interface, enhancing the bonding effect. Some small cracks and oxide inclusions were also observed in regions of the coating layer. As mentioned above, such features are usual in similar hardfacing processes and did not affect their good performance in service.



(b)



(c)



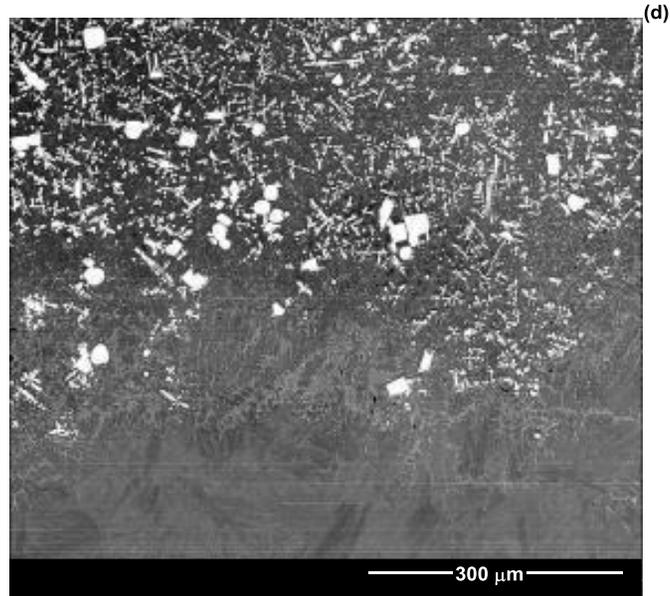


Figure 6. Macro (a) and microstructural (b), (c) and (d) images of the interface between the carbon steel tip and the FeNbC layer deposited by laser cladding.

Field Trials of the Loader Bucket Teeth

Aiming to evaluate the performance of the low alloy carbon steel teeth coated with FeNbC in relation to the same uncoated wear parts, both types of tips were assembled alternately on the same loader bucket, as shown in Figure 7. From the eight teeth coated with FeNbC, Figure 5(b), the tips numbered 5, 6, 7 and 8 were chosen for the first field trial and mounted initially in the positions i, iii, vi and viii (left to right as viewed in the figure), while the uncoated teeth occupied the positions ii, iv, v and vii.

The field trials were conducted from March to September, during the dry season of the year (2014). The Volvo wheel loader was used mainly for excavation and subsequent loading and filling of the ore transport trucks. It was also employed for building mine road berms, and cleaning and gross leveling of the pit benches. The equipment was operated approximately 21 hours per day during three shifts.



Figure 7. Assembling of the loader bucket teeth; (a) the four low alloy carbon steel tips coated with FeNbC are indicated with white arrows, (b) start of the field trials at CBMM's mine.

During the field trial of the coated and uncoated teeth, seven inspection stops were made to weigh and measure the tips. All worn coated and uncoated teeth and their respective adaptors were taken out and replaced after a total of 2,200 work hours. The criterion for replacing all the worn teeth, and consequently, for ending the trial was a minimum thickness of 3 mm of the heel of the bottom of the tip to ensure that it did not slip out of the locking mechanism. It is worth noting that in this trial none of the bottom surfaces of the tips were coated with FeNbC.

The total of 2,200 work hours before change outs represented an increase in the service life of the bucket teeth of approximately 64% above their best previous performance of 1,340 hours, and about 80% over the average service life, for uncoated tips, of 1,220 hours.

The field trial results related to the weight loss of the coated and uncoated tips registered during the inspections are shown in Figure 8.

The results of the final inspection after 2,200 working hours are presented in Table I. The uncoated tips in the middle positions iv and v were not disassembled for the inspections because they were welded to the tip adaptor.

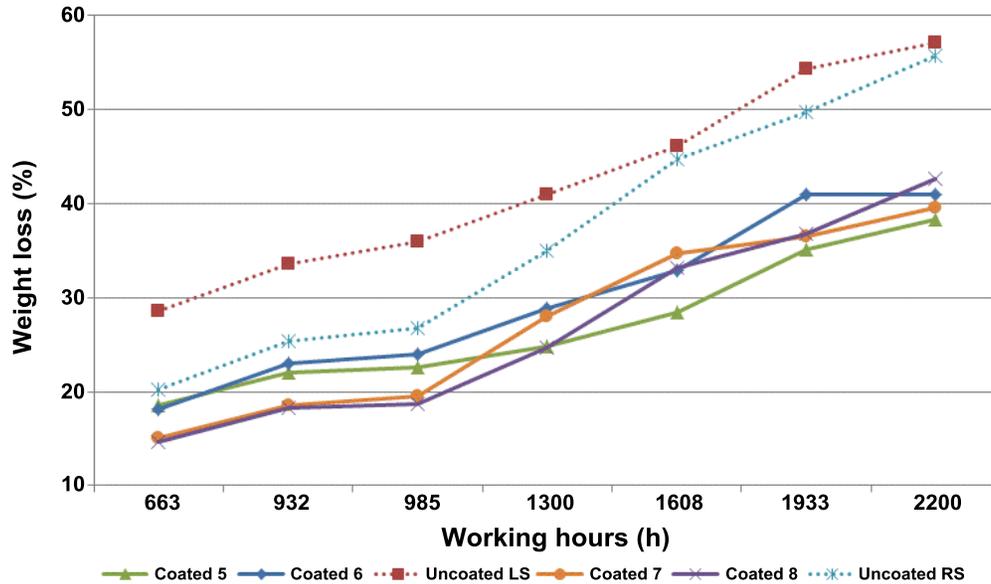


Figure 8. Weight loss of the coated and uncoated teeth during the field trial.

The weight loss of the uncoated tips was always higher than that of the coated parts at the seven inspections. After 2,200 working hours the weight loss of the uncoated teeth varied from approximately 56% to 57%, while the weight loss of the FeNbC coated teeth varied only from approximately 38% to 43%. The weight loss of the coated tips was 21% to 31% lower than the weight loss of the uncoated tips after 2,200 working hours.

Table I. Final Inspection Results of the Field Trial After 2,200 Working Hours.

Tooth Number (Fig.5a)	Position	Original Weight (kg)	Type (FeNbC)	Coating (FeNbC) (kg)	Initial Service Weight (kg)	Final Weight (kg)	Weight Loss (kg)	Weight Loss (Absolute) (%)	Weight Loss (Relative*) (%)
5	i	10.88	Coated	0.22	11.10	6.85	4.25	38.3	-31.4
-	ii	10.85	Uncoated	0	10.85	4.65	6.20	57.1	0
6	iii	10.90	Coated	0.27	11.17	6.60	4.57	40.9	-26.2
-	iv	10.85	Uncoated	-	-	-	-	-	-
-	v	10.85	Uncoated	-	-	-	-	-	-
7	vi	11.05	Coated	0.13	11.18	6.75	4.43	39.6	-26.7
-	vii	10.85	Uncoated	0	10.85	4.80	6.05	55.8	0
8	viii	10.87	Coated	0.21	11.08	6.35	4.73	42.7	-21.0

*Relative to the adjacent uncoated tooth, ii or vii

As illustrated in Figure 9, the weight loss of the coated teeth was higher on the bottom surface since none of them was coated with FeNbC. The uncoated teeth also suffered heavy wear in their upper and side regions. The reduction in the length of the coated teeth was from 16% to 18% lower than the length reduction of the uncoated tips after 2,200 working hours.

(a)



(b)



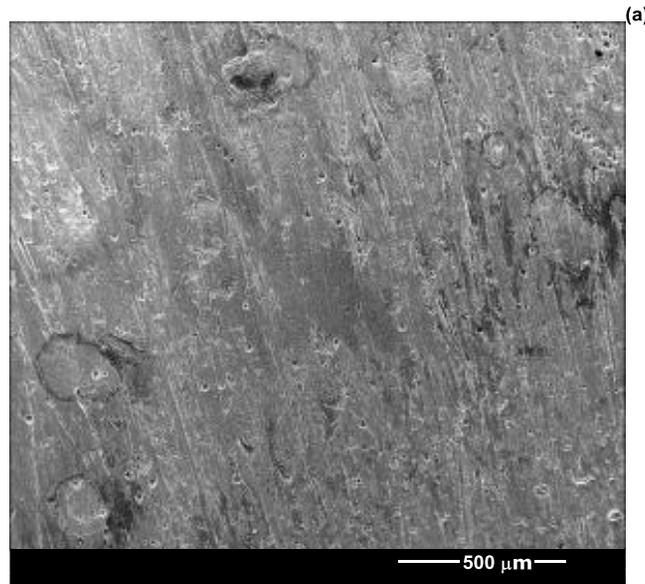
(c)

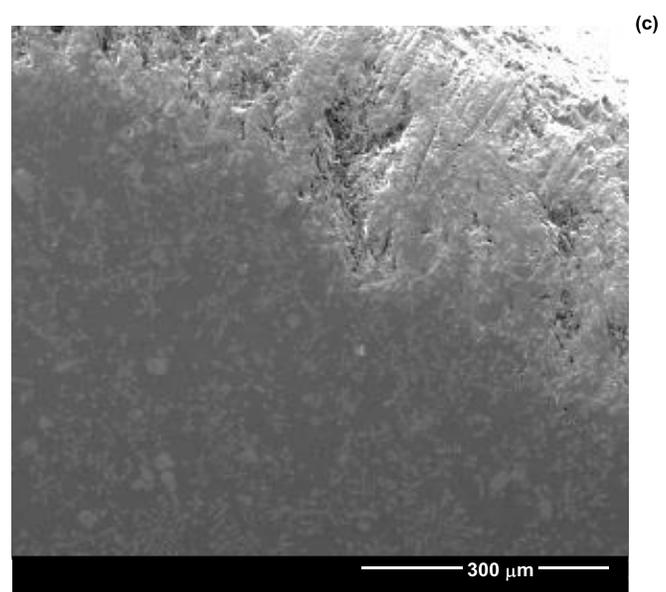
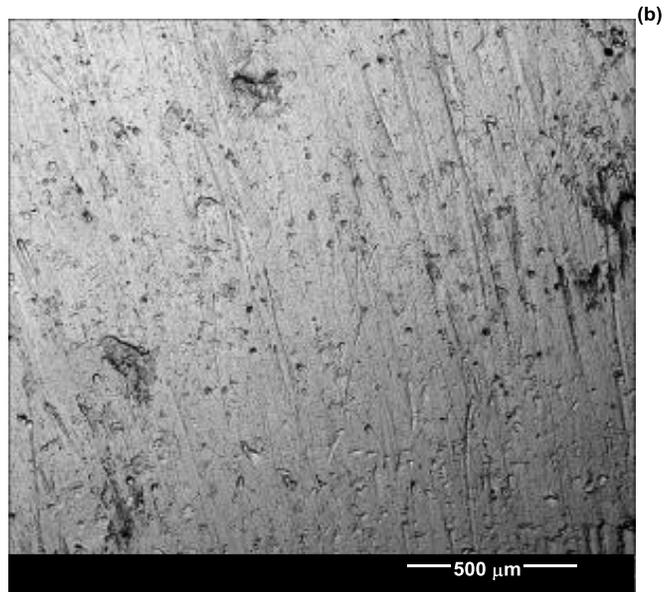


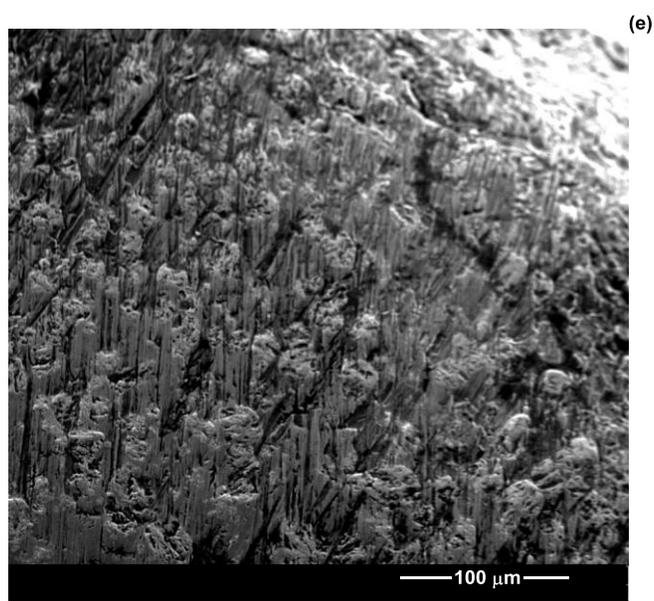
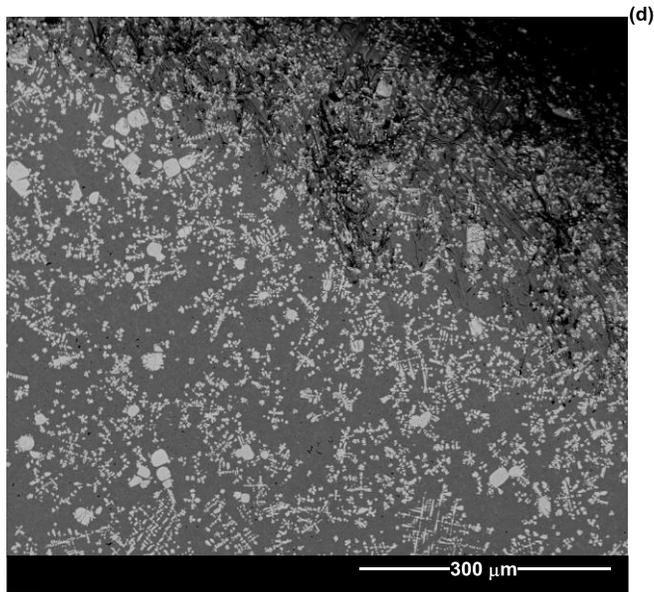


Figure 9. Wear patterns of the coated and uncoated teeth after the field trial. Top (a), (b), bottom (c), (d) and side (e), (f) views.

Figure 10 depicts microstructural aspects by SEM with secondary electron and backscattered electron images of the worn surfaces of both the uncoated (a) and (b) and coated teeth (c) to (f). The low alloy carbon uncoated steel teeth exhibited several scratches and micro-grooves throughout the worn surface (a) and (b) while the FeNbC coated tips showed similar scratches and micro-grooves only across the iron aluminide (Fe_3Al) matrix, with the remaining NbC particles well preserved (c) to (f). This wear morphology is analogous to that observed in Figure 11 after dry sliding tests of $\text{Fe}_3\text{Al-NbC}$ carried out under controlled conditions (counter body: 99.7% alumina; $s = 5,000$ m (or 50,000 cycles), and initial maximum contact stress $P_{0\text{max}} \sim 660$ MPa). The wear tracks indicate that the interface NbC-matrix withstood shear and NbC remained almost unbroken while the iron aluminide experienced severe wear [8]. This is explained by the formation of a metallurgical interface between the Fe_3Al matrix and the NbC [9], because carbon is soluble in Fe_3Al forming the harder phase Fe_3AlC , Figure 1(a). Dissolution of some carbon from the NbC into Fe_3Al is unproblematic for the stability of NbC, as NbC can exhibit a range of carbon content of NbC_x ($0.75 \leq x \leq 1.0$).







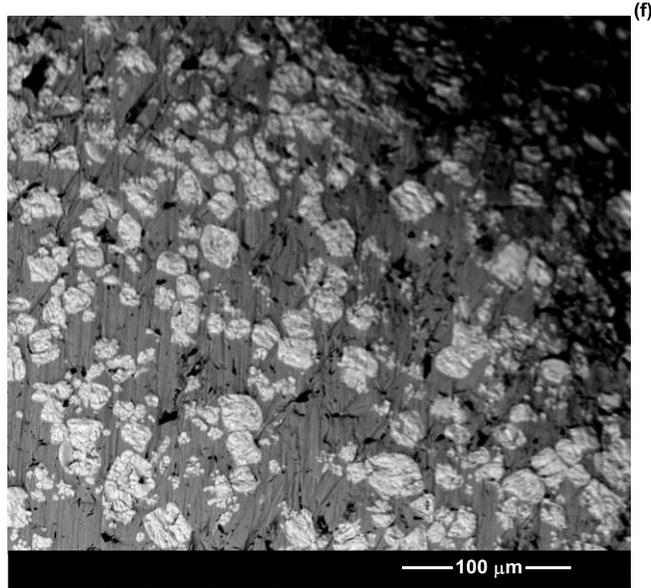
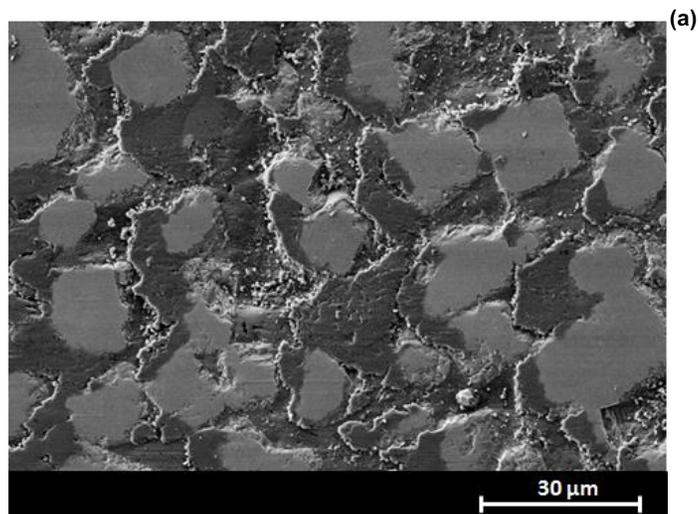


Figure 10. Morphologies of wear of the uncoated (a), (b) and coated (c) to (f) teeth after the field trial.

The worn surface in Figure 10 indicates that the wear of the FeNbC coated surface occurred mainly by the abrasion of the ductile iron aluminide matrix promoting later the fallout of free exposed reinforcing NbC particles. The metal loss was minimized in the FeNbC coated tips by the presence of a high volume of hard reinforcing NbC. Figure 10 also indicates no fragmentation of the NbC grains under rough mining operations. In consequence, it was shown under practical conditions, that NbC is well suited for wear protection.



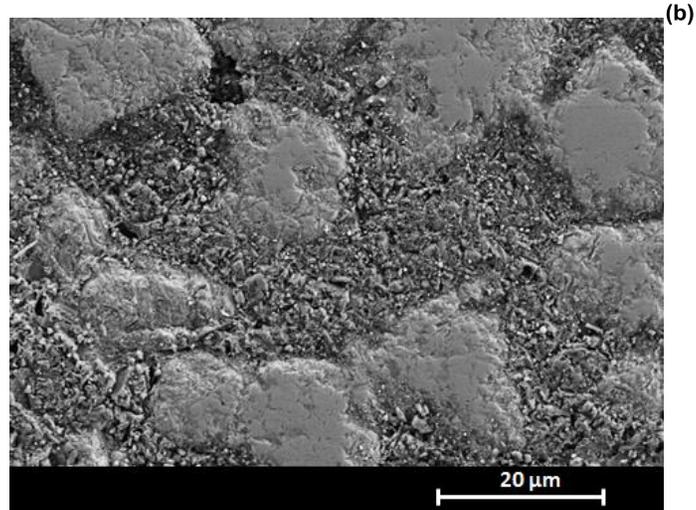


Figure 11. Morphology of the wear tracks at 22 °C after dry sliding tests of Fe₃Al-NbC (counter body: 99.7% alumina; s = 5,000 m (or 50,000 cycles), P_{0max} = ~660 MPa); (a) v = 1 m/s and (b) v = 7 m/s. [8]

In order to improve the performance of the FeNbC as a hardfacing material applied by laser cladding for coated loader teeth, additional trials are in progress under similar conditions, but with tips covered on all surfaces, including the bottom, as shown in Figure 12.





Figure 12. Volvo wheel loader steel tips coated with FeNbC; (a), (b) partial and (c), (d) total.

Conclusions

The application of FeNbC, a metal matrix composite, as a hardfacing material for ground engaging tools was investigated. The coating of conventional low alloy carbon steel bucket loader teeth with FeNbC deposited by laser cladding was characterized and their performance in field trials was evaluated. The following conclusions were drawn:

1. The FeNbC hardfacing layer deposited by laser cladding presented good adhesion to the low alloy carbon steel bucket teeth, and as a result it did not spall off under rough operation. The coating layer, on completion of the field test, showed the same morphology and phases found in the original deposited FeNbC particles.
2. The FeNbC coated bucket teeth worked for about 2,200 hours, representing an increase in the service life of 64% above best performance, and about 80% higher than the average service life of conventional carbon steel teeth.
3. The weight loss of the coated tips was between 21% to 31% lower than the weight loss of the uncoated tips after 2,200 work hours.
4. The reduction in the length of the coated teeth was between 16% to 18% lower than the length reduction of the uncoated tips after 2,200 work hours.
5. The wear of the loader bucket teeth occurred predominantly by abrasion, which caused metal loss due to surface micro-grooving. The metal loss was minimized by the presence of a high volume of hard reinforcing NbC. The wear of the coated surface occurred mainly by the erosion of the iron aluminide matrix, promoting the fallout of exposed reinforcing NbC particles. This indicates that FeNbC is well suited for wear protection as no fragmentations of the NbC particles were seen under severe mining operations.

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