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Assessment of Materials for Gouging Abrasion Applications

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Abstract

Various materials are used to resist wear in crushing and sizing equipment in mining and mineral processing. They include steels, white irons and hardfacing deposits. Within each of these classes there are a number of options available.

Jaw crusher testing using a modified ASTM G81 procedure, has been carried out to assess the resistance of some of these materials to gouging abrasion. The method involves a comparison of the wear losses that occur for reference and selected test plates when a controlled amount of standard feed rock is comminuted in a laboratory jaw crusher.

Materials evaluated are Q&T abrasion resistant (AR) plate steels, cast austenitic manganese steel, chromium and chromium molybdenum white irons as plain castings and in laminated forms, and also chromium carbide and tungsten carbide overlaid wear plates and hardfacing.

In addition to obtaining a performance ranking for material selection purposes, the microstructural, compositional and hardness influences on gouging abrasion attack have been investigated.

1. INTRODUCTION

Crushing and grinding in mineral processing involve some of the most severe contact interactions and arduous wear conditions in industrial service. In hard rock operations it has been a traditional high maintenance problem and a variety of ferrous-based materials are used mainly, to resist the combination of impact, indentation and gouging and also high and low stress sliding abrasion that occurs in different locations with the diverse equipment that are employed.

The oil sands industry in Northern Alberta is a relatively new but rapidly growing mining and mineral processing sector with enormous strategic and commercial value to Canada. Latterly the traditional dry mining schemes used in the first decades of commercial operation, have been replaced by hydraulic ore transportation. This has brought about an increased need for effective and reliable crusher, breaker, sizer (Figure 1) and classifying systems to comminute, screen and handle large rocks and oil sands lumps prior to slurrying and pipelining the ore to bitumen extraction and separation processes. This is particularly demanding when the oil sand is in a frozen state during winter mining when temperatures can fall to below -40°C.

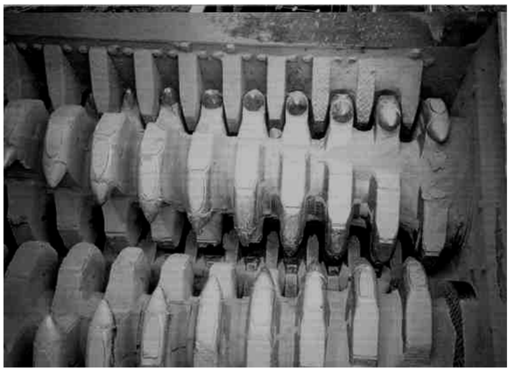

Figure 1. Sizer for crushing rock and frozen oil sands lumps

This situation has presented another wear materials challenge to an industry that has perpetually faced very severe abrasion and erosion problems caused mainly by fine quartz grains that constitute the bulk of oil sands deposits. Gouging abrasion involving larger solids and high indentation and impact forces, has made a much lower contribution to overall wear in previous dry mining schemes than low and high stress abrasion and rolling contact abrasion modes (Llewellyn, 1997). Unlike these mechanisms, laboratory testing under gouging abrasion conditions has not been carried out previously to evaluate and compare material options specifically for oil sands service.

A procedure based on the ASTM G81 specification has been used in the present work. It is a method for determining gouging abrasion resistance using a jaw crusher. It and variants have been employed mainly to assess materials for crushing and grinding service (Tylczak *et al*., 1999; Hawk *et al*., 1999; Marks *et al*., 1976, and Borik, 1972).

It has been claimed that it closely models field abrasion conditions on crushers, shovel and excavator teeth and scoop lips thus it has direct relevance to the oil sands industry which employs double roll crushers and sizers with arrays of breaker tips (Figure 1). However, the evaluation also has relevance to materials for rotary breakers, tractor undercarriage parts, shovel bucket lips, truck boxes, open gears and chains.

A range of materials has been evaluated in the past. These have included structural steels, white irons, manganese steels and chrome carbide (CrC) overlay materials (Tabrett *et al*., 1996; Bednarz, 1999; Hawk *et al*., 1999; Tylczak *et al*., 1999).

The materials selected for this program covered a range of well-established and more recently developed products. This included abrasion resistant, quenched and tempered rolled steel plates to nominally 600 HB hardness, austenitic manganese steel and hypereutectic and CrMo white iron castings and laminates, CrC overlays and plasma transferred arc welded (PTAW) tungsten carbide (WC)-based hardfacing deposits. With the exception of Mn steel, which is a traditional choice for some crusher components in hard rock mining, all material types are being used in various gouging abrasion and other high wear situations in oil sand operations. The successful use of WC hardfacing particularly as PTAW deposits, on a variety of oil sands wear components has grown very significantly over the last ten years but there have been no comparative properties data available for this specific wear condition.

2. MATERIALS

The test and reference plates used for this work were nominally 19 mm or 25.4 mm in thickness. Details of the materials tested are given in Tables 1 & 2.

The plates were cut to provide 76.2 mm wide, 229 mm long sections with ends tapered to fit into specially designed holders. In addition, test surfaces were ground to a flat, consistent finish to remove any decarburized layers in steels and any surface zones in tungsten carbide overlays that could have suffered sinking of dense carbide particles in the weld pool during deposition. Hardness tests were carried out on all ground test surfaces and are also reported in Tables 1 & 2.

3. GOUGING ABRASION TESTING

3.1 Equipment

The crusher system and plate assembly are shown schematically in Figure 2. As stipulated, plates were arranged such that a test material was facing a reference steel. The minimum jaw opening was set as specified at 3.2 mm. The test was stopped regularly to confirm the gap and reset if necessary.

Table 1. Steels and white irons

Type	Ident.	Hardness - HB	Description
Steels	Q & T 100	232 -240	Reference ASTM A 514 Grade B rolled structural steel
	AR 400	384	Rolled CMnB abrasion resistant (AR) steels. Quenched and tempered to various nominal hardness levels.
	AR 450	390	
	AR 500	462	
	AR 600	552	
	AR 450 (TRIP)	435	TRIP (Transformation induced by plasticity) AR steel
	AustMnSt	205	Solution treated ASTM A 128 Grade A austenitic manganese steel casting
White Iron Castings	CrMo WI	730	ASTM A532 11B (3%C 15%Cr 3%Mo) alloy
	HyperCrWI	710	Proprietary hypereutectic Cr white iron
Laminated White Iron Wear Plates	Lam. CrMo WI	755	ASTM A532 11B alloy casting brazed to a steel backing plate
	Lam. HyperCrWI	640	Proprietary hypereutectic Cr WI casting brazed to a steel backing plate

Table 2. Overlays

Type	Ident.	Hardness – HB(*HRC)	Description
Chrome carbide overlaid wear plate & hardfacing	CrC SOL wear plate	564	6.4 mm one pass ~ 4%C 30%Cr bal. Fe deposit
	CrC DOL wear plate	595	9.6 mm two pass ~ 4%C 30%Cr bal. Fe deposit
	CrC 1	585	9 mm two pass 7%C 28%Cr bal. Fe deposit
	CrC 2	621	9 mm two pass 5%C 25%Cr 1%Mo 0.5%B bal. Fe deposit
PTAW tungsten carbide / Ni alloy matrix deposits (1 pass 4mm thick)	WC1	46-49*	60Wt.% cast and crushed WC.W_2C eutectic carbide in a 50HRC matrix
	WC 2	40.6*	60Wt.% macrocrystalline (monolithic) WC in a 30HRC matrix
	WC 3	48.5*	60Wt.% macro. WC in a 50HRC matrix
	WC 4	42-55*	65Wt.% macro. WC in a 30-35HRC matrix
	WC 5	52-55*	65Wt.% macro. WC in a 50HRC matrix

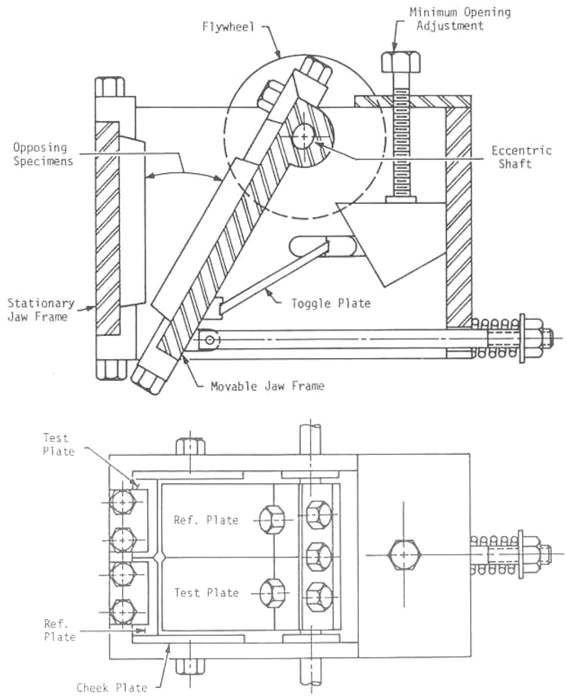

Figure 2. Schematics (top) of jaw crusher and (lower) of test/reference plate arrangement.

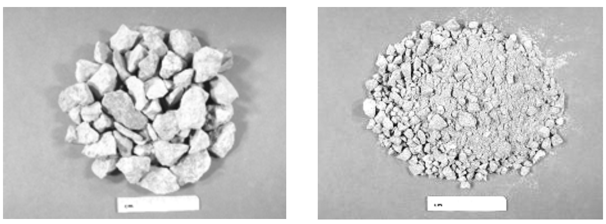

Figure 3. Pre-crushed rock feed (left) and crushed product (right).

Pre-crushed morainal rock with a size range of 25 to 50 mm was used as the jaw crusher feed. The weight % composition consisted of the following fractions: 44.2% volcanic, 20.7% metamorphic, 18.8% granitic and 16.3% of other rock types. A comparison of the rock before and after crushing is illustrated in Figure 3.

3.2 Procedure

In an initial test, plates were weighed at four ~ 227 kg intervals up to the ASTM G81 recommendation of 909 kg of rock throughput. It was determined that there was a linear relationship between the plate weight loss and the amount of material crushed. These results correlated with information published previously (Marks *et al.*, 1976).

It was decided that reliable results could be obtained for steels and white iron castings after crushing only 455 kg of rock. This significantly reduced testing time and labour. However, since there was no gouging abrasion test results for WC overlay materials and no quantified data for CrC overlays, and as it was anticipated that they would both display very low losses, they were tested using 909 kg of rock to obtain more easily measured values. This difference does not invalidate data as every assessment also involved a comparison against reference plates.

Moveable and stationary test and reference plates were cleaned and weighed before and after crushing and the mass loss recorded. From this result a volume loss could be easily obtained for all the ferrous-based materials evaluated using reported density values. A final test wear ratio WF could then be calculated using the following formula.

$$WF = 0.5\ (X_S/R_S + X_M/R_M) \qquad (1)$$

Where X_s and X_m are the volume losses for the stationary and movable test plate and R_S and R_M are the volume losses for the stationary and moveable reference plates. In all instances except for WC overlays, the densities of the test materials were very similar and the mass losses could be used to calculate WF values.

In the case of composite WC materials, theoretical density values of 11.73 g/cc for WC overlays and 12.17 g/cc for the eutectic $WC.W_2C$ form were used for 60% carbide deposits and 13.08 g/cc for 65% WC overlays. These were based on reported densities of 15.6 g/cc and 16.55 g/cc for monolithic and eutectic carbides respectively and 8.4 g/cc for nickel matrix alloys.

The validity of this approach has been supported using high stress (HS) steel wheel abrasion tests on identical materials. Calculated volume losses compared fairly closely with values measured directly by laser profilometry. HS abrasion wear scars were relatively small and very suitable for laser profilometry compared to the areas involved in gouging abrasion test plates which were too large to be scanned reliably.

One very noticeable characteristic was that stationary plates suffered much greater attack than moveable parts.

4. GOUGING ABRASION TEST DATA

Wear Factor values are presented in Figures 4 and 5. The value for CrMo white iron laminated wear plate which was the superior performer in the first testing campaign, has also been included in Figure 5 for comparison purposes.

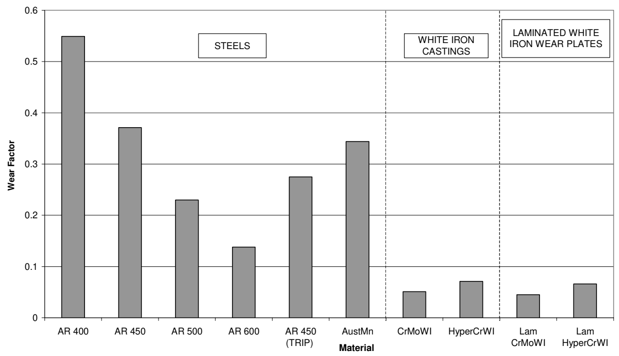

Figure 4. ASTM G81 WF values for steels and white iron castings and laminated wear plates.

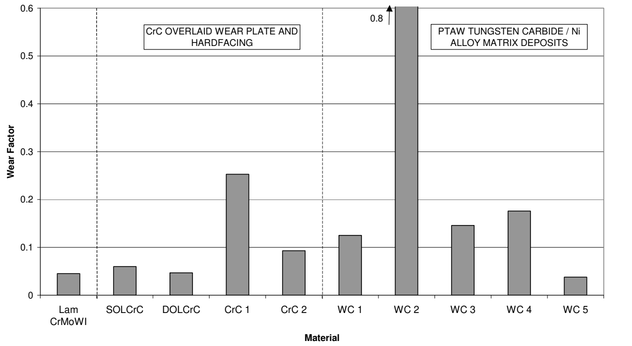

Figure 5. ASTM G81 WF values for CrC wear plates and hardfacing and PTAW WC overlays.

Multiple tests were carried out on several of the materials and good consistency was obtained.

5. WEAR SURFACES AND STRUCTURES

Sections were cut for scanning electron microscopy and metallography from the regions of highest gouging abrasion attack. These were located approximately 25 mm from the bottom edge of stationary plates.

Steels were examined metallographically, after etching with 4% nital except for AustMnSt which was etched in 4% nital, rinsed in methanol and re-etched in 15% HCl. The reagent used for white irons castings and CrC overlays was Glyceregia. The PTAW WC based deposits were examined in the unetched condition.

5.1 Surface Damage

Significant micro-scratching had occurred to the soft reference steel (Figure 6) compared to scoring attack of AR steels which decreased as their hardness increased. There was much lower damage to CrMo castings and laminates (Figure 7).

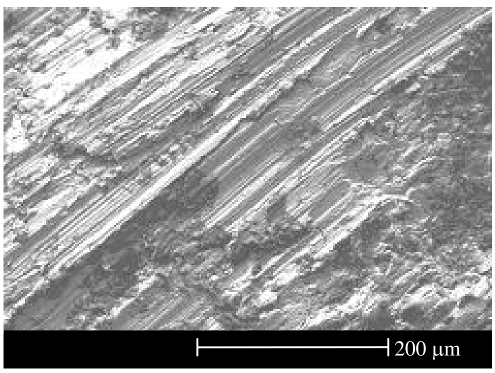

Figure 6. Scoring damage to the surface of a Q&T 100 steel reference plate.

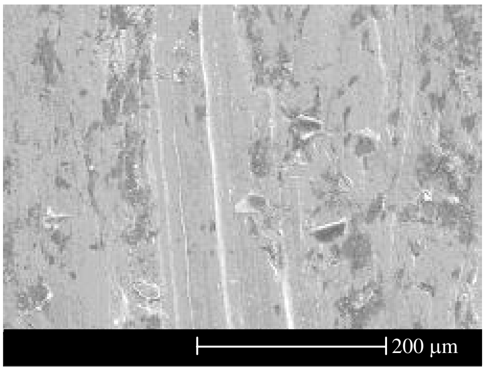

Figure 7. Limited depth micro-scoring and indentation in the surface of LamCrMoWI plate.

Surfaces of many of the overlay materials particularly those with structures with higher volume fractions (CVF) of hard carbides, exhibited a combination of micro-fracturing of M_7C_3 carbides in CrC materials (Figure 8) and of WC and eutectic carbides in PTAW tungsten carbide-based overlays (Figure 9). Micro-scoring was also pronounced in the softer Ni alloy matrices of the latter deposits.

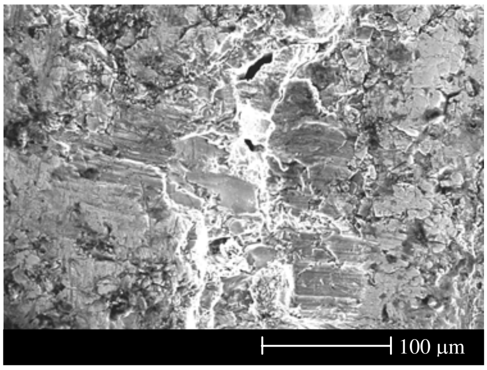

Figure 8. Scoring and widespread micro-fracturing of M_7C_3 carbides in the high C content CrC1 hardfacing.

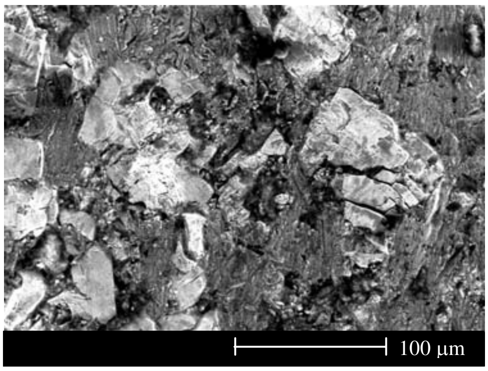

Figure 9. Micro-cracking of WC carbides and micro-scratching of the Ni-based matrix in the WC5 PTAW overlay.

5.2 Microstructural Features

Surface zones of reference steel plates had suffered significant deformation and grain distortion (Figure 10). This became less pronounced in AR steel test plates with increasing hardness, as illustrated for the AR 450 (TRIP) steel in which adiabatic shear bands had developed in the worked surface zone (Figure 11).

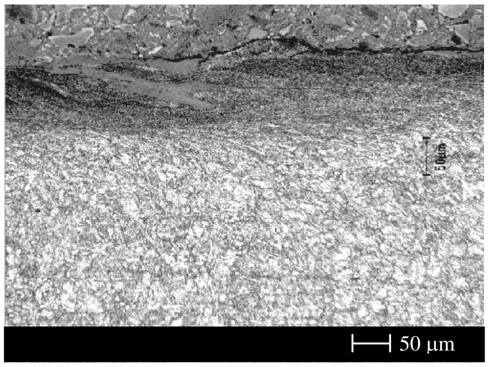

Figure 10. Pronounced grain distortion in the rock crushing contact zone of Q&T 100 reference steel.

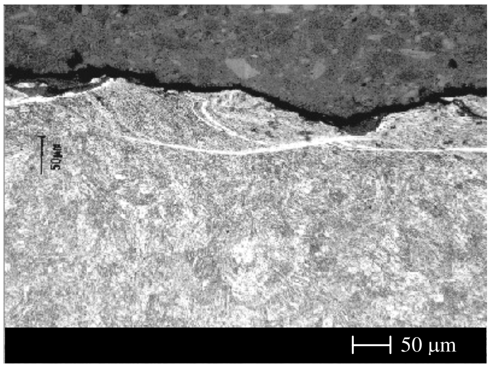

Figure 11. Less grain distortion and adiabatic shear bands in the AR 450(TRIP) steel contact zone.

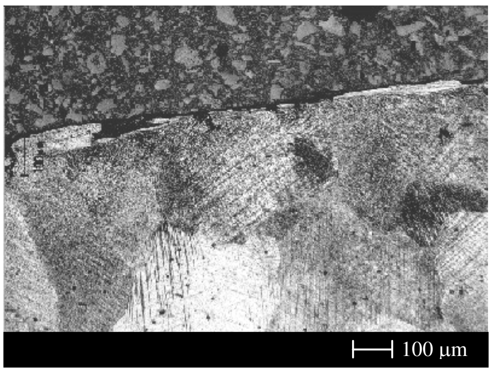

Figure 12. Work hardened surface of the AustMnSt casting.

Mechanical twinning (Figure 12) and microhardness values in excess of 450 HV provided evidence of significant work hardening in the contact zone of the austenitic manganese steel plate.

Cr and CrMo white iron materials as castings and weld deposits, exhibited similarities in surface damage when their carbide structures were comparable. Hypoeutectic or eutectic forms displayed some ability to be indented and to deform without resulting in micro-fracture of eutectic M_7C_3 carbides (Figure 13).

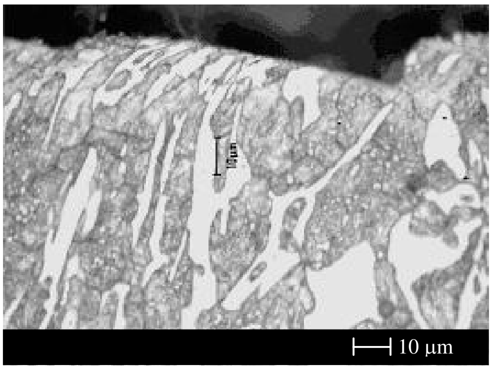

Figure 13. Indentation and deformation of the eutectic structure in the surface of LamCrMoWI.

An increased propensity to cracking and spalling of primary carbides was prevalent in hypereutectic forms at higher CVF and at larger primary carbide sizes (Figure 14).

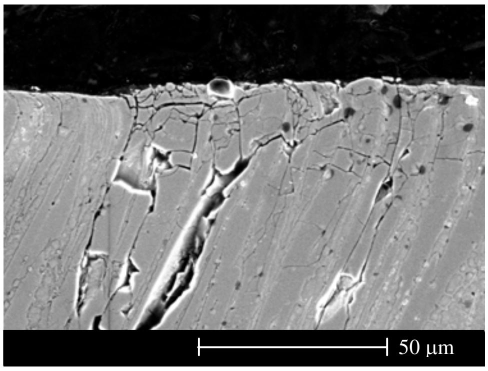

Figure 14. Significant primary M_7C_3 carbide cracking at the contact surface of the 7% C, high CVF CrC1 hardfacing.

Damage to tungsten carbide PTAW deposits was influenced by the uniformity of carbide distribution; its volume fraction and its nominal matrix hardness. Of the two 65Wt.% carbide bearing overlays, WC5 was the most resistant product evaluated. It consisted of a dense monolithic carbide dispersion in a hard matrix. It exhibited much less carbide cracking and spalling damage (Figure 15) compared to WC4 which was a soft matrix product with an uneven carbide structure (Figure 16).

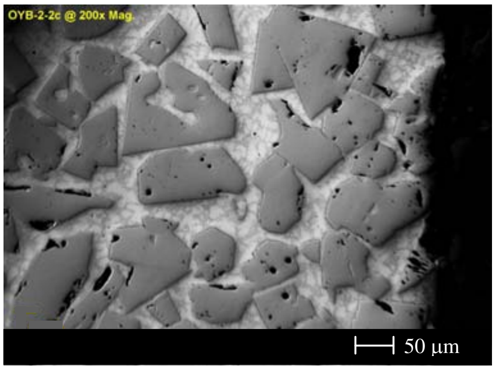

Figure 15. Limited carbide cracking in an uniformly distributed carbide structure of the hard matrix WC5 PTAW deposit.

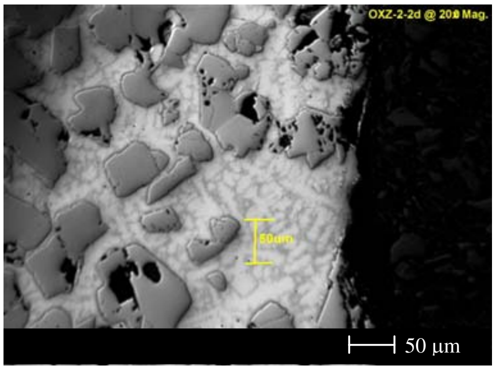

Figure 16. Uneven distribution of micro-fractured WC grains at the contact surface of the soft matrix WC4 PTAW overlay.

6. DISCUSSION

Very pronounced differences in gouging abrasion performance were observed between the different classes of materials and also between products from the same class.

The most resistant materials displaying the lowest WF values were: a 65% WC-bearing PTAW overlay; ASTM A532 IIB CrMo white iron (casting and laminate) and a double pass CrC weld overlay plate material.

The heat - treated, eutectic structure of CrMo WI plates containing a significant distribution of fine eutectic and secondary M_7C_3 carbides in a hard martensitic matrix, appeared to be particularly well suited for resisting gouging abrasion attack.

These products also have a capability to be produced in relatively thick sections.

The likely service performance benefits suggested by the slightly superior WF value for the PTAW deposit, would arguably be overshadowed by the fact that the thickness of its protective surface layer would be much less than that available for CrMo WI, in either straight casting or laminate forms.

The behaviour of the DOL CrC wear plate was considered to be non-representative as it was not in its nominal hypereutectic condition. Ironically its high hardness hypoeutectic structure involving relatively fine eutectic carbides, provided a much tougher condition than its intended form. As in the case of all weld-deposited hardfacing layers, it would suffer from thickness limitations and likely base metal dilution. Thus it would not compare favourably with CrMo white iron castings and laminates, in overall protection capability.

The presence of high M_7C_3 carbide volume fractions and particularly those containing coarse primary carbides, affected deleteriously the gouging abrasion performance of hypereutectic Cr white iron castings and more obviously CrC weld overlays and hardfacing. The WF values for these alloys became higher as the increasing fraction and size of hard and brittle primary M_7C_3 carbides enhanced their propensity to cracking and spalling damage.

Raising the nominal carbide content in PTAW deposits from 60 to 65% resulted in superior performance but more important influences appeared to be the matrix hardness and to a lesser extent the uniformity of carbide distribution. It is considered that the wear resistance and support provided by a high matrix hardness and the presence of a consistent dense carbide structure in the contact surface, are critical requirements to minimize micro-cracking and spalling damage.

There was no clear distinction between monolithic / macrocrystalline WC and the cheaper, slightly harder, cast and crushed eutectic form, when present in similar nominal contents in PTAW deposits with the same matrix hardness.

The performance of AR steels was influenced by their hardness with the AR 600 grade exhibiting GA resistance that was superior to some of the commercial PTAW WC and hypereutectic CrC hardfacing products. Steel plate properties would also be maintained throughout their thickness

The TRIP AR 450 steel was more resistant than a standard Q&T AR 450 steel plate but it did not satisfy a claim that it could match the performance of AR 500 steel.

The surface of the austenitic manganese steel had work hardened to 450 HB and in this condition it had displayed a WF value that was similar to that of 450 HB Q&T AR steel.

7. CONCLUSIONS

ASTM A532 11B CrMo white iron castings exhibited very high resistance to gouging abrasion.

They were considered to be the superior option of the products assessed when the thickness of available wear protection layer was included in the comparison.

High C - bearing Cr white iron castings and CrC hardfacing alloys were prone to micro-cracking and micro-spalling of primary M_7C_3 carbides and were less resistant

A relatively thin PTAW 65% WC/50HRC nickel alloy matrix deposit, provided the lowest WF value or highest GA resistance.

Higher WC-bearing PTAW deposits combined with hard Ni alloy matrices displayed superior GA resistance compared to lower carbide content /softer binder composites.

Soft Ni–based matrices were not conducive to achieving low GA wear factors in PTAW WC deposits.

Macrocrystalline and eutectic tungsten carbides behaved similarly in PTAW deposits when other factors were comparable.

The WF of AR steels was inversely proportional to hardness.

AR 600 steel plate exhibited superior WF values to more expensive and thinner claddings of some hypereutectic CrC overlays and soft matrix PTAW WC deposits.

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