

Effects of matrix hardness on the wear resistance of WC-Co reinforced weld overlays for ground engaging tools

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ABSTRACT

Ground engaging tools (GET) require higher hardness and good abrasive wear resistance to extend their life. Conventionally, wear protection for GET is provided by weld overlays with the addition of hard particles like cemented tungsten carbide (WC-Co). The preferential wear of the softer matrix in the weld overlay leads to reduced life as the hard particles get knocked off. Thus the understanding of the wear performance of weld overlays with increasing matrix hardness is of significant importance. Different welding wires with hardness of the weld metal deposit ranging from 170 to 650 HV_{0.2} were chosen. The weld matrix shows a richer chemistry than the typical alloy content expected. EDS analysis identified dissolution of the cemented carbide and iron diffusion at the interface between the WC-Co particulate and matrix forming hard complex carbides increasing the matrix hardness. The low alloy wire with carbides shows a hardness of the overlays were studied using an ASTM G65 dry sand rubber wheel abrasion tester. The low alloy wire overlay with no carbides shows a wear loss of 0.608 g which is 21% higher than the weld overlay with carbides (0.502 g). In comparison, the hardfacing wire with an average weld matrix hardness of 756 HV_{0.2} shows a mass loss as low as 0.189 g.

Keywords: Ground engaging tools, three-body abrasive wear, Vickers microhardness, WC-Co cemented carbides, weld hardfacing.

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INTRODUCTION

Ground Engaging Tools (GET) used in earth moving and other applications undergo severe wear conditions in the field. Abrasive wear resistance is of great importance in these applications. Parts for GET are generally made of low alloy steels that wear down and get replaced. This results in increased operating cost as the downtime required to replace parts is very high. The life of GET has to be increased in order to keep the downtime and maintenance cost to a minimum. Surface engineering is an enabling technology to improve the life of GET (Shibe and Chawla, 2013). Surface treated parts give a better wear resistance and high hardness on the surface leaving a soft core to withstand impact loads. Several procedures such as heat treatments, cladding, thermal diffusion techniques and weld hardfacing are used in order to improve the wear life of GET (Hintermann, 1983; Hutchings, 1992).

Weld hardfacing is a popular technique employed to introduce a high wear resistant surface layer by the addition of hard cemented carbides. Cemented carbides are metal matrix composites made using hard particles like tungsten carbide (WC) cemented in a cobalt or nickel matrix during sintering or Hot Isostatic Pressing (HIP). WC is the most popular hard material used in these sintered tools due to its high hardness, some amount of plasticity and good wettability by molten metals (Gassmann, 1996). WC-Co cemented carbides exhibit a higher degree of toughness and excellent wear properties. Weld hardfacing using low cost carbon steel wires with cemented carbides embedded in them is used in GET applications (Jones and Roffey, 2009). This process has proven to be a great success commercially in attaining high wear resistance at a reasonable cost. Well distributed cemented carbide particles with a hardness ranging from 1500 to 2200 HV embedded in a softer matrix (200 HV) provide excellent abrasive wear resistance. The full life and advantage of the cemented carbide particles may not be utilized due to preferential wear of the softer matrix surrounding them. In certain abrasive conditions involving smaller particles, the softer matrix preferentially wears out and the protruding hard cemented carbides fall off prematurely (Crook and Farmer, 1992). This can be prevented by increasing the hardness of the matrix and the bond between the hard phase and the matrix by modifying the weld matrix chemistry (Ambroza and Kavaliaskiene, 2009).

The present study investigates the characteristics of weld overlays with cemented carbides for GET. Welding techniques like Gas Metal Arc Welding (GMAW). Shielded Metal Arc Welding (SMAW), Submerged Arc Welding (SAW) and Plasma Transferred Arc (PTA) can be used for hardfacing (Deuis, 1997; Mendez et al., 2014; Anderson et al., 2003). GMAW is used in the current work because of its low cost and flexible operation. The hardness and wear life of the metal matrix composite (MMC) weld overlays mainly depend on the carbides and weld matrix alloy content. The performance of the weld surface depends on the hardness of other phases in the microstructure as well (Hutchings, 1992). It is found that carbon and chromium improve wear resistance, hardness and refine microstructure of the weld overlavs (Selvi et al., 2008). The alloy content in the weld matrix can be modified by using high alloy wires or by addition of alloying elements. Five welding wires with different chemistry (and thus increasing hardness) were chosen to study the effect of matrix hardness on the abrasive wear behavior of the weld overlays.

MATERIALS AND EXPERIMENTAL PROCEDURES

Welding wires with different alloy compositions and thus different hardness values were chosen as shown in Table 1. The substrate material is a low alloy steel plate material ($200 \times 150 \times 16$ mm) used in a quenched and tempered condition (composition and hardness are shown in Table 1). The expected hardness and composition of the overlays are also reported in Table 1 for all the wires used.

The weld overlays were prepared using a Gas Metal Arc Welding (GMAW) technique. The crushed cemented carbides (10/20 mesh) were added to the weld pool from a hopper. The weld deposits made were about 25 mm width.

The weld overlays were characterized using Rockwell Hardness (HRC), Optical Microscopy (OM), Vickers Microhardness (HV_{0.2}), Scanning Electron Microscopy

(SEM), Energy Dispersive X-Ray Spectroscopy (EDS), and Image Analysis. A Clemex digital microhardness tester (Model MMT-X7) was used with Clemex Vision Lite® image analysis software. Hardness profile was done using the automated Clemex Vickers microhardness machine at a load of 200 gf (ASTM E384-11e1). SEM with EDS analysis was performed using a Tescan Vega-3 microscope available at the University of Alberta.

ASTM G65 dry sand rubber wheel abrasion testing has been used as a standard method to evaluate the wear performance and as a reliable low stress abrasion test to assess the performance of the hardfacing deposits used in actual service conditions (Chatterjee and Pal, 2003). Samples for wear testing were cut to $75 \times 25 \times 10$ mm in size and ground flat with a surface finish of 0.8 µm. Procedure B was followed with a total wheel revolutions of 2000 at a speed of 200 RPM. The force against the specimen was 130 N. The type of abrasive used according to ASTM G65 was AFS 50/70 mesh sand (reported hardness of 850 HV [Anderson et al., 2003]) with a flow rate of 400 g/min. The sample mass loss was measured within 1 mg accuracy.

RESULTS AND DISCUSSION

Optical microscopy

Optical microscopy of the cross section was done on the samples to characterize the weld overlay. Figure 1 shows the mosaic image of the cross section obtained by stitching the images at 25X magnification of the weld overlay (Wire 5). Two types of carbides - with and without reaction zones around them - in the weld overlay can be observed. A polished cross-section of the as-received particles resembles the one with no reaction zone in the weld overlay (Figure 2).

Vickers microhardness

The actual weld matrix hardness measured using the Vickers microhardness tester and the expected hardness from the wire manufacturer are shown in Table 2. Wire 5 shows the highest matrix hardness as expected among the wires tested. It is observed that higher matrix hardness can be achieved by adding cemented carbides to the weld overlay with the same wire. Also the actual weld matrix hardness is always higher than the specified hardness of the weld overlay. Figure 3 shows a hardness profile of the weld overlay done from the surface towards the steel substrate. The spike seen in the graph corresponds to a reading on the carbide particle. The graph also shows fairly uniform weld matrix hardness above 750 HV_{0.2}.

The two zones observed in the cemented carbide

Sample		Hardness					
	С	Si	Mn	Cr	Ni	Others	HBW (HRC)*
Substrate steel	0.17	0.23	1.22	0.84	0.12	0.031P; 0.005S; 0.39Cu; 0.0038B; 0.033Al	37.9 HRC
Wire 1	0.06 - 0.11	0.80 - 1.00	1.45 - 1.55	-	<0.15	0.025P; <0.025S; 0.30Cu; <0.15 Mo; <0.02 Al	170 (5.4)
Wire 2	0.10	0.50	2.00	1.00		0.30Mo	250 - 277 (25 - 29)
Wire 3	0.20	0.40	1.50	2.00		0.50Mo	326 - 363 (35 - 39)
Wire 4	0.20	1.20	2.00	2.80		0.40Mo; 0.20V	382 - 432 (41 - 46)
Wire 5	0.60	1.40	1.70	6.20			553 - 653 (55 - 60)

 Table 1. Wire composition and hardness.

*Wire manufacturers' hardness data.



Figure 1. A mosaic image of the cross section of the weld overlay (wire 5) showing WC-Co particles in the weld matrix, (25X).



Figure 2. Cross section of a polished virgin WC-Co particulate mounted in epoxy, (50X).

Sample	Expected*	Actual, HV _{0.2}
Wire 1	178	498
Wire 2	292	579
Wire 3	383	676
Wire 4	455	741
Wire 5	697	756
Wire 1 with no carbides	178	263

Table 2. Expected and actual hardness of the weld matrix.

*Expected hardness is the maximum weld deposit hardness (data supplied by manufacturer).





Figure 3. Hardness profile from the top of the weld overlay towards the substrate (Wire 5).

particles were probably the result of dissolution of cemented carbides during the weld overlay process. The microhardness measurements taken across such carbides (Figure 4) show a hardness variation in the outer zone compared to the inner zone. This, in turn, might affect the abrasive wear performance of the overlays. However, the dissolution of cemented carbides may have a positive impact. Complex carbides formed due to dissolution and subsequent precipitation might increase the hardness of the surrounding matrix along with other alloying elements eventually resulting in harder overlays. As discussed earlier, this increase in matrix hardness would enhance the overall abrasive wear performance of the overlay by providing support to the carbides.

Abrasive wear testing results

A few of the selected weld overlays were tested for ASTM G65 abrasive wear performance. Table 3 shows the wear loss measurements obtained for the different weld overlays. Wire 5 shows the highest wear resistance or the lowest wear loss. As expected, the higher the hardness of the weld matrix the higher the wear resistance. The low alloy wire with an average weld



Figure 4. Hardness profile across a cemented carbide particle with two zones in Wire 1 (I – Outer and II – Inner).

Table 3. ASTM G65 mass loss and the actual hardness of the weld matrix.

Sample	Weld Matrix Hardness, HV _{0.2}	Wear loss, g
Wire 1	498	0.502
Wire 4	741	0.225
Wire 5	756	0.189
Wire 1 with no cemented carbide	263	0.608

matrix hardness of 498 HV_{0.2} resulted in a mass loss of 0.502 g. Wire 5 with an average weld matrix hardness of 756 HV_{0.2} shows the lowest wear loss of 0.189 g. The weld overlay with Wire 1 shows a wear mass loss almost three times higher than the hardest wire (Wire 5).

For comparison, the weld overlay of Wire 1 with no carbide addition is the least wear resistant. The wear loss is 21% higher than the weld overlay of the same wire with carbide addition.

SEM with EDS analysis

The hardness of the weld matrix can be increased by modifying the wire chemistry using alloying elements in the wire and/or the dissolution of the cemented carbides. Weld overlays containing cemented carbides surrounded by a harder matrix perform better than that of a softer matrix under abrasive conditions. The weld matrix shows a richer chemistry in comparison to the weld wire. In

	Wire	e 1 (Wt. %)	Wire 5 (Wt. %)		
Element	Near the carbide interface	Matrix - away from the carbide	Near the carbide interface	Matrix - away from the carbide	
С	2.39	1.95	3.41	2.86	
Cr	0.27	0.57	2.85	3.01	
W	5.86	-	6.46	3.43	
Fe	90.08	95.95	85.05	88.79	

Table 4. EDS point analysis for samples Wire 1 and Wire 5.



Figure 5. Actual vs. expected hardness of the weld matrix for different wires.

general, the dissolution of cemented carbides and some alloy diffusion are observed for all the weld overlays. EDS mapping of the cemented carbides confirms this finding. Near the matrix interface, higher levels of alloying elements such as tungsten, cobalt and carbon are seen compared to a region away from the interface (Table 4).

EDS mapping on a reacted cemented carbide particle confirms its dissolution. EDS analysis on the outer zone of the carbide shows some iron diffusion forming complex (Fe, W, Cr)-carbide. This outer zone shows a higher hardness compared to the inner zone (Figure 4). The adjacent interface regions between the carbide particles and the matrix also show relatively higher amounts of W and C diffusion into the matrix resulting in a higher hardness of the weld matrix than expected (Table 4). For instance, the low alloy wire (178 HV_{0.2}) with carbides show matrix hardness up to 498 HV_{0.2} compared to the one with no carbides at 263 HV_{0.2}. The high alloy wires show a consistent increase in weld matrix hardness as shown in Table 2.

Hardness and abrasive wear resistance of the weld overlays

The weld wires used in this study were chosen based on increasing values of expected hardness of the weld matrix through alloying. The results also show an increasing trend for the hardness as expected but the actual hardness of the weld overlays were much higher than expected as shown in Figure 5.

An interesting result to note is that the weld matrix hardness of the low alloy wire (Wire 1) with and without the cemented carbides. The low alloy wire with no or little alloy content with an expected hardness of 178 $HV_{0.2}$ shows an actual average hardness of the weld matrix around 498 $HV_{0.2}$. This is a significant increase in hardness by the addition of cemented carbides in the weld overlay. Note that the average matrix hardness of same wire without the addition of carbides is 263 $HV_{0.2}$. There is a significant increase in hardness of the weld overlay with cemented carbide additions. This trend has



Figure 6. Wear loss vs. actual weld matrix hardness for selected weld overlays.

been observed for all the wires used but more significantly for wires with lower expected hardness values. The high alloy wires # 3-5 with higher C and Cr almost show similar average hardness around 700 $HV_{0.2}$ even though the expected values are much lower. The hardness curve in Figure 5 does not show as steep an increase as in the lower hardness range above the expected hardness of around 400 $HV_{0.2}$.

The wear loss measurements of the samples show a similar trend of increasing wear resistance with increasing weld matrix hardness (Figure 6). Wire 1 with no carbide addition shows the highest wear loss among all the samples. For the same Wire 1 with carbides the hardness and wear resistance were higher than the expected values as shown in Figures 5 and 6. The difference in wear loss for Wires # 3-5 is minimal. This indicates the wear resistance of weld overlays does not improve much beyond certain matrix hardness.

EDS mapping was done on both the unreacted and reacted particles. Figure 7 shows carbide with no dissolution whereas Figure 8 and 9 show carbides with dissolution (Wires 1 and 5). The hardness values of the particles vary based on the extent of dissolution and location of the particles as well. Particles on the surface of the weld overlay did not dissolve much in general and showed higher hardness. For example, the hardness of the unreacted particle. On the other hand, reacted particles at the bottom of the weld show a lower hardness range in both the diffused zone and the inner core (Table 5). In general, the hardness of the cemented carbides is higher in Wire 5 than that of Wire 1 which shows values closer to the virgin carbides.

The dissolution of the cemented carbides and alloy

diffusion result in the formation of hard brittle phases like W_2C and other MC type carbides. According to the literature and EDS mapping, the outer reaction zone possibly consists of M(Fe-W-Cr)₆C carbides. The higher hardness of the outer zone might be due to the presence of hard and brittle W_2C and M_6C carbides (Lou et al., 2003). The inner core might have the re-precipitated softer carbides (Co₃W₃C, and WC+W₂C) (Jones and Roffey, 2009).

When the wear scars are observed under a stereoscope, slightly deeper grooves can be seen on the G65 sample of Wire 1 than that of Wire 5 (Figure 10). On the reacted carbides the harder outer zone shows less wear than the softer inner core which is clearly visible from the difference in the topography or surface profile. well with the microhardness This correlates measurements on the particles. Some chipping on the hard abrasive carbides from both the weld overlays can also be seen in Figure 10, but no particle pull out was observed.

The increase in hardness of the weld matrix than the expected values may be attributed by the dissolution of the cemented carbide particles as well as alloying elements in the wire. This dissolution may be beneficial in a way which forms complex carbides with higher hardness that increases the hardness of the matrix protecting the carbides. This, in turn, helps enhance the abrasive wear resistance of the weld overlays.

CONCLUSIONS

1. Hardness and the wear resistance of the weld overlays increase with the addition of cemented carbide particles



Figure 7. EDS mapping of a cemented carbide particle with no dissolution in Wire 5.





W La1



Co Ka1

Fe Ka1

Figure 8. EDS mapping of a cemented carbide particle with dissolution in Wire 1.



Figure 9. EDS mapping of a cemented carbide particle with dissolution in Wire 5.



Figure 10. Stereoscopic images of the wear surface obtained at 4X magnification for Wire 1 (left) and Wire 5 (right). Arrows pointing to the reacted particle showing higher wear at the center.

in the weld matrix.

2. The weld matrix hardness increases with the level of alloying elements and thus the hardness of the welding wire.

3. The actual hardness of the weld deposit is much higher than those expected from the weld matrix hardness. SEM/EDS analysis shows the diffusion of alloying elements into the weld matrix and formation of hard complex carbides in the outer zone of the dissolved cemented carbides. This possibly increases the weld matrix hardness and thus the wear resistance of the weld overlays.

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