NRC Publications Archive Archives des publications du CNRC

Sliding abrasion resistance assessment of metallic materials for elevated temperature mineral processing conditions

Jones, L. C.; Llewellyn, R. J.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version
acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien
DOI ci-dessous.

Publisher's version / Version de l'éditeur:

<https://doi.org/10.1016/j.wear.2009.06.023>

Wear (Amsterdam, Netherlands), 267, 11, pp. 2010-2017, 2009-06-21

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=8b7250be-d600-4f47-9fca-c73f49f3d761>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=8b7250be-d600-4f47-9fca-c73f49f3d761>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the
first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la
première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez
pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research
Council Canada

Conseil national de
recherches Canada

Canada

Sliding abrasion resistance assessment of metallic materials for elevated temperature mineral processing conditions

L.C. Jones^{*}, R.J. Llewellyn

National Research Council Canada, Vancouver, B.C., Canada V6T 1W5

ARTICLE INFO

Article history:

Received 19 September 2008

Received in revised form 5 June 2009

Accepted 12 June 2009

Available online 21 June 2009

Keywords:

High temperature

Sliding abrasion

Irons

Steels

Mineral processing

ABSTRACT

The multiplicity of harsh environments in mining, processing and transporting ore and related waste, cause severe wear, extremely high maintenance costs and lost production.

Elevated temperature processing is one of the conditions that influence the performance of possible materials of construction. This takes the forms of reduced hardness and strength, deleterious changes in the structure and properties of materials during protracted exposure and increased oxidation and corrosion.

Drag chain conveying of hot solids e.g. in smelting, typically results in three-body sliding abrasion and adhesive wear of connecting pins and hole surfaces in link assemblies and of moving paddles that impel the particulates in enclosed channels. Selected materials have been assessed for this type of service under reciprocating sliding abrasion contact conditions using an adapted Cameron-Plint TE77 wear rig at 20 °C and 350 °C. These include the current carburised low alloy steel, other steels, Cr white irons and Co-based alloys in bulk, overlay and surface treated forms.

Examination of wear scars, using scanning electron microscopy, identified the main wear mechanisms affecting the highly resistant powder metallurgical (PM) tool steels and HVOF coating as micro-scratching and as indentation leading to micro-fracture. Materials with lowest resistance displayed evidence of significant material removal by micro-ploughing. The formation of oxide layers on some samples during testing appeared to be beneficial.

Crown Copyright © 2009 Published by Elsevier B.V. All rights reserved.

1. Introduction

Abrasive wear is arguably one of the most damaging and costly issues for many industries, particularly mining and mineral processing, where severe interactions between equipment and hard solids, ores or waste products, result in very high maintenance costs and production losses. There is a wide array of components that are required to operate effectively in such extremely harsh environments. Conditions are often exacerbated by elevated temperatures, and the associated lower hardness and strength, as well as increased chemical attack and deleterious changes to a material's microstructure and properties during protracted exposure [1] often result in significantly increased wear and/or corrosion rates.

There have been many studies conducted to examine elevated temperature sliding wear behaviour of materials in both unidirectional [2–5] and reciprocating [6–12] motion, however, the influence of abrasives on sliding wear mechanisms is generally concentrated on unidirectional rotation, due to the difficulty of

ensuring that the abrasive is always present in the area of contact. Limited studies have been conducted to examine the influence of abrasives on sliding wear mechanisms at elevated temperatures.

The presence of an abrasive and the generation of wear debris between sliding bodies may result in either two- or three-body abrasion, or a combination of both depending upon the relative hardness of the materials in contact, thereby increasing the complexity of the tribological system.

In many situations, the prevention or reduction of wear is achieved by the use of superior alternative materials or the application of coatings or other surface treatments. There has, however, been a significant amount of research conducted to examine the formation of oxide scales or 'glazes' during sliding wear and to establish the influence of such layers on the wear resistance of specific materials [13–15].

The drag chain conveying of hot solids in smelting operations is one particular problem where elevated temperature environments lead to rapid degradation of equipment (see Fig. 1). The link bore and pin combination, which hold individual chains together, experience a relative reciprocating movement and the ensuing wear rapidly results in an increase in bore dimensions and hence in the overall chain length. As the degree of slack in the chain increases, the efficiency of hot solids movement is reduced and the opportunity

^{*} Corresponding author. Tel.: +1 604 221 3000.

E-mail address: lynsey.jones@nrc.gc.ca (L.C. Jones).

Fig. 1. (a) Single link/paddles assembly from a drag chain conveyor, (b) schematic showing location of wear for link bore and pin.

grows for increased ingress of abrasive process solids into contact zones between pins and bores.

The Cameron-Plint TE77 high frequency friction machine (Phoenix Tribology Ltd., Newbury, UK) is a well-established tool in the research of reciprocating sliding contact conditions [16–20]. For applications such as the drag chain conveyor, the rig has many advantages for assessing the compatibility of specific material couples. Currently, one principal material of choice for the linkage bar is a carburised low alloy steel casting, however, the thickness of the carburised layer is in the region of 500 μm and therefore offers only temporary protection. Due to the current unsatisfactory service life in the aggressive smelting environment, an investigation was undertaken to assess potential substitute materials to mitigate the wear of the pin and link bore during service. The need for improvement was also related to a plan to operate the system at higher temperature thus exacerbating the conditions.

The formation and comminution of wear debris within the contact area for sliding wear often adapt from two- to three-body abrasion. This additional debris component is considered likely to influence the formation of a compacted oxide layer [21]. This is a particularly important area of understanding for applications such as the drag chain link bore and pin where a third body, in the form of hot process solids, is present from the start.

The work reported herein describes an appropriate test procedure that has been developed for assessing materials for this application and examines several possible replacement options. These are in bulk form or as thickness dependent, surface treated layers or hardfacing deposits.

Table 1
Materials assessed under reciprocating sliding abrasion conditions.

Sample	Material class	Description	Hardness–HRC
A	Existing drag chain conveyor material	Low alloy steel	47.0
B		As above + carburising treatment	62.0
C	AR steels	CMnB AR 400 steel	40.0
D		CMnB AR 600 steel	55.6
E	Tool steels	Powder metallurgy high alloy tool steel	69.2
F		Powder metallurgy high Cr tool steel	65.7
G	White irons	Hypoeutectic Cr white iron casting (~24–28% Cr, 2.4–2.8% C)	57.4
H		Hypereutectic Cr white iron casting (~30% Cr, 3.5–5% C)	60.5
I	Wrought Co-based alloys	Stellite 6B	37.6
J		Stellite 712	48.0
K		Tribaloy 400	53.7
L	Overlays/coatings	Chrome carbide bulk weld overlay (Nom. 28%Cr, 4%C)	54.7
M		HVOF sprayed WC–NiCoCrFeMo	73.8

2. Experimental methods and materials

2.1. Test products

The materials which have been assessed are listed in Table 1. The choice was intended to both evaluate the capability of the test procedure and some of the influences on performance (e.g. original steel hardness) and to evaluate possible candidates for use in elevated temperature sliding wear environments. The former motive resulted in the inclusion of several materials not specifically intended for protracted high temperature service (e.g. quenched and tempered AR steels). A cross-section of wear materials classes was selected that offered some potential benefits in terms of high wear and softening resistance and low oxidation susceptibility.

The relative motion of the drag chain link bore and pin involves a reciprocating sliding action with entrainment of particles between components [22]. The Cameron-Plint TE77 is suitable for assessing such movement and a 'horizontal cylinder-on-flat' sample geometry was chosen to ensure a suitable uptake of abrasive into the space between the two contacting surfaces.

2.2. Test specimens

Flat sections with dimensions of 13 mm $\times$ 25 mm $\times$ 7 mm were ground to a 1200 SiC grit finish. The cylindrical 'counterbody' samples were prepared from hardened O1 tool steel (60 HRC) with a diameter of 6.35 mm and length of 20 mm. A 45° chamfer at both ends of the cylinder gave an initial line of contact of 18 mm and

Fig. 2. Image and schematic of the reciprocating arm and specimen holder.

reduced the influence of specimen edge effects. The holder for the cylindrical counterbody was such that it could be accurately positioned relative to the static flat specimen prior to a test commencing, thereby minimising any issues associated with specimen alignment or uneven loading.

In service the carburised low alloy steel is not coupled against O1 tool steel but against itself. This tool steel was readily available in the required form and chosen to provide a constant comparison throughout the range of tests. In addition, tool steels offer high potential as possible substitute materials for the current application. Future tests will involve an O1 tool steel like-on-like combination.

2.3. Test equipment

The apparatus and a schematic of the sample contact area are shown in Fig. 2. The reciprocating motion of the counterbody is controlled by means of an eccentric and a scotch yoke mechanism. The oscillation frequency was set throughout to 3 Hz, which is representative of the type of movement experienced in the drag conveyor application.

A modified specimen holder was designed and employed in combination with the heating system of the machine, to assess the reciprocating sliding abrasion of materials at both 20 °C and 350 °C. The holder was adapted from the as-supplied equipment so that sufficient AFS 50–70 silica sand (212–300 μm) abrasive was held in the area surrounding the specimen and counterbody. This arrangement ensured that hard abrasive grains were continually replenished by gravity in the contact area during the reciprocating action.

For elevated temperature tests, the heating plate was switched on following application of the load and the system left for 10 min prior to the test commencing to allow the required temperature to be attained and stabilised. Table 2 identifies the key test parameters used with this work.

Following testing, the samples were placed in acetone in an ultrasonic bath to remove any loose debris or residual abrasive from the wear scars, then thoroughly dried. All samples were weighed, using an analytical balance (Mettler Toledo AT 201, Mississauga, ON, Canada) with a readability of 0.015 mg, before and after testing to determine the average weight changes. The volume loss for each combination of materials was calculated using known density values.

Initial tests were conducted using both uncarburised (Sample A) and carburised (Sample B) low alloy steel specimens, to determine a base requirement/target for the selection of possible replacement materials and/or surface treatments. The results were then compared with values obtained for the other materials listed in Table 1. A minimum of two tests per material combination were carried out.

Wear surfaces generated during testing were characterised using a Hitachi S-3500N scanning electron microscope combined with energy dispersive X-ray (EDX) analysis.

Table 2
Sliding abrasion test parameters.

Stroke length	4.56 mm
Frequency	3 Hz
Temperature	20 °C and 350 °C
Applied load	8.75 kg
Duration	20 min

Fig. 3. Volume losses from sliding abrasion at 20 °C and 350 °C for existing material used for drag chain conveyor.

3. Experimental results

The 15 materials listed in Table 1 were separated into different material classes for easier comparison. The volume loss results for both the specimens and associated O1 tool steel counterbodies are presented separately for each category. It is important to identify and understand the combined wear behaviour of the material couple, as the drag conveyor application experiences simultaneous wear of both the link bore and pin.

3.1. Currently used steels

Fig. 3 displays the results for the low alloy steel (Sample A) and the carburised low alloy steel (Sample B). At 20 °C the carburising treatment produced a reduction in volume loss for the specimen and counterbody by 65% and 82% respectively, whilst at 350 °C those values were 31% and 63%.

Sample A exhibited high volume losses for both the specimen and counterbody at 20 °C and comparing the original surface state (Fig. 4a) with the heavily deformed wear surface (Fig. 4b), clearly highlights the significant wear which occurred during testing. Plastic deformation, ploughing and the formation of wear platelets with significant edge cracking are evident. Testing at 350 °C resulted in the formation of an oxide layer on the specimen surface (Fig. 4c).

The considerable improvement in wear resistance as a result of carburising is displayed in Fig. 5. The reduced wear of both the specimen and counterbody is also characterised by the prevalent degradation mechanisms of micro-cutting and indentation. There was little change in the resistance or degradation mechanisms of the carburised layer (Sample B) from 20 °C to 350 °C.

Fig. 5. Evidence of micro-cutting and indentation on the carburised surface of Sample B at 20 °C.

3.2. Other ferrous materials

Fig. 6 presents volume losses for the ferrous-based test materials (Samples C through H). At 20 °C, the AR steels (Samples C and D) exhibited excellent wear resistance with the differences between the two correlating with hardness values. Minimal wear was observed for O1 tool steel counterbodies. SEM examination of the wear surfaces showed evidence of three-body wear, with micro-cutting and indentation leading to limited plastic deformation. At 350 °C, a slight increase in the amount of wear for the counterbodies was observed combined with a greater attack for the flat specimens.

Tool steel specimens (Samples E and F) have high hardness (see Table 1) which, when coupled with that of the counterbody, reduces the ability of the abrasive to embed and be retained substantially in either surface, thereby retaining a three-body wear mechanism. The high magnification images in Fig. 7 show wear scars for Sample E at 20 °C and 350 °C, with indentation and micro-scratching

Fig. 6. Volume losses from sliding abrasion at 20 °C and 350 °C for AR steels, tool steels and cast chrome white irons.

Fig. 4. (a) Original polished surface, (b) heavily deformed wear scar surface for Sample A at 20 °C, and (c) formation of protective oxide layer on Sample A at 350 °C.

Fig. 7. Wear scars from P/M high speed tool steel (Sample E) at 20 °C and 350 °C, containing micro-scratching and indentation.

Fig. 8. Wear at 350 °C of (a) hypereutectic CWI and (b) O1 tool steel counterbody.

features. The counterbodies showed evidence of some oxide formation, which may have also helped to mitigate any material removal.

The hypereutectic chrome white iron (CWI) (Sample G), which contains approximately 25 vol.% hard chromium carbides in a hardened ferrous matrix, exhibited high volume losses at both test temperatures. The counterbody also displayed high wear at 20 °C, however, it is speculated that the oxide scale formed on the surface of the wear scar during testing at the higher temperature, provided improved abrasion resistance.

The highly alloyed hypereutectic CWI (Sample H), however, contains 50 vol.% carbides and this was reflected in the abrasion resistance results which were approximately 2.5 times superior to Sample G at 20 °C and exhibited twice the resistance at 350 °C. The results for the hypereutectic CWI were only equivalent to those obtained for the carburised low alloy steel (Sample B). At 350 °C, the material couple exhibited preferential wear of the ferrous matrix (Fig. 8a) combined with a roughening of the counterbody surface (Fig. 8b) and intermittent oxide formation.

EDX analysis was used to examine the oxide scales, which had formed on the majority of the ferrous-based materials during testing at 350 °C. A typical trace is shown in Fig. 9. In all cases the main components were Fe, O and Si. It is assumed that a predominant

proportion of the latter elements was present in the form of silica as a consequence of comminution of sand abrasive and entrainment of the resulting smaller abrasive particles within plastically deformed body/counterbody wear debris.

3.3. Co-based alloys

The results displayed in Fig. 10 identify the major differences in behaviour for the three materials examined and the images in Figs. 11 and 12 show the surface conditions of the specimens after testing at 20 °C and 350 °C.

Stellite 6B (Sample I) exhibited the lowest wear resistance at 20 °C, but the retention of its hardness at high temperatures provided it with good abrasion resistance at 350 °C. Stellite 712 (Sample J) contains additional Mo in place of W, primarily to provide significantly improved corrosion resistance. The abrasion resistance for this alloy at 20 °C was superior to Stellite 6B; however, the comparatively high resistance was not retained at the higher test

Fig. 9. A typical EDX trace for oxide scales formed on a ferrous material surface during reciprocating stroke abrasion testing.

Fig. 10. Volume losses from sliding abrasion at 20 °C and 350 °C for wrought Co-based alloys.

Fig. 11. Wear scars for wrought Co-based alloys at 20 °C, (a) Stellite 6B, (b) Stellite 712, and (c) Tribaloy 400.

Fig. 12. Wear scars for wrought Co-based alloys at 350 °C, (a) Stellite 6B, (b) Stellite 712, and (c) Tribaloy 400.

temperature. Tribaloy 400 (Sample K) contains hard intermetallic phases of Mo and Si, which provide excellent properties over a wide range of temperatures as highlighted by the low volume loss results. All counterbody samples exhibited low losses.

3.4. Coatings/overlays

The chrome carbide bulk weld overlay (Sample L), showed improved abrasion resistance (Fig. 13) over the original low alloy steel and the CWI castings (Samples G and H), with the results comparable to powder metallurgical tool steels. With this material neither the overlay thickness nor deposit adhesion are likely to be an issue, although possible checking of the surface may cause entrapment of hard particles. This may lead to more aggressive two-body abrasion, thereby increasing the wear of the counterbody, or more constructively the provision of a 'dead-bed' effect, minimising contact between the two surfaces thus reducing the overall wear.

The HVOF WC-based coating exhibited exceptionally high wear resistance (Fig. 13). The usefulness of this type of coating may be limited because of restricted thickness/toughness. HVOF coatings have typically been deposited with thicknesses in the order of 200–400 μm , however, newer developments are allowing coatings up to 5–6 mm thick to be applied.

Fig. 13. Volume losses from sliding abrasion at 20 °C and 350 °C for chrome carbide overlay and HVOF WC-based coating.

4. Discussion

Table 3 shows a ranking of the 13 materials assessed at 20 °C and 350 °C, with respect to the measured volume losses for the specimen materials. The rankings varied only slightly when the volume losses of the counterbodies were taken into account. It was evident from the results (Figs. 3, 6, 10 and 13) that the abrasion resistance at 20 °C of the low alloy steel (Sample A, i.e. the current base material for drag chain links), was significantly inferior to the majority of specimens apart from the hypoeutectic CWI. At 350 °C, the abrasion resistance of Sample A appeared to show some improvement due to the formation of a protective oxide scale (Fig. 4c), however, it was still inferior when compared to P/M tool steels or the HVOF WC-based coating. The carburising treatment (Sample B), applied to the low alloy base steel for the commercial application, provided considerably enhanced wear resistance at 20 °C, however, it was less effective at 350 °C.

SEM examination of the carburised surface (Fig. 5) showed evidence of micro-cutting and indentation. This highlighted the difference in hardness of its surface compared to the non-carburised

Table 3

Performance rankings for all specimens at 20 °C and 350 °C.

Sample	Material class	Performance ranking at 20 °C	Performance ranking at 350 °C
A	Existing drag chain conveyor material	13	10
B		10	6
C	AR steels	5	11
D		2	8
E	Tool steels	3	2
F		4	3
G	White irons	12	12
H		9	7
I	Wrought Co-based alloys	11	8
J		8	13
K		7	5
L	Overlays/coatings	6	4
M		1	1

Key: 1—best, and 13—worst.

Fig. 14. SEM images showing (a) specimen with high hardness due to the presence of reinforcing particles (Sample E), and (b) formation of a coherent oxide layer (Sample M).

low alloy base steel (Sample A), which exhibited a highly deformed topography with evidence of plastic deformation and the formation of large debris particles.

The AR steels exhibited excellent abrasion resistance at 20 °C, however, the high volume losses recorded by these materials at 350 °C were expected as they are not designed for use at elevated temperatures. They exhibit reduced hardness at temperatures above 250 °C combined with tempering/softening characteristics. Although neither the AR steels (Samples E and F) nor the CWI castings (Samples G and H) appeared to offer the high temperature protection capability required for the current application, the results contained in Fig. 6 clearly showed that the test procedure could distinguish between the sliding abrasion resistance of materials and confirmed the influence of hardness on the abrasive wear of opposing surfaces.

Of the materials examined, it was considered that two predominant protective mechanisms were operating for the flat specimens (Fig. 14):

- (1) high hardness preventing damage by the abrasive, and
- (2) formation of a coherent protective oxide layer enhancing the surface.

Both provided wear protection that significantly reduced volume losses from the specimen and counterbody, typically by retaining a three-body wear mechanism.

Whilst the development and presence of oxide scales on certain material couples afforded some protection against abrasive wear, the degree of formation and protection provided varied widely. In the low alloy steel (Sample A) and the hypoeutectic CWI (Sample G), where high volume losses were recorded, the adherence of an oxide scale has obviously been inhibited by the presence of the abrasive. This prevented a coherent layer being formed and instead produced an intermittent oxide scale of little benefit. For more resistant materials, the formation of oxide debris from both the specimen and counterbody was followed by the comminution, agglomeration and apparent sintering of such particles to produce an intermittent layer across the surface of both opposing faces.

The lowest losses were obtained with the P/M high speed tool steel (Sample E) and the HVOF WC-based coating (Sample M). Similar wear mechanisms were evident for the P/M tool steels (Samples E and F) at both test temperatures. The influence of the fine, hard carbides distributed widely throughout the martensitic matrices, in providing enhanced wear resistance was readily apparent. The well-dispersed WC particles in the HVOF coating also provided superior wear protection, however, the mechanical bond formed by a HVOF coating on the substrate is unlikely to be sufficient for the proposed application and could lead to premature failure of components as a result of coating spallation. The softer substrate material, with much lower resistance would degrade rapidly if the coating

were breached. Spray and fuse options may help to overcome this deficiency.

The distribution of comparatively coarser primary and eutectic M_7C_3 carbides in the cast CWI specimens (Sample G and H) did not provide the same level of protection as did the fine vanadium and tungsten carbides in the P/M tool steels. It is therefore deemed that the use of such higher alloyed materials, as possible replacements for carburised low alloy steel in this service, could not be justified on technical nor economic grounds.

The Co-based alloys offer obvious potential for the current application as a result of their excellent high temperature wear resistance, retention of hardness at elevated temperature, oxidation resistance and anti-galling properties. The hardness difference between the O1 tool steel and Co-based alloys, however, is significant. With the softer Co-based alloys a two-body abrasion mechanism is promoted with the abrasive embedding in the specimen surfaces and causing higher wear of the counterbody. The results, however, indicated relatively low volume losses for the counterbodies at both temperatures, suggesting that the difference in hardness was not the only contributing factor. Of the three materials, Stellite 712 (Sample J) provided the highest resistance at 20 °C, however, the enhanced wear resistance produced by replacing the W with Mo was not retained at 350 °C. It was surmised that the excellent wear resistance shown by the wrought Tribaloy 400 at 350 °C was due to a combination of hard intermetallics and the volume percentage of Laves phases present.

5. Conclusions

The results presented identified several materials that exhibit potential for improving the service life of the drag conveyor components.

A powder metallurgical high speed tool steel and a WC-based HVOF coating exhibited the highest elevated temperature abrasive wear, mainly as a result of their high hardness and volume fraction of hard carbide constituents. Both materials offer potential as replacements for the proposed drag chain application. The selection of the HVOF coating, however, is questioned due to its relatively low thickness and the possibility for coating spallation.

Material cost will obviously influence choice, however, it is a possibility that materials could be used either as bulk castings or as bushings/cladding within the link bore. This would therefore enable some of the higher cost materials with improved wear resistance to be utilized.

The suitability of the Cameron-Plint TE77 machine for assessing materials under high temperature abrasive wear has been demonstrated.

Analysis of two AR steels with different hardness highlighted the capability of the test procedure for assessing the behaviour of materials under abrasive wear conditions. As expected, they exhibited

excellent wear resistance at 20 °C but significantly lower reduced resistance at 350 °C. These observations correlated with lower hardness at elevated temperature and possibly tempering influences.

Acknowledgements

The authors would like to express their thanks to colleagues in the Wear and Corrosion Group for their technical assistance and recognize NRC management and members of the Collaborative NRC/Industry Mining Wear Materials for their support and sponsorship of this work.

References

- [1] D.A. Rigney, W.A. Glaeser, The significance of near surface microstructure in the wear process, *Wear* 46 (1978) 241–250.
- [2] M. Kirchgassner, E. Badisch, F. Franek, Behaviour of iron-based hardfacing alloys under abrasion and impact, *Wear* 265 (5–6) (2008) 772–779.
- [3] M.A. Bejar, E. Moreno, Abrasive wear resistance of boronized carbon and low-alloys steels, *Journal of Materials Processing Technology* 173 (3) (2006) 352–358.
- [4] A.J. Gant, M.G. Gee, Abrasion of tungsten carbide hardmetals using hard counterfaces, *International Journal of Refractory Metals and Hard Materials* 24 (1–2) (2006) 189–198.
- [5] G.B. Stachowiak, G.W. Stachowiak, O. Celliers, Ball-cratering abrasion tests of high-Cr white cast irons, *Tribology International* 38 (11–12) (2005) 1076–1087.
- [6] I.A. Inman, S.R. Rose, P.K. Datta, Development of a simple 'temperature versus sliding speed' wear map for the sliding wear behaviour of dissimilar metallic interfaces, *Wear* 260 (2006) 919–932.
- [7] J. Glascott, F.H. Stott, G.C. Wood, The effectiveness of oxides in reducing sliding wear of alloys, *Oxidation of Metals* 24 (3/4) (1985) 99–113.
- [8] I.A. Inman, P.K. Datta, H.L. Du, J.S. Burnell-Gray, S. Pierzgaliski, Q. Luo, Studies of high temperature sliding wear of metallic dissimilar interfaces, *Tribology International* 38 (2005) 812–823.
- [9] J.C.G. Milan, M.A. Carvalho, R.R. Xavier, S.D. Franco, J.D.B. De Mello, Effect of temperature, normal load and pre-oxidation on the sliding wear of multi-component ferrous alloys, *Wear* 259 (2005) 412–423.
- [10] I.A. Inman, S.R. Rose, P.K. Datta, Studies of high temperature sliding wear of metallic dissimilar interfaces II: Incoloy MA956 versus Stellite 6, *Tribology International* 39 (2006) 1361–1375.
- [11] I.A. Inman, S. Datta, H.L. Du, J.S. Burnell-Gray, Q. Luo, Microscopy of glazed layers formed during high temperature sliding wear at 750 °C, *Wear* 254 (2003) 461–467.
- [12] B.V. Manoj Kumar, B. Basu, M. Kalin, J. Vizintin, Load-dependent transition in sliding wear properties of TiCN-WC-Ni cermets, *Journal of the American Ceramic Society* 90 (5) (2007) 1534–1540.
- [13] P. Blau, Mechanisms for transitional friction and wear behaviour of sliding metals, *Wear* 72 (1981) 55–66.
- [14] F.H. Stott, D.S. Lin, G.C. Wood, The structure and mechanism of formation of the 'glaze' oxide layers produced on nickel-based alloys during wear at high temperatures, *Corrosion Science* 13 (1973) 449–469.
- [15] F.H. Stott, G.C. Wood, The influence of oxides on the friction and wear of alloys, *Tribology International* 11 (1978) 211–218.
- [16] J. Galligan, A.A. Torrance, G. Liraut, A scuffing test for piston rig/bore combinations Part 1. Stearic acid lubrication, *Wear* 236 (1999) 199–209.
- [17] Standard test method for linearly reciprocating ball-on-flat sliding wear, ASTM Standard G 133–02.
- [18] L. Prchlik, S. Sampath, Effect of the microstructure of thermally sprayed coatings on friction and wear response under lubricated and dry sliding conditions, *Wear* 262 (2007) 11–23.
- [19] H. So, R.C. Lin, The combined effects of ZDDP, surface texture and hardness on the running-in of ferrous metals, *Tribology International* 32 (1999) 243–253.
- [20] P.J. Blau, M. Walukas, Sliding friction and wear of magnesium alloy AZ91D produced by two different methods, *Tribology International* 33 (2000) 573–579.
- [21] A. Pauschitz, M. Roy, F. Franek, On the chemical composition of the layers formed during sliding of metallic alloys at high temperature, *Tribologia* 188 (2003) 127–144.
- [22] R.J. Dawson, S. Shewchuk, J.E. Pritchard, Selection and use of hardfacing alloys, *Welding Journal* 1 (39) (1982) 15–23.