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Assessment of oxide scales influence on wear damage of HSM work rolls

O. Joos^{a,*}, C. Boher^a, C. Vergne^b, C. Gaspard^b, T. Nylén^c, F. Rezaï-Aria^a

^a CROMeP-Ecole des Mines d'Albi-Carmaux, Albi, France

^b AKERS Belgium, Seraing, Belgium

^c AKERS A.B., Sweden

Abstract

Improvement of hot rolling process involves the lengthening of rolling campaigns. This can be achieved through the wear resistance improvement of work roll grades. The wear damage observed in service on the hot working rolls is the result of a complex interaction between oxidation, friction and thermal fatigue. An approach is to assess the coupled effect of oxidation and friction on the overall tribological behaviour at high temperature. A first step consists in a good knowledge of the material behaviour against each stress.

Tribological behaviour of roll grades at high temperature is indeed strongly affected by the nature, the thickness and the thermo-mechanical properties of their oxide scales involved into the contact. All these parameters depend on roll grade microstructure.

An experimental methodology has also been performed to assess the influence of the roll grade microstructure on their tribological behaviour at high temperature. It constitutes the subject of the present paper.

Results have focussed on high temperature friction tests and on the analysis of oxide morphologies (through TGA tests and environmental SEM, ESEM, observations). Nevertheless this approach does not aim to reproduce strictly rolling conditions, but only to analyse the chemical and mechanical response of roll grades regarding thermal and mechanical stresses involved in hot rolling.

Material investigations have shown heterogeneous oxidation according to the different microstructural states and the environmental testing conditions. A particular scale roughness, depending on grades and oxidation conditions, and influencing the tribological behaviour, has been brought out.

Keywords: Wear; Friction; Hot rolling; Oxidation

1. Introduction

The development of high speed steels (HSS) in the early of 1990s aims at substituting HSS for high chromium cast irons (HiCr) in the finishing stands of hot strip mills [1]. The roll damage mechanisms usually observed in-service are abrasion, adhesion, thermal fatigue and oxidation [2–5].

Typical microstructures of HiCr and HSS are well described in the literature [2–9]. It should be noticed that the name of HSS is relative to a grade family with a larger range of chemical composition than HiCr one.

Generally, HSS differ to HiCr by their lower carbon contents and their higher carbide former contents. The differences in chemistry and heat treatment allow to modify the nature and distribution of both eutectic and secondary carbides [10].

From these first developments, it resulted that HSS wear resistance is much higher in comparison with HiCr [11]. MC carbides, more particularly VC carbides, are normally the main carbides in HSS, whereas M_7C_3 carbides are preponderant in HiCr. MC carbides are harder and their distribution as secondary precipitates in the matrix is relatively fine and homogeneous [2,9]. The wear resistance of the HSS matrix at high temperature is also higher than HiCr and performances of hot strip mills are consequently increased (in terms of lengthening of rolling campaigns).

Nevertheless an increase of friction [2,12], peeling phenomena, and sometimes a drop of spalling resistance, were

* Corresponding author. Tel.: +33 563493224; fax: +33 563493099.
E-mail address: olivier.joos@enstimac.fr (O. Joos).

industrially observed in the case of HSS grades. All these phenomena tend to increase the mill power consumption and to alter the surface quality of the strip due to rolled-in-scale defects [13].

Literature attributes this ambivalent tribological behaviour of HSS to [2]:

- A preferential wear of the matrix, which microhardness is too low compared with the hardness of MC eutectic carbides.
- A lower adhesion resistance due to a lower carbide volumetric fraction in comparison with HiCr.
- The fragility of MC carbides that can be removed during contact and lead to gripping.

Next developments consisted in finding for both grades a compromise in order to:

- Ensure a high wear resistance with hard eutectic carbides and homogeneously distributed small secondary carbides [14].
- Maintain a good roughness retention capacity with a reduced hardness difference between matrix and eutectic carbides [11,14].
- Obtain a high resistance to thermal fatigue with eutectic carbides relevant regarding the crack nucleation and forming discontinuous primary carbide networks to limit crack propagation paths [3,7,11].
- Have good adhesion and spalling resistances, by the way of high carbide volumetric fraction and without M_7C_3/M_2C carbide network [2,13].

Researches allow for example to reduce the friction coefficient of HSS without decreasing their wear resistance in a large scale [14].

The grade oxidation behaviour holds an important part in wear and friction behaviour: the oxide scale has to be homogeneous, thin and adherent to be efficient against wear. A high carbide fraction (as M_2C) favours oxidation because the interfaces with matrix are excellent sites of nucleation for oxidation [2,8,11,14]. In HSS, M_7C_3 carbides are very resistant to oxidation, whereas MC carbides and the matrix oxidise heavily. M_2C carbides have a halfway behaviour [11].

Oxidation rate depends also on the chromium content, the nature and the distribution of carbides [11]. Moreover, the tribological behaviour is strongly affected by the nature, the thickness, the adherence, and the morphology of the oxide scales [9]. On the one hand, thick oxide layers induce a lower friction coefficient and act as a lubricant. On the other hand, thin layers adhere better to the substrate and they are also more difficult to remove [15]. The mechanical properties of scales are important: a soft oxide scale may induce a decrease in wear and friction while a hard layer is abrasive, increasing wear and friction.

Previous experimental works [1,4–6,12] compared some HSS and HiCr grades in studying their tribological behaviour at different temperatures. The large differences between experimental set-ups (wear test device configuration, counter-part body, normal load, sliding speed), and between used grades, prevent from making general comparisons and conclusions and lead to still debated results.

De Mello and co-workers [4,5] brought out a stabilization period of the friction coefficient at the beginning of PinT wear tests for both grades. This period corresponds to the formation of oxidized regions at the interface between the two rubbing surfaces. The higher the temperature is, the shorter the period of stabilization is. Moreover, for both grades, higher the temperature is, lower is the friction. At 20 °C, the wear rate of HiCr is five times higher than HSS. At a higher temperature, friction curves and SEM observations of wear scar show that the tribological behaviour and wear mechanisms of both grades are quite similar.

Pellizzari et al. [6] studied the wear behaviour of several HSS grades and a HiCr grade at 700 °C with an Amsler tribometer. They showed that abrasion and oxidation are here the main wear mechanisms occurring for both grade families. High hot hardness of HSS makes the wear rate lower in comparison with HiCr, because of a higher resistance to abrasion and a higher oxide scale load bearing capability. In addition, they explained the tendency of HiCr rolls to decrease in roughness with the increasing rolling distance by a lower oxidation resistance in comparison with HSS. That allows to maintain a low surface roughness, despite the high matrix wear rate.

Finally, Vergne et al. [1,12] showed that the coefficient of friction, on a pin-on-disc tribometer, is higher for HSS than for HiCr, only if the rubbing counter-face temperature is lower than 650 °C. Above 650 °C, the trend is inverted. Activation energy has been determined by thermogravimetric analysis in the thermal range of 650–950 °C. For a HSS grade, the value is 160 kJ/mol, whereas for HiCr the value reaches 330 kJ/mol. These values are representative respectively of the oxidation of iron alloys and the oxidation of chromium iron alloys. Oxide scales are also thin and adherent on HiCr.

The main objectives of the present study are to identify and assess wear mechanisms involved in the hot tribological behaviour for the two roll grades through coupled analysis methods [1,12]. The effect of temperature on friction, through the formation of oxide on the pins, is studied. The thermal fatigue behaviour is not taken into account in this approach.

2. Materials, equipments and experimental set-ups

2.1. Materials

The chemical compositions of both roll grades involved in this study are given in Table 1.

The HSS microstructure is made of a matrix of tempered martensitic and a high fraction of primary carbides and secondary hardening precipitation carbides. Primary carbides are essentially:

Table 1
Chemical composition (in weight percent) of the two grades

	C	Mn	Cr	Mo + W + V	Mo + V
HSS	1–2	0.5–1	4–6	8–9	–
HiCr	2–3	0.5–1	15–20	–	2–4

- MC carbides, rich in vanadium, less in iron, chromium, molybdenum and tungsten;
- M₂C carbides, rich in molybdenum, less in chromium, iron and vanadium;
- M₇C₃ carbides, rich in chromium, less in iron, vanadium and molybdenum.

The two last carbides are often mixed.

As HSS, the HiCr microstructure is made of a tempered martensitic matrix with a high fraction of primary carbides and secondary hardening precipitation carbides. Nevertheless, primary carbides are essentially M₇C₃ carbides, rich in chromium. M₂C carbides, rich in molybdenum, are present too.

In conclusion, the significant difference between both microstructures lies in two points:

- The volumetric fraction of carbides rich in molybdenum is much higher in HSS than in HiCr.
- The carbides rich in chromium are most widely present in HiCr whereas carbides rich in vanadium are preponderant in HSS.

2.2. Equipments and experimental set-ups

An experimental methodology has been performed to correlate the work roll grade microstructure to oxidation and high temperature tribological behaviours. It consists in confronting experimental results obtained from:

- High temperature tribological tests completed by SEM observations and chemical analyses.
- SEM observations on TGA samples (completed by chemical analyses).
- In situ growth oxide tests (high temperature environmental SEM (ESEM)).

2.2.1. High temperature tribological tests

They have been performed on high temperature pin-on-disc tribometer [1,12]. The device is not a hot rolling simulator, but this laboratory apparatus may allow to understand oxidation wear mechanisms involved in hot rolling.

In this configuration, the pin represents the tool and is made of a work roll grade (HSS or HiCr). The disc represents the rolled material and is made of a strip material (AISI 1018). The chemical composition of AISI 1018 is given in Table 2. Its structure is ferrite-pearlitic and the mean hardness is around 170 HV.

The disc, which has a continuous rotating motion, is heated by high frequency induction. The disc surface temperature is

Table 2
Mean chemical composition (in weight percent) of AISI 1018

Fe	Bal.
C	0.18
Si	0.26
Mn	0.62
Cr	0.15
Cu	0.18

Table 3
Tribological tests conditions

Disc temperatures (°C)	Normal load (N)	Sliding speed	Atmosphere
20 650 950	20	0.345 m/s (300 tr/min)	Ambient air

monitored by an infrared pyrometer. The spherical-ended pin (curvature radius of 20 mm) is heated during contact by conductive, radiative, convective thermal transfer and friction-released thermal energy.

During a tribological test, the disc is heated up to the test temperature while the pin is kept outside the contact at room temperature. When the setting temperature is reached, the pin is put on the disc, the load is applied and sliding starts.

In a hot strip mill, a scale breaker is often found between the rougher and the finishing stands in order to remove the strip oxide layer. In these conditions, the strip oxide scale is rather thin as its entry in the finishing stands. In our test configuration, at the beginning of friction, the disc oxide scale is thicker than in the industrial conditions but not enough to take in charge all the tribological contact.

Tests conditions are summarised in Table 3.

During each friction test, friction forces are recorded. Energetic power dissipated by friction is calculated in order to compare the tribological behaviour of both grades (Eq. (1))

$$P = \frac{F_N V}{\Delta t} \int_0^{\Delta t} \mu dt \quad (1)$$

where P is the power dissipated by friction (J/s); F_N , the normal load (N); V , the linear sliding speed (m/s); Δt , the friction test duration (s); and μ , the Coulomb friction coefficient.

2.2.2. SEM observations on TGA samples

Operating conditions for the thermogravimetric tests [1,12] are given below (Table 4).

Surface as well as cross-section observations on TGA samples are compared with those made on the pins after friction tests to assess the nature and the morphology of oxide scales.

2.2.3. Environmental SEM observations

Isothermal in situ oxidation is carried out in an environmental scanning electron microscope ESEM-FEG. In order to reduce the number of samples, an only thermal cycle with three successive temperature stages is carried out (Fig. 1). The temperature is recorded by thermocouple close to the heating region, and

Table 4
Operating conditions of TGA tests

Atmosphere	Temperatures (°C)	Duration (h)
Ambient air	650 800 950	1–2–3

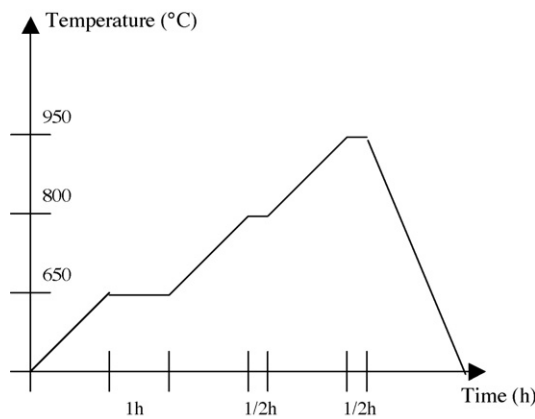


Fig. 1. Temperature cycle in ESEM tests.

could be slightly higher than the real temperature of the sample. The oxygen partial pressure is always fixed to 0.25 Torr, and is consequently much lower than in TGA or tribological tests. Nevertheless, thermodynamic reactions and phase reactivity occurring during oxidation are not changed in comparison with atmospheric pressure oxidation tests. The test atmosphere is the laboratory air. The heating and cooling rates are in agreement with the TGA tests [1,12].

This equipment allows to understand the growth mechanisms of oxide scales (correlation between microstructure and oxide morphology, phase reactivity in oxidative ambience) and to give information about oxide involved in friction contact.

3. Results

3.1. Study of tribological behaviour

3.1.1. Macroscopic approach through friction curves

The evolution of the Coulomb friction coefficient versus the disc temperature is displayed in Fig. 2. The variation of the energetic power dissipated by friction is given in Fig. 3.

For both grades, friction coefficient decreases with disc temperature. Values lower than 0.5 are only reached for disc temperatures higher than 650 °C. For a disc temperature of 20 and 650 °C, the coefficient of friction and the power dissipated by friction are higher for HSS than HiCr. For a disc temperature of 950 °C, the trend is inverted: the power dissipated by friction goes on to drop for HSS while it keeps quite constant for HiCr.

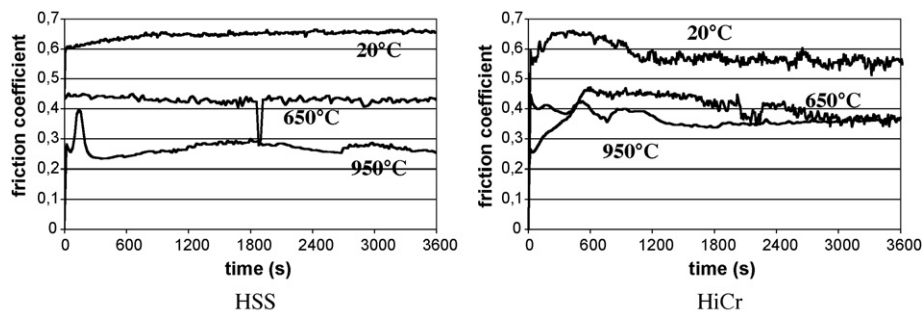


Fig. 2. Typical friction curves (Coulomb coefficient vs. time) for both grades.

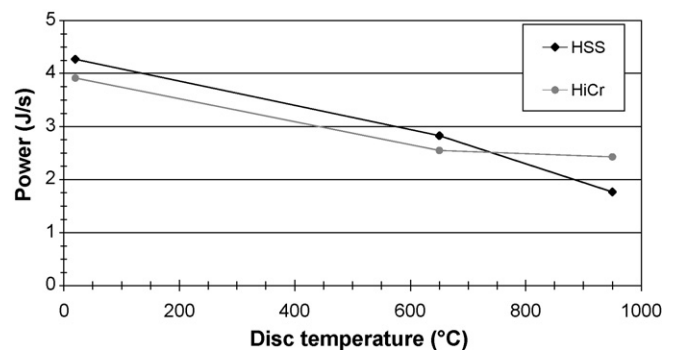


Fig. 3. Energetic power dissipated by friction for both grades.

For HSS, the running-in period (instability of friction coefficient) is short. Then, the friction coefficient remains stable, whatever the temperature.

Contrary to HSS, there is strictly no running-in or stability period for HiCr.

For the same sampling rates, the HiCr friction coefficient is locally and macroscopically less stable compared to HSS friction curves.

3.1.2. Microscopic approach through pin SEM observations

On the following figures, the coarse white arrows indicate the sliding direction.

At 20 °C, strips of abraded and agglomerated debris are observed on the wear track for both grades. These strips are finer and more homogeneously distributed in the case of HSS pins. Between strips, matrix and carbides are not oxidised at all. Moreover, the carbides could be considered as large asperities, which retain oxide debris. Shedding of carbides is observed only for HiCr (Fig. 4).

For a disc temperature of 650 °C, the surface is partially covered by oxide strips, composed of compacted debris. In these iron oxide strips, residues of chromium are found only on HiCr pin, but with a very low percent. In the case of HSS, the light areas correspond to sintered iron oxide, whereas in HiCr they correspond to the matrix slightly oxidised (Fig. 5).

At 950 °C (Fig. 6a and b), the rubbing surface is mainly composed of sintered and glazed oxides that take in charge the contact. The regions close to glazed surfaces are surrounded by porous oxidised areas and rounded oxide debris. The density of re-oxidation cells attests the high level of mechanical stresses

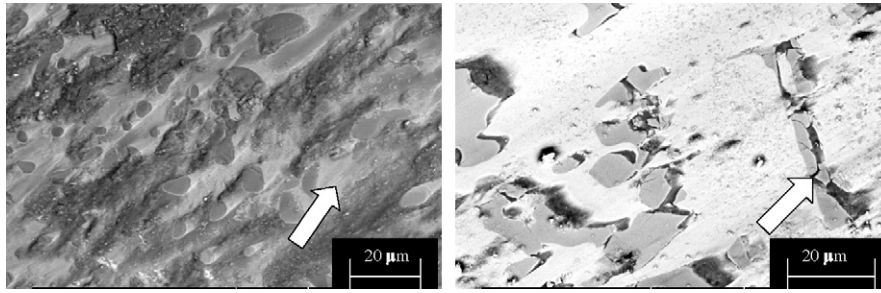


Fig. 4. Wear scar for HSS (left) and HiCr (right) for a disc temperature of 20 °C.

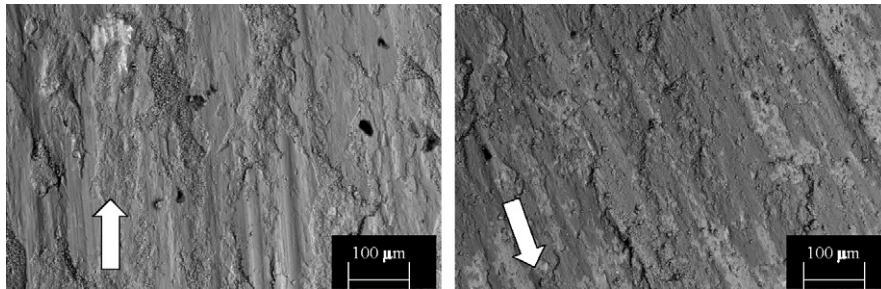


Fig. 5. Wear scar for HSS (left) and HiCr (right) for a disc temperature of 650 °C.

achieved during the friction tests. In the case of HiCr, the glazed oxide scale presents cracks.

The surface observations on the pin wear scar have been completed by observations in cross-section. The cross section is taken parallel to the sliding direction. SEM observations out of wear scars are added to show the effect of thermo-mechanical contact stresses.

Out of wear scars (Fig. 7a and b), a duplex, continuous and thick oxide scale with protuberances is observed on HSS. On HiCr, a preferential oxidation of the matrix leads to a thin and discontinuous oxide scale (protuberances).

In the wear scars of HSS pins (Fig. 7c and d), contact pressure and abrasion lead to a very smooth and compacted oxide scale, thick enough to support the contact. On HiCr, the oxide appears essentially above the matrix and oxide debris are issued from matrix oxidation. The scale is still very thin and discontinuous.

SEM observations (Fig. 7) well exhibit two oxide scale morphologies on the pins after the friction tests. These morphologies influence the tribological behaviour of grades. In the next section, the aim consists in understanding the influence of grade

microstructures on oxide scale morphologies with static oxidation tests.

3.2. Morphology, nature of the oxide scales and the relation to microstructure

3.2.1. Global characterization of oxide scales

Experiments of thermogravimetric analysis (TGA) give data on global oxidation rates [1,12]. Morphology and nature of oxide scales can be studied moreover.

For both grades, protuberances grow at the surface at a temperature higher than 800 °C. The duration of oxidation for a given temperature leads to an increase of both oxide scale surface roughness and surface fraction covered by protuberances. (Fig. 8a and b).

These evolutions versus oxidation duration have not been yet quantified by topography measurements. Nevertheless, SEM observations show that, for given sets of parameters, the oxide scale surface roughness is higher for HSS than for HiCr, whereas the protuberance surface fraction covered by protuberances

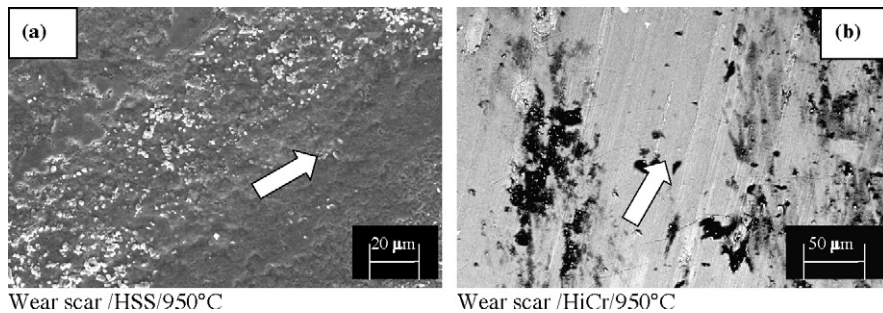


Fig. 6. Surface SEM observations of pin wear scar for disc temperature of 950 °C for HSS (left) and HiCr (right).

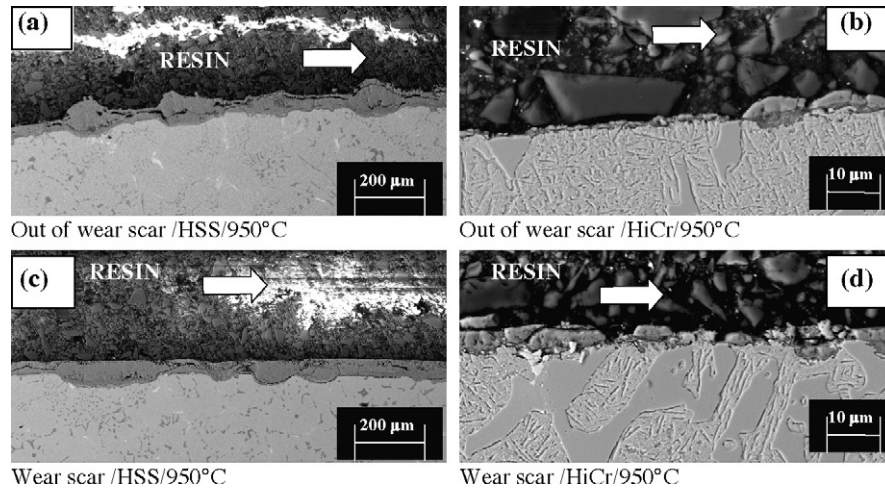


Fig. 7. Cross-section SEM observations of pin for disc temperature of 950 °C for HSS (left) and HiCr (right).

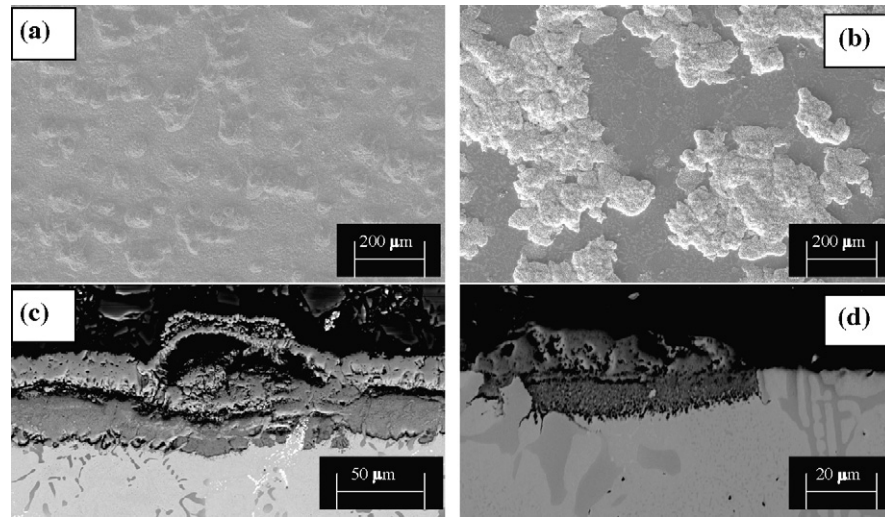


Fig. 8. Surface SEM observations of oxide scale for HSS (a) and HiCr (b), cross-section SEM observations of oxide scale for HSS (c) and HiCr (d), After TGA test at 800 °C for 3 h.

becomes much higher for HiCr than for HSS for long oxidation duration.

The main difference between the two grades is that oxide scales are composed of protuberances surrounded by a thick and duplex base oxide scale for HSS, whereas the oxide scale is composed only of protuberances for HiCr. In this last case, oxidation-free zones correspond to coarse M_7C_3 carbides, leading to a very discontinuous oxide scale (Fig. 8c and d).

The chemical composition of oxides versus their morphology is given in Table 5 for both grades.

3.2.2. Comprehension of growth mechanisms of oxide scales

ESEM observations are carried out for both grades. The most interesting steps of oxidation are illustrated in this section.

3.2.2.1. HSS grade. For the HSS grade, during the first temperature ramp, a slight oxidation of matrix/mixed carbides (M_2C and M_7C_3) interfaces occurs near 350 °C. (Fig. 9a—arrows1).

The oxidation of the matrix at the level of dendritic cells begins near 400 °C. Oxide of the matrix presents a granular morphology. The interface between matrix and M_7C_3 carbides is less oxidised (Fig. 9b—arrow 2).

Between 400 and 650 °C (Fig. 10a), oxidation of M_2C – M_7C_3 /matrix interfaces and dendritic cells goes on. The oxidation of interfaces between matrix and MC carbides begins

Table 5
Morphology and chemical composition of oxide scales on TGA samples

Zones	HSS	HiCr
Protuberances		
External layer	Pure ferrous oxide	Pure ferrous oxide
Internal layer	None	Chromium-ferrous oxide
Duplex base scale		
External layer	Pure ferrous oxide	None
Internal layer	Alloyed (Cr, V, Mo) ferrous oxide	None

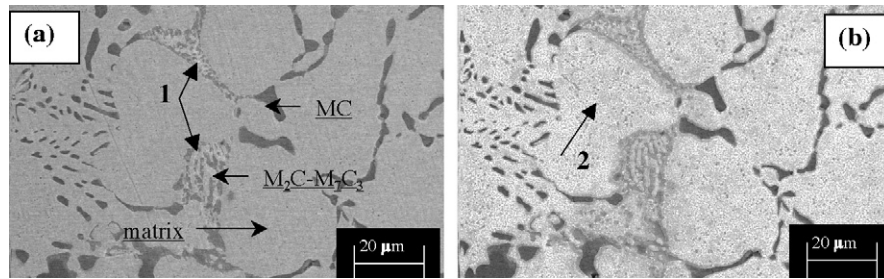


Fig. 9. (a) M₂C/M₇C₃ surrounding matrix oxidation at 350 °C for HSS grade, (b) dendritic cells oxidation at 400 °C for HSS grade.

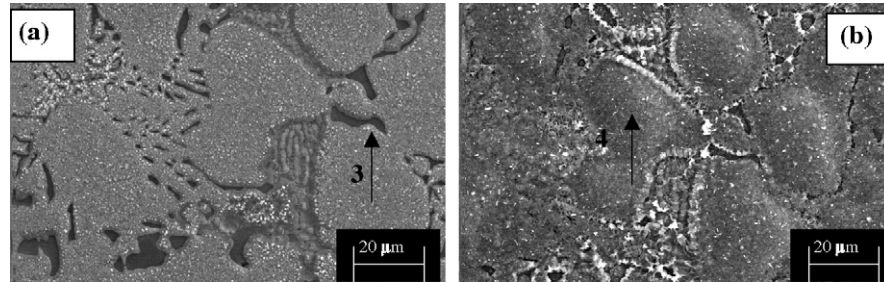


Fig. 10. (a) M₂C/matrix and M₇C₃/matrix interfaces oxidation between 400 and 650 °C for HSS grade, (b) MC carbides oxidation at 650 °C for HSS grade and growth in-depth of matrix oxide scale.

(Fig. 10a—arrow 3). These carbides are not oxidised. The oxide growth is higher at the matrix/M₇C₃ carbides interfaces than at the matrix/M₂C carbides interfaces. Both morphologies tend to become granular.

At 650 °C (Fig. 10b), MC carbides oxidation occurs. They are simultaneously covered by the lateral growth of the matrix/MC carbides interface oxide and by their core oxidation. The slight growth in depth of the matrix oxide scale is also observed (Fig. 10b—arrow 4).

During the stage at 800 °C, lateral and in-depth growth of the matrix oxide takes place rapidly and induces the formation of protuberances. Primary carbides are totally covered, even the chromium-rich carbides.

At 950 °C, the oxide scale, that covers the network of MC carbides grows rapidly and the oxidation products are very porous grains.

At the end of the heating stage, the oxide scale on the HSS ESEM specimens is composed of:

- Protuberances with compact and cuboidal grains, which correspond to the oxidation of dendritic cells.

- An oxide scale constituted of porous grains (which corresponds to the oxidation of the surrounding matrix oxide covering MC carbides), and with a second morphology resulting from the oxidation of M₂C/M₇C₃ carbides and their interfaces with matrix.

3.2.2.2. *HiCr grade.* For HiCr, a very slight oxidation of the dendritic cells begins near 300 °C. A very thin and homogeneous oxide scale grows on M₂C carbides at this temperature.

At 400 °C (Fig. 11a), fine cuboidal oxide crystallites nucleate on the M₇C₃ carbides (arrow 1). This oxidation is heterogeneous. A porous scale grows on dendritic cells (arrow 2). The oxidation rate is higher near the M₂C/matrix interface (arrow 3).

From 650 to 950 °C, oxidation of dendritic cells remains low and homogeneous. The scale is quite porous.

At 650 °C, the oxidation rate at the interface M₂C/M₇C₃ increases (Fig. 11b—arrow 4): only grains and needles compose the morphology. The oxidation of M₇C₃ and MC carbides is slight.

From 800 to 950 °C, growth of oxide needles at M₂C/M₇C₃ interface continues. The needles become coarse.

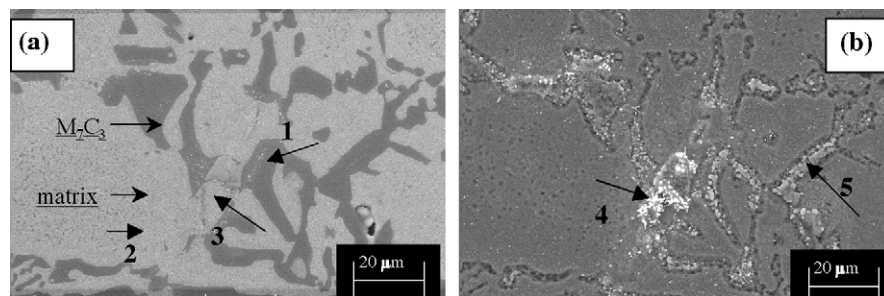


Fig. 11. (a) M₂C/matrix oxidation at 400 °C for HiCr grade, (b) M₂C/M₇C₃ interface oxidation between 650 and 950 °C for HiCr grade.

From 950 °C, the oxidation rate of M_7C_3 carbides increases but the scale seems to be very thin (Fig. 11b—arrow 5). Nevertheless, at the end of heating stage, oxide scale morphology is similar to this observed at 650 °C.

4. Discussion

SEM and ESEM (in ambient air) observations highlight the large influence of grade microstructures on the final morphology of oxide scales.

Interfaces between carbides and matrix are preferential sites for oxide nucleation for both grades. Microstructures of HSS allow to form thick, duplex and continuous oxide scales, whereas the oxide scales are thin and very discontinuous for HiCr. The matrix is very prone to oxidation, in comparison with carbides, especially chromium-rich carbides. Roughness of oxide scales is linked to the presence of protuberances surrounded by a thick base oxide scale for HSS, to oxide protuberances surrounded by oxidation-free areas for HiCr.

The differences in microstructure allow to explain these two oxidation behaviours.

ESEM results confirm that for HSS, the matrix is poor in chromium and, in this way, less resistant to oxidation in comparison with the HiCr matrix. Despite the depletion of chromium due to the precipitation of the M_7C_3 carbides, the HiCr matrix chromium content is high enough to ensure high oxidation resistance.

In addition, ESEM results show the contribution of the carbide distribution (fraction and size) in the oxidation mechanisms of the two grades.

These two contributions (matrix and carbide distribution), added to low oxidation resistances of matrix and carbides, lead to a continuous oxide scale at the surface of the HSS grade. In HiCr, the coarse carbides are resistant to oxidation. Their high fraction prevents from forming a continuous external oxide layer, which could totally cover the substrate surface.

The differences of oxide scale morphologies between TGA and ESEM specimens for HiCr could be explained by the very low oxygen partial pressure in ESEM tests and the high oxidation resistance highlighted in previous studies [1,12].

The different tribological behaviours of grades between 650 and 950 °C was previously [1,12] explained in considering mostly the influence of disc oxide scales. Nevertheless, SEM observations of worn pin surfaces give complementary results and the variations of friction coefficient versus the disc temperature for each grade seem to be well explained by nature of contact. These differences, summed up in Table 6 for HSS and in Table 7 for HiCr, provide complementary results for discussion.

For a disc temperature of 20 °C, the contact is metal against metal for both grades. The wear mechanism is abrasion. Debris attrition phenomena lead to the formation of oxide debris. The friction coefficient is high for both grades.

For a disc temperature of 650 °C, oxidation of the pin surface is low for both grades. The wear mechanism is still abrasion by disc oxide scale. The decrease of the friction coefficient for both grades could be only attributed to disc oxide layer that plays the role of solid lubricant.

For a disc temperature of 950 °C, the low oxidation resistance of HSS leads rapidly to the formation of a continuous oxide scale on the pin surface, thick enough to take in charge the contact. That contributes to the drop of friction in comparison with tests at 650 °C. At 950 °C the pin oxide scale contribution becomes important. In contrary to HSS, for friction tests at 950 °C, the peculiar microstructure and chemical composition of HiCr do not allow to form thick and continuous oxide scales on pin, which could contribute to the friction drop, as disc oxide scales. In this case, the pin contact surface is still quite similar to 650 °C tests and the friction coefficient remains constant.

Structure and roughness of pin oxide scales are quite similar to those observed on TGA samples for both grades. But the role of oxide scale protuberances, exhibited from TGA and ESEM

Table 6
Contact nature in tribological tests for HSS

Disc temperature (°C)	First bodies		Third body
	On pins	On discs	
20	Metallic substrate	Metallic substrate	Oxidised debris
650	Continuous oxide scale	Thin and continuous Fe_2O_3/Fe_3O_4 oxide scale	Oxidised debris
950	Thick and continuous glazed oxide scale	Thick and continuous ferrous $Fe_2O_3/Fe_3O_4/FeO$ oxide scale	Oxidised debris

Table 7
Contact nature in tribological tests for HiCr

Disc temperature (°C)	First bodies		Third body
	On pins	On discs	
20	Metallic substrate	Metallic substrate	Oxidised debris
650	Thin and discontinuous oxide scale + oxidation-free zones	Thin and continuous Fe_2O_3/Fe_3O_4 oxide scale	Oxidised debris
950	Thin and discontinuous glazed oxide scale	Thick and continuous ferrous $Fe_2O_3/Fe_3O_4/FeO$ oxide scale	Oxidised debris

experiments, during sliding is difficult to assess in case of HSS. The assumption is that, either the protuberances are abraded, or the vertical growth is constrained by contact pressure. Moreover, SEM observations showed that the external oxide layer on HSS TGA samples adhere poorly for the highest temperature tests. That might have an effect on HSS tribological behaviour during rolling through roll oxide scale removal.

5. Conclusions

The aim of this study is to link oxidation and high temperature tribological behaviours of two roll grades (HSS and HiCr) that differ strongly from their microstructure. During static oxidation tests, the contribution of matrix, carbides and interfaces between matrix and carbides induces the formation of continuous external oxide layers on HSS, and discontinuous external oxide layers on HiCr.

This difference of growth and morphology of oxide scales is still present on pin surfaces during the pin-on-disc friction tests. For a disc temperature below 650 °C, the decrease of the friction coefficient is essentially taken in charge by the disc oxide scale for both grades. Above 650 °C, the contribution of the pin oxide scale influences the friction evolution. For HSS, friction drops due to a thick and continuous pin oxide scale. In contrary, friction of HiCr remains constant because of thin and discontinuous pin oxide scales.

References

- [1] C. Vergne, et al., Contribution of laboratory tribological investigations on the performance appraisal of work rolls for hot strip mill, in: Proceedings of the Steel Rolling Conference, 2007.
- [2] M. Boccalini, A. Sinatora, Microstructure and wear resistance of high speed steels for rolling mill rolls, in: Proceedings of the 6th International Tooling Conference, Karlstadt University, September, 2002, pp. 425–437.
- [3] C.R. Serantoni da Silva, M. Boccalini, Thermal fatigue of high speed steels for rolls, in: ABRASION 2005 Conference, 2005, pp. 93–106.
- [4] J.C.G. Milan, et al., Effect of temperature, normal load and pre-oxidation on the sliding wear of multi-component ferrous alloys, *Wear* 259 (2005) 412–423.
- [5] J.D.B. De Mello, Tribological behavior of multi-component ferrous alloys, in: ABRASION 2005 Conference, 2005, pp. 19–45.
- [6] M. Pellizzari, et al., Tribological behaviour of hot rolling rolls, *Wear* 259 (2005) 1281–1289.
- [7] A. Molinari, et al., High speed steels for hot rolls with improved impact and thermal fatigue resistance, *Mater. Sci. Technol.* 18 (2002) 1574–1580.
- [8] A. Molinari, et al., Oxidation behaviour of ledeburitic steels for hot rolls, *Mater. Sci. Eng. A280* (2000) 255–262.
- [9] A. Molinari, et al., Primary carbides in spin cast HSS for hot rolls and their effect on the oxidation behaviour, in: Proceedings of the 6th International Tooling Conference, Karlstadt University, September, 2002, pp. 365–377.
- [10] C. Vergne, et al., Influence of oxide s on friction in hot rolling: experimental investigations and tribological modelling, *Wear* 260 (2006) 957–975.
- [11] D.B. Collins, Factors affecting the use of HSS rolls in the hot strip mill, in: 36th Mechanical Working and Steel Processing Conference Proceedings, vol. XXXII, Baltimore, MD, October, 1994, pp. 33–36.
- [12] C. Vergne, et al., Experimental investigations on the influence of oxidation of hot rolling working roll grades on their tribological behaviour against a strip material—Consequences at the industrial level, in: Proceedings of the 7th Tooling Conference.
- [13] P. Thonus, et al., Off-line analysis of the HSS roll behaviour in the hot strip mill by the use of a rolling load prediction model, in: 38th Mechanical Working and Steel Processing Conference Proceedings, vol. XXXIV, Cleveland, Ohio, 1997, pp. 43–49.
- [14] M. Pellizzari, et al., Wear and friction behaviour of high chromium iron and high speed steels for hot rolls, in: ABRASION 2005 Conference, 2005, pp. 189–198.
- [15] A. Munther, J.G. Lenard, The effect of scaling on interfacial friction in hot rolling of steels, *J. Mater. Process. Technol.* 88 (1999) 105–113.