CONSIDERATIONS ABOUT PROPERTIES AND BEHAVIOUR OF HSS IN HOT ROLLING[1]

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Abstract

The thermal fatigue and wear behaviour of five different steels for hot rolling have been investigated by means of laboratory tests and then related to their mechanical properties and microstructural features. The results obtained have been compared to the performances shown by the rolls in the plants.

Key words: Hot rolling; High speed steel; Thermal fatigue; Wear

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INTRODUCTION

Wear and thermal fatigue represent the most relevant causes for roll deterioration during hot strip rolling. These stresses do not act separately and the damage they produce is further enhanced by the occurrence of high temperature oxidation. The synergistic effect strongly limit the yield of rolls, usually expressed as tons rolled per millimetre, so that big efforts have been made in the last years to produce materials with improved properties.(1-4) The industrial experience learns, however, that it is often very difficult to evaluate their performances by trials on hot strip mills, due to the high intrinsic variability of the industrial process. So, it is not seldom to find strong discrepancies of performances for the same roll grade on different hot strip mills. The occurrence of stochastic events as mill accidents, further contributes to the mentioned uncertainness. These drastic events imply a heavy damage on the surface of the roll, with a consequent severe shortening of its life. Unfortunately, these kinds of accidents are not always documented, making not reliable the interpretation of the data from the mills. Far all these reasons, laboratory tests have been developed to reproduce (as well as possible) the thermo-mechanical conditions occurring during hot rolling. As a first approach it was decided to separate the different forms of damage and two different tests set-ups were designed at Trento University for hot wear(5) and thermal fatigue,(4) respectively. In this work the behaviour of five different high speed steel grades is evaluated on the basis of such tests with respect to their microstructure. The chemical composition is modified to obtain steels showing different microstructures, i.e., different amount, type and morphology of primary carbides and different properties for the steel matrix. In particular, the ratio between the elements of the fifth group, like V and Nb, and the others alloying elements as Cr, Mo and W, is changed to obtain different relative amount respectively of proeutectic and eutectic carbides; at the same time, the carbon amount varies in order to have an enough hardenable matrix. Laboratory test results are corroborated by those recorded in hot strip mills.

MATERIALS

In the present work, five different high speed steels for hot rolling have been investigated. Depending on their specific chemical composition, these materials are distinguished by different amount of carbides. They are characterized by a large amount of alloying elements to improve their hardenability and mechanical properties. In table 1 is reported the chemical composition of these steels. HSS B and HSS C have a quite lower amount of carbon and alloying elements and consequently of carbides. These materials are planned for rougher stands, hence they have to withstand to thermal fatigue solicitations; in previous works(4) it has been shown that the presence of high amount of carbides is detrimental for this aim, thus the quantity of carbon and elements forming carbides is kept as lower as possible. HSS D and E, instead, have a large amount of alloying elements in order to give them a greater hardness and then better wear resistance.

Table 1 Chemical composition of the investigated steels (* W_{eq} = W+2Mo)

	% C	% Cr	% W_{eq}*	% MC Formers
HSS A	1.7	5.0	8.0	4.5
HSS B	1.5	4.5	6.0	4.5
HSS C	1.6	3.0	4.0	5.5
HSS D	1.8	3.9	17.0	4.0
HSS E	1.8	3.5	10.0	6.0

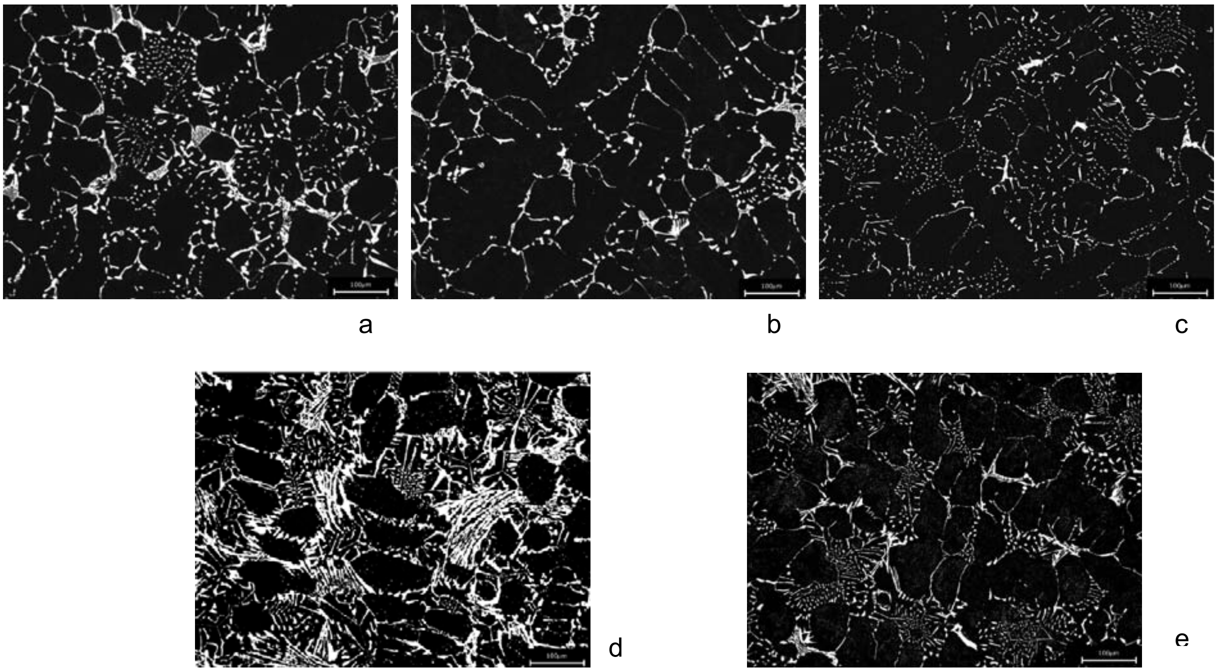
EXPERIMENTAL PROCEDURES

A material characterization was carried out grinding a sample for each steel, then etching with Cogne reagent in order to determine the carbide volume percentage. The amount of M_7C_3, MC and M_2C was evaluated by means of selective etchings, in particular Murakami's and Groebeck's reagents. The determination of the mechanical properties was led by means of hardness and impact tests; the latter were carried out using a Charpy pendulum on unnotched specimens. Microhardness tests were led too in order to characterize the martensitic matrix. The resistance to firecracking was evaluated by means of a self designed rig. The sample was heated up to 670°C by an inductor and subsequently rapidly cooled down nearly at 80°C by a water flow; more details about the test procedures can be found elsewhere.(6) The damage was determined by the measure of the cracks length and density after 180 cycles; in particular, the pyrocracking factor (P_f), defined as the product of the cracks density for the maximum and for the medium cracks length, was used to compare the thermal fatigue resistance of the steels. The evaluation of the wear behaviour involved the use of an Amsler apparatus. The tests were led in dry rolling sliding condition; the specimen was forced to rotate against a counterpart in C40 steel heated up to 700°C by means of an inductor. A 300 N load was applied during the test, realizing a contact pressure of nearly 300 MPa.(5)

The results obtained on the thermal fatigue simulations and on the wear test have been validated by the collection of data in the mills; more in detail, the examination of the surface damage on operating rolls allows to compare the damage mechanism acting with that observed on laboratory. It should be underlined how the estimation of the wear behaviour in operating rolls is quite critical, as the pick up of data about the performances of a roll is deeply affected by the turning modality adopted in the mill; very often the experience and the sensitiveness of the mill operators assure a greater importance than the steel quality to determine the roll performance. In this situation, the interest on visiting a plant is mainly focused on the characterization of the surface features of the rolls rather than on the pure collection of data about their efficiency.

RESULTS

In Figure 1 the microstructures of the investigated steels are reported. All the materials have a typical solidification structure with eutectic carbides along dendrite boundaries; dissociated eutectic MC carbides distributed mainly in solidification cells may be also revealed. After the heat treatment, consisting in a quenching followed by double tempering, the matrix is constituted by martensite and secondary carbides. In Table 2 is reported the amount and the typology of carbides for the five steels.



a b c

d e

Figure 1. Microstructure of (a) HSS A, (b) HSS B, (c) HSS C, (d) HSS D and (e) HSS E

Table 2. Carbide volume percentage

	Carbides	M_7C_3 (~1500$HV_{0.1}$)	MC (~2500$HV_{0.1}$)	M_2C (~1900$HV_{0.1}$)
HSS A	10 %	6.0	4.0	-
HSS B	6.5 %	2 %	4.5 %	-
HSS C	8 %	< 0.5 %	8.0 %	-
HSS D	14 %	3.0 %	3.0 %	8.0 %
HSS E	10 %	-	6.0 %	4.0 %

HSS A shows the presence of nearly 10% in volume of carbides, mainly M_7C_3 and MC. Both in HSS B and HSS C the amount of carbides is a few lower. However, despite its low content of carbon and alloying elements, HSS B has a rather interconnected network of carbides; this can be due to the relatively high quantity of Chromium that promotes the precipitations of M_7C_3 eutectic carbides along dendrite boundaries. On the contrary, the carbides of HSS C are mainly dissociated MC carbides. HSS D is characterized by a very large amount of carbides, mainly M_2C, promoted by the high presence of Mo and W. HSS E has a microstructure similar to HSS A, but with a larger percentage of dissociated MC, thus reducing the interdendritic carbides.

In Table 3 the mechanical properties and the results of the wear and fatigue tests are summarised. HSS B and C show the lowest matrix hardness as the precipitation of a large amount of MC carbides causes the impoverishment from carbon and alloying elements.(7,8) HSS D shows quite higher matrix hardness than the others steels, due to its high content of alloying elements that gives a pronounced secondary hardening.(9) The material with the higher matrix microhardness shows also the more elevated hardness. However, it should be pointed out how the materials with the harder martensite have also the higher volume percentage of carbides.(5) The impact tests carried out on HSS A and HSS C show that these steels are characterized by a very low toughness. This can be explained by the intrinsic brittleness of a ledeburitic microstructure. Although, it can be underlined how the presence of dissociated proeutectic carbides as well as low matrix hardness improves the impact energy.(4)

Table 3. Results of the laboratory tests

	HRC ($HV_{0.1}$)	Impact Energy (J)	Wear Rate(mm^3 m^{-1})	P_f (mm)
HSS A	58 (720)	4.8	$3.06 \cdot 10^{-6}$	2.13
HSS B	57 (610)	n.a.	$4.08 \cdot 10^{-6}$	1.12
HSS C	56 (650)	8.3	$3.35 \cdot 10^{-6}$	0.77
HSS D	62 (790)	n.a.	$0.85 \cdot 10^{-6}$	4.35
HSS E	58 (700)	n.a.	$3.24 \cdot 10^{-6}$	1.00

The thermal fatigue tests show very different behaviours among the analysed steels. HSS D has the worse behaviour, evidencing the nucleation of a restricted number of cracks able to propagate towards the core. This can be explained by the presence of a large amount of interdendritic carbides that represent a preferential path for the cracks propagation because of their brittleness.(10) Metallographic analysis on the tested specimens confirms this fracture mechanism, evidencing how the cracks follow the interconnected network of carbides, avoiding the crossing of the tougher martensitic solidification cells. Thus, the good resistance of HSS C and E can be explained by the high quantity of dissociated MC carbides and the minimal presence of precipitates along the dendrites boundaries. The firecracking damage observed on the tested specimens was compared to that of rolls operating as rougher in a mini-mill. It should be pointed that in the industrial practice many factors not reproducible in laboratory act on the thermal fatigue phenomena, as the roll undergoes to a compounded solicitation because of the presence of the working stresses; moreover, the small dimensions of the samples don't allow reproducing the plane strain conditions generated on the rolls. The analyses on the operating roll were carried out checking both its surface and its section. The work surface shows a mesh of cracks interesting the entire surface. Looking to the roll section it can be evidenced that the cracks nucleate at the carbide-matrix interface, and then develop perpendicular to the surface for a depth of nearly 0.2 mm. Then, they began to propagate along the brittle interdendritic carbides, as observed on laboratory test (Figure 2).

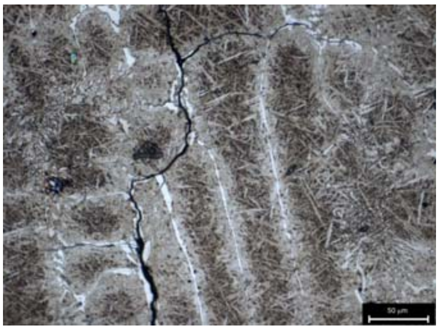


Figure 2 Thermal fatigue damage on an HSS A operating roll

The examinations evidence that the laboratory tests, though are not able to reproduce entirely the damage mechanism observed on the operating rolls, are very useful for the evaluation of the firecracking resistance of the rolls.

The wear resistance was evaluated after three hours long tests by the examination of the contact surface and by the wear rates. The analysis on the wear surface evidences a marked oxidation; all the materials show a roughness between 0.2 and 0.3 μm. The wear surfaces are characterized by an oxide scale covering the martensitic matrix and by the interdendritic network of carbides protruding from this layer; this is both because the carbides are generally less prone to oxidize(11) and because they well withstand to the wear due to their elevated hardness. It is quite easy to recognize deep wear tracks on the oxide layer; the presence in the contact zone of oxide fragments (from the counterpart and from the sample) and of hard carbides removed from the sample causes a three body abrasion increasing the wear rate. Thus, the wear can be ascribed to an abrasive and mild triboxidative mechanism.(5) Figure 3 evidences that the wear rate of the investigated steels can be related to their microhardness. In fact, elevated matrix hardness assures the capability of the steels to bear the oxide scale that reduces the friction forces and protects the material.(12) At the same time, as the harder materials have the larger carbides volume percentage, a positive influence against abrasion can be attributed to the carbides.(13)

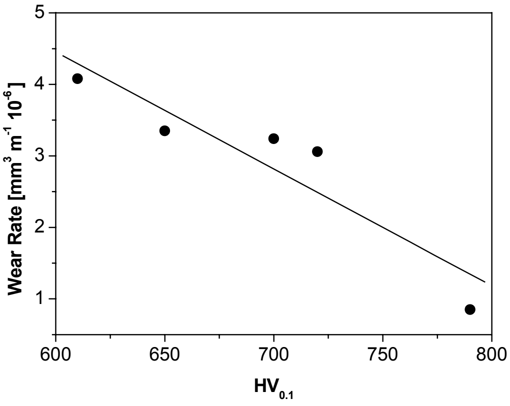


Figure 3. Wear rate vs. matrix microhardness after 3 hours tests

The wear surfaces of the specimens tested in laboratory were compared to those of operating rolls. The main difference is represented by the oxidation state: while the laboratory samples have a quite depth and generally not homogeneous oxide scale, the working surfaces of the rolls are characterized by a very compact and thin oxide layer. This can be adducted to the longer times to which rolls undergo to wear solicitations that allow the formation of a more homogeneous and less porous oxide scale.

Figure 4. Wear surface of a HSS A roll operating in R4 and R5 stands

In Figure 4 is reported the wear surface of a roll operating on rougher stands; it can be evidenced a uniform oxidation; the roughness is a few higher than that measured on laboratory specimens (nearly 1.5 μm). However, though the tests results are not able to reproduce exactly the rolling conditions, it is possible to evidence the wear mechanism responsible of the surface damage in rolling sliding at elevated temperatures. In particular, it is expected that the steels showing good performances on the plants are characterized by the combination between the capability to form and support a compact oxide layer in short times and an elevated hardness.

DISCUSSION

It is well known that the rolling conditions to which rolls undergo during hot rolling cannot be reproduced by any laboratory test. Anyway, in the last years, from the knowledge of the mills solicitations, it has been possible to study the main phenomena responsible of the rolls damage, such as thermal fatigue, oxidation and wear. This has led to understand the main mechanisms affecting the performances of the cylinders and thus to improve the roll materials. However, as it is inevitable that the laboratory tests differ from the plants conditions, the collection of data from the mills in order to validate the experimental results assures a basic importance. Though, it has to be pointed out how actually is not easy to estimate the performances of operating rolls. Considering, for example, thermal fatigue, it is very difficult to evaluate the heat checking resistance of a roll as it varies from plant to plant as a function of the adopted maintenance procedure. In fact, some rolls are grinded as the first thermal fatigue cracks appear, while other are kept on their position until the cracks reach a critical dimension. In the former situation the roll will show a drop on performances that is formally incorrect to ascribe to its poor thermal fatigue resistance. On the contrary, laboratory tests have allowed evidencing a mechanism responsible of the heat checking and thus offer a mean to evaluate on the basis of the mechanical and microstructural characteristics of the steel which is the better material for withstanding to thermal solicitations.

In the same way, it should be paid attention on regarding the data concerning the wear resistance. In Table 4 the performances of a HSS E on a F1 stand are reported.

Table 4 Performances variations as a function of grinding practice

Tonnes	Roughness Ra (μm)	Grinding (mm)	Performances (ton/mm)
5460	1.0 – 1.5	0.5	10920
7091	1.0 – 1.5	0.45	15758

Among the two rolls, both in the same grade and operating in the same stand, there is a difference in efficiency of nearly 40 percent. This has to be ascribed to the practice of grinding the rolls as a function of the mill stops rather than when the working surfaces show critical conditions for the strip rolling; that becomes particularly important when the roll material well withstands to the wear as an unnecessary grinding more deeply affects its efficiency. As in the previous case, laboratory tests assures a key role for the wear evaluation too; in fact, as these tests show which are the mechanism ruling the wear, it's possible to determine which are the materials with the better wear resistance. However, it should be pointed out the importance to collect data from the plants in order to warrant that the experimental trials reproduce the same damage mechanisms to which rolls undergo in the mills. At the same time, it should be expected a positive confirmation of the rolls performances deduced by laboratory tests.

Regarding to the results obtained by the experimental test, it should be underlined how the HSS show elevated resistance both to wear and thermal fatigue if compared to High Chromium Irons.(14) In particular, thank to its elevated toughness and thermal fatigue resistance, HSS C represents the better compromise between roll efficiency and reliability against accidents; thus, it has to be expected that HSS rolls can evidence a good behaviour also on intermediate finishing stands, where there are higher risks of overloads due to the impact with the head and tail end of the strip.

CONCLUSIONS

The thermal fatigue resistance and the wear behaviour of five different high speed steels for hot rolling have been investigated and related to their mechanical properties and microstructural features. The tests have evidenced the main mechanisms responsible of the roll damage. The thermal fatigue resistance is mainly ruled by the carbides: the presence of an interconnected carbides network along dendrites boundaries represents a preferential path for the cracks propagation. The results of the tests have been validated by a comparison with the damage shown on the wear surface of an operating roll, confirming that in both the cases a similar mechanism of injury.

Wear resistance is mainly affected by the oxidation behaviour, by the carbides amount and by the matrix hardness of the steels. The formation of an oxide scale on the roll surface reduces the friction forces and protects against the wear; at the same time, materials with higher matrix microhardness better bear the constituted oxide layer showing low wear rates. Generally, a high amount of hard carbides is related to a low mass loss during the test. The wear surfaces of operating rolls confirmed the importance assured by the formation of an oxidation layer.

REFERENCES

1 A. Molinari, M. Pellizzari, A. Biggi, G. Corbo, A. Tremea, "Metallurgical Development of Hot Rolls with improved Rolling Performances", *Proc. of Saruc 2002*, 17-18 October 2002, Gauteng (RSA), p.37.

2 M. Pellizzari, A. Molinari, A. Biggi, "Optimization of the Hot Roll Performances through Microstructural Tayloring", Proc. Mathen 2002, *4th International Conference on Materials and Manufacturing Technologies*, Cluj-Napoca (Romania), Sept. 2002, in *Acta Technica Napocensis*, NuovaSerie, 2002, Vol. 45, 329-334.

3 A. Molinari, M. Pellizzari, A. Biggi, G. Corbo, A. Tremea, "Development of Spincast Hot Rolls through Microstructural Tailoring", *Proc. 44th Mechanical Working and Steel Processing*, Orlando (Florida), 8-11 September, 2002, Iron & Steel Society, Vol. XL, 1233-1244.

4 A. Molinari, A. Tremea, M. Pellizzari, A. Biggi, G. Corbo, "High Speed Steels for Hot Rolls with Improved Impact and Thermal Fatigue Resistance", *Materials Science and Technology*, Vol.18, No. 4, 2002, 1574-1580.

5 M. Pellizzari, A. Molinari, G. Straffelini, "Tribological Behaviour of Hot Rolling Rolls", *Wear*, No. 259, 2005, 1281-1289.

6 M. Pellizzari, A. Molinari, A. Biggi, G. Corbo, A. Tremea, "Semi High Speed Steels for Roughing Rolls with Improved Thermal Fatigue Resistance", *La Metallurgia Italiana*, Vol.9, 2005, 57-61.

7 S.W. Kim, U.J. Lee, K.D. Woo, D.K. Kim, "Solidification Microstructures and Mechanical Properties of Vertical Centrifugal Cast High Speed Steels", *Materials Science and Technology*, Vol. 19, Num. 12, 2003, 1727-1732.

8 J.W. Park, H.C. Lee, S. Lee, "Composition, Microstructure, Hardness and Wear Properties of High Speed Steel Rolls", *Metallurgical and Materials Transactions A*, Vol.,1998 30, 399-409.

9 C.K. Kim, J.I. Park, S. Lee, Y.C. Kim, N.J. Kim, J.S. Yang, Effects of Alloying Elements on Microstructure, Hardness and Fracture Toughness of Centrifugally Cast High Speed Steel Rolls, *Metallurgical and Materials Transactions A*, Vol. 36, 2005, 87-97.

10 A. Molinari, M. Pellizzari, A. Tremea, A. Biggi, G. Corbo, "Effect of the Matrix Microhardness on Thermal Fatigue Behaviour of Spincast High Speed Steels for Hot Rolls", *Materials Science and Technology,* Vol. 21, Num. 3, 2005, 352-356.

11 A. Molinari, G. Straffelini, A. Tomasi, A. Biggi, G. Corbo, "Oxidation Behaviour of Ledeburitic Steels for Hot Rolls", *Materials Science and Engineering*, Vol. A280, 2000, 255-262.

12 P.A. Munther, J.G. Lenard, "The Effect of Scaling on Interfacial Friction in Hot Rolling of Steels", *Journal of Materials processing Technology*, No. 88, 1999, 105-113.

13 T. Koseki, "Recent Activities in Research of Casting", Kawasaki *Steel Technical Report*, No. 41, October 1999, 67-69.

14 M. Pellizzari, A. Molinari, D. Cescato, A. Tremea, G. Corbo, A. Biggi, "Wear and Friction Behaviour of High Chromium Iron and High Speed Steels for Hot Rolls", Abrasion 2005, São Paulo, Brasil, 189-198.