ISSN 2179-3956

INFLUENCE OF LASER HARDENING ON THE TRIBOLOGICAL PROPERTIES OF A PERLITIC CAST IRON FOR HOT ROLLS[1]

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Abstract

The wear behaviour of a laser hardened perlitic cast iron (PCI) for hot rolls is evaluated. The role of the higher hardness pertaining to a fresh untempered martensite microstructure obtained by laser hardening is examined in view of the complex wear mechanism operating during laboratory test, including abrasion, triboxidation and adhesion. Dry rolling-sliding wear tests have been carried out using a disc on disc configuration involving the contact between the sample and a C40 plain carbon steel counterpart. In order to modify the relative contribution of abrasion and triboxidation test at different temperature were carried out. The tests at low temperature (without auxiliary heating of the C40) demonstrate that laser hardening is a valuable method to increase wear resistance. At higher temperature (C40 induction heated at 700°C) the relatively higher contribution of triboxidation than abrasion allows just a minor improvement to be observed. The formation of wear protective oxide layer on the soft metallic matrix of base material causes a relatively higher resistance. This phenomenon is not supported by a the hard martensitic matrix of laser treated samples.

Keywords: Perlitic cast iron; Laser hardening, abrasion; Triboxidation; Adhesion; Hot wear; Friction.

1 *Technical contribution to the First International Brazilian Conference on Tribology – TriboBr-2010, November, 24th-26th, 2010, Rio de Janeiro, RJ, Brazil.*
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ISSN 2179-3956

1 INTRODUCTION

The cost of rolls represents an important topic for hot rolling mills. The possibility to prolong rolling campaigns on the basis of improved surface durability represents an important goal. Due to economical reasons, profiled rolls for long products (bars, billets…) are made by cast irons. The industrial experience learns that wear of rolls occurs preferentially in critical regions, like the flanks of the profile, being much lower at the root. The need to increase surface durability without renouncing at proper toughness at the core suggests the use of surface treatments aimed at improving surface hardness. Laser transformation hardening is a valuable selective method including controlled case depth, minimal distortion and high processing speed.[1,2] It was claimed to be very efficient to increase the wear resistance of a wide range of steels and cast irons.[3-7] Under proper conditions this treatment also increases fatigue strength, due to a compressive stress state induced on the surface of the component .[8-12]
On the market, conventional CO_2 and Nd:YAG lasers,[13-15] the only available few years ago, are going to be replaced with more efficient High Power Diode Lasers (HDPL),[13,16] which can provide sufficient power density to cover a wide range of applications, without the need of coatings to improve laser adsorption. During the processing of conductive materials as steel and cast iron, the high local energy density transferred by the laser beam allows high temperature gradient. As a result, the surface of the component is austenitized, the core being completely unaffected. The rapid heat extraction by the cold substrate, acting as heat sink, does not provide the need for external quenching media. From this point of view materials with poor hardenability, that cannot be hardened by conventional methods, can be laser hardened.[1,2]
The simulation of the hot wear damage of rolls by means of experiments on a laboratory scale was demonstrated to be a very tough job for tribologists. During service the wear of these components occurs by the complex superimposition of abrasion, triboxidation and adhesion which is often combined with thermal cracking due to thermal fatigue. In real conditions lubrication also gives a contribution which has been seldom taken into account by researchers. Several wear configurations were proposed, including pin on disc and disc on disc. It is believed that the conclusions drawn in these papers about wear mechanism and the relative behaviour of different materials have to be considered in the frame of the specific test conditions. A customary test developed at the University of Trento will be used for the present investigation.[17,18] As proposed by other authors,[19] it was stated that the wear and frictional properties evaluated by this configuration are strictly system-dependent and have been clearly correlated to the ability of the contact surfaces towards the formation, accumulation, agglomeration and sintering of wear particles, i.e., towards the formation of wear-protective oxide layers.
This present research is part of an RFCS European project (Research Found for Coal and Steel) “LASERHARD, Laser treatment of profiled rolls, RFSR-CT-2006-00012” aimed at the development and implementation of a laser based strategy for the treatment of roll surfaces. The aim of the present paper is to evaluate the influence of microstructure on the wear properties at low and elevated temperature of a perlitic cast iron (PCI). Small disc samples were laser hardened and tested to determine the optimum process parameters to be used for the treatment of the industrial roll. In particular, the role of the higher hardness pertaining to a fresh untempered martensite microstructure obtained by laser hardening is examined in

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view of the complex wear mechanism operating during laboratory test, including abrasion and triboxidation.

2 MATERIALS AND METHODS

Material tested is a perlitic cast iron with the nominal composition listed in Table 1.

Table 1: Chemical composition of perlitic cast iron

C	Si	Mn	Ni	Cr	Mo	P	S
3.25	1.62	0.55	2	0.37	0.32	0.04	0.01

It was delivered in bars of 40mm diameter after conventional industrial normalizing heat treatment. On each bar four single laser tracks were realized taking care that no overlapping occurred and also that last track was not thermally affected by the following one. Different laser sources and different treatment conditions were used as explained in more detail in the following paragraph. Wear disc samples of 40mm external diameter, 10mm width and an internal hole of 16mm have been obtained after cutting and drilling.

The laser used in the present study were a Nd:YAG Rofin DY 044 power source with a variable output power of up to 4.4 kW. The experiments were carried out using an optical fibre of 0.4 mm diameter to guide the beam, with the focussing optics incorporated in the laser head itself. The focal length of the lens used equalled 338 mm and the transverse speed was set to 100mm/s. Samples were produced using a variable programmed temperature in the range 950-1050°C. The laser head was mounted in a robot model ABB IRB 6600 175/2.8 and samples were placed in a 7th Axis Positioner ABB IRBPL 250 for their surface laser treatment. A second laser mounting a CO_2 source with variable power up to 5 kW was also used. In any case, no post hardening treatment (stress relieving or tempering) were carried out on the samples.

Dry rolling-sliding hot wear tests have been carried out using a disc on disc configuration.[17,20] The sample (40mm external diameter, 10mm width) is allowed to rotate against a C40 plain carbon steel heated up to 700°C by means of an inductor. The C40 disc was preliminarily oxidized in order to get a metal-oxide contact at the start of test, like in real rolling. The rotating speed of the C40 is 200rpm, while that of the sample is 180rpm, thus realizing 28% sliding. A load of 150N is applied corresponding maximum contact pressure of 300MPa. The total duration of the test is of 135 minutes, with stop at every 45 minutes to measure the mass losses of sample and counterpart. In order to avoid excessive deformation of the C40 a new disc is mounted after each stop. Friction was continuously monitored and data were collected by means of a linear transducer connected to PC. Single track laser hardened samples of the approximate width of 10mm were used so that, in order to realize the contact between the C40 and the homogeneous part of the hardened layer (see Figure 1 in the following), the width of the counterpart disc was reduced to 5mm. In order to change the test temperature, a second sequence of tests was carried out using the same configuration described above but without auxiliary heating of the counterpart.

The microstructure before and after the test was characterized by optical and scanning electron microscopy. Microhardness profiles were measured to evaluate the extent of surface hardening and the occurrence of softening/hardening phenomena during the tests.

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3 RESULTS

The microstructure of the lens shaped transformation hardened region is shown in Figure 1. The microstructure of the perlitic cast iron (Figure 2a) is constituted by perlite in the metallic matrix and interdendritic eutectic region of austenite and cementite (ledeburite). The high graphitizing potential of the melt further allows the formation of graphite nodules. Different zones can be distinguished within the laser-affected zone, which are outlined in Figure 1 and Figure 2.[18] At the top a completely martensitic structure was found in the metallic matrix which was addressed as the hardened zone (HZ) (Figures 2b and 2c). In this layer the fraction of cementite is lower than in the base material, since the heating during laser beam irradiation promotes the local evolution of the system towards equilibrium, i.e., the formation of graphite at expense of the iron carbide. The transition zone (TZ) consists of a partly austenitised and eventually hardened structure and material fractions which did not transform to austenite during heating. Beneath the transition zone, depending on the state of the base material, a heat affected zone (HAZ) was determined and finally the unaffected base material (BM) was reached.

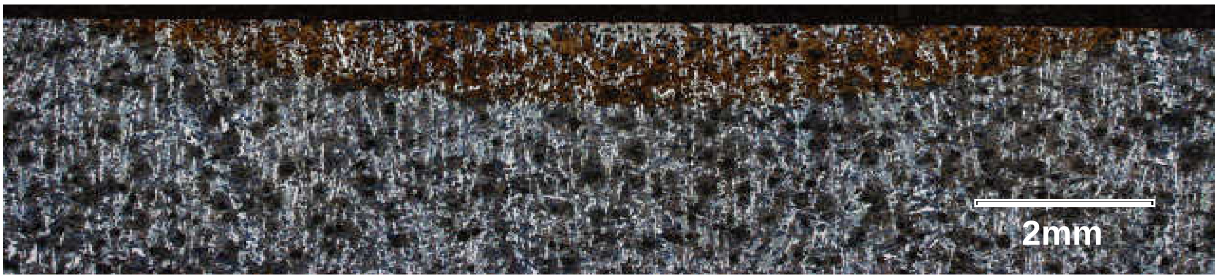

Figure 1: typical aspect of the transverse section of a laser track.

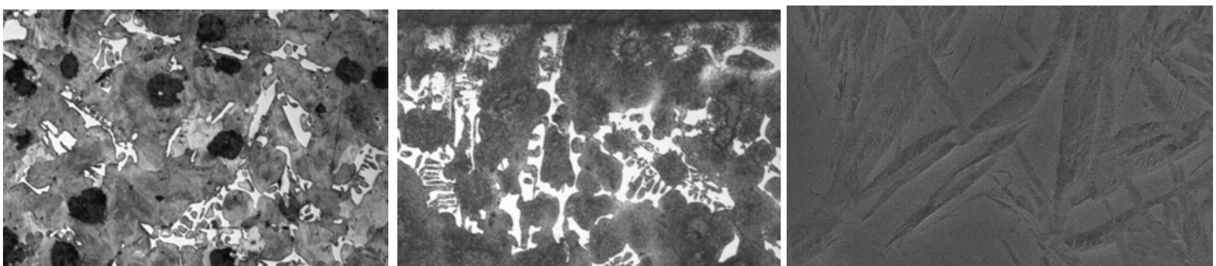

Figure 2: microstructure of a) the base material (BM) and b) the hardened zone (HZ) consisting of c) martensite plates (M) and retained austenite (RA).

Moreover, due to occasionally poor temperature control and/or material unhomogeneity (eutectic regions have lower melting point than dendritic ones), remelting also occurred, so that a uniform melt zone (MZ) was found in the outermost part of the laser affected zone (Figure 3a).[21] Remelting could also be observed on a local scale (Figure 3b), i.e. in correspondence of eutectic regions, even if the temperature was close to the target (950-1000°C).

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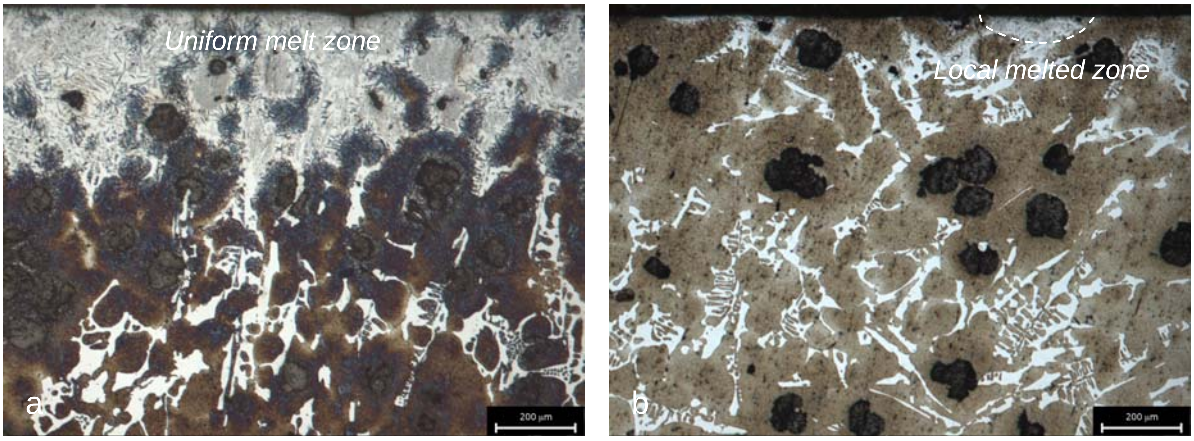

Figure 3: a) uniform melt zone (white layer) and b) local melt zone (dashed region) in samples laser hardened with different parameters.

The microhardness profiles evidence a total depth of hardening comprised between 1.2 and 2.4mm, depending on the specific laser parameters used (Figure 4). The surface microhardness of the metallic matrix is higher than 700HV0.1, with exception of samples subjected to occasional remelting, which showed lower hardness. In these cases a peak of hardness is located 0.5-0.7mm below the external surface, since the hardened zone (HZ) is found below the melt zone (MZ). This phenomenon is more evident in the sample treated with the CO_2 laser, because of the use of a graphite layer to promote laser absorption, to increase the efficiency of the energy transfer to the metallic samples.

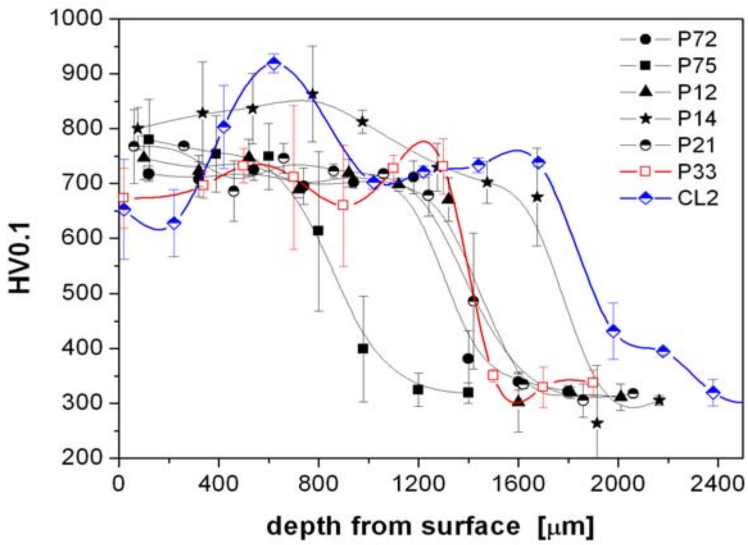

Figure 4: microhardness profiles of the laser treated samples

3.1 Wear Mechanism

As shown in a previous paper the wear mechanism observed using the present high temperature test configuration is given by a combination of abrasion, triboxidation and adhesion, the relative contribution of which depends on the hardness of the material but, more in general, on the system capability to form and entrap wear particles, aiming the formation of wear protective oxide layers.(17) Abrasion scratches are produced by the cutting action of the oxide developing on the hot surface of the

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counterpart. These are mostly localized in the soft metallic matrix of the eutectic alloy, which is worn out preferentially with respect to eutectic carbides. In the case of the base material, the cavities produced by wear of the metallic matrix are completely covered by oxide, giving rise to the formation of protective oxide layers, i.e, glazes (gray areas in Figure 5a) and a smooth wear profile. At the end of the test carbides are not oxidized (white areas in Figure 5a). Adhesion promotes the occasional spalling of the oxide (black elongated areas in Figure 5a). The surface of laser hardened samples (Figure 5b) also shows the preferential wear of the metallic matrix but this is not oxidized, confirming a relative poor contribution of triboxidation for harder materials. Occasional cracking was observed inside/along eutectic carbides (see arrow in Figure 5b).

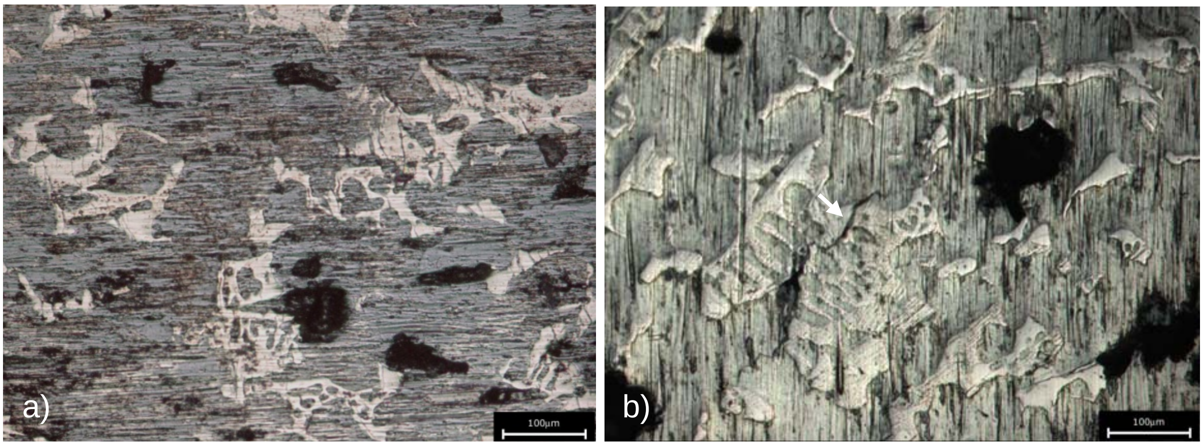

Figure 5: wear track morphology of a) base and b) laser hardened PCI

The linear trend of wear curves (Figure 6) highlights the establishment of a steady damage regime, which can be characterized by a single value of the wear rate, calculated as the slope of the straight line interpolating the last three experimental points. For all samples the laser treatment allows a reduction of the wear rate, which becomes particularly low in the case of P33 and CL2, samples showing the lowest surface hardness (Figure 7). Despite of the high increase in surface hardness Nd:YAG samples 72 to 31 display a minor increase in wear resistance.

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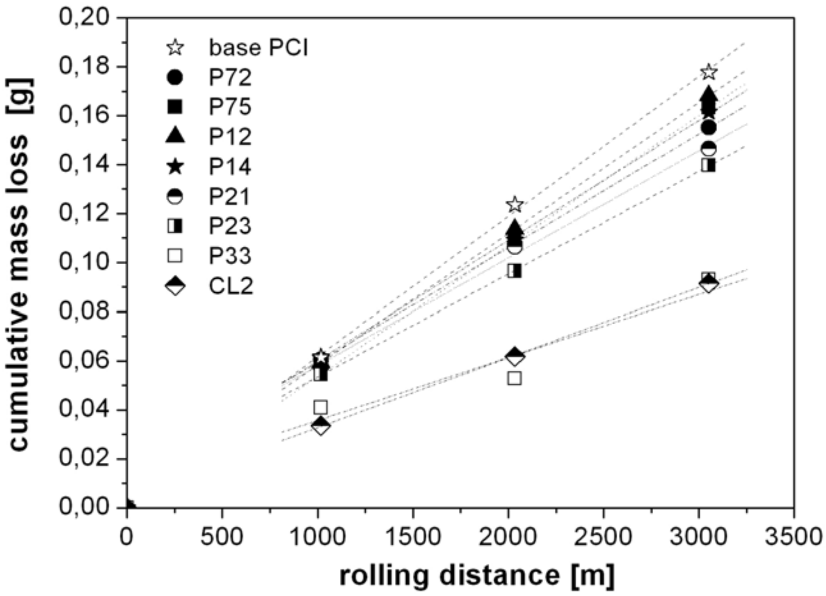

Figure 6: curve of cumulative mass loss recorded during the tests at high temperature.

The increase in wear resistance after laser transformation hardening is much more evident by carrying out the test at lower temperature, i.e. with no auxiliary heating of the counterpart. In this condition, while the wear rate of the base material is very close (slightly higher) to that at high temperature, those of laser treated samples are reduced to less than one third (Figure 8).

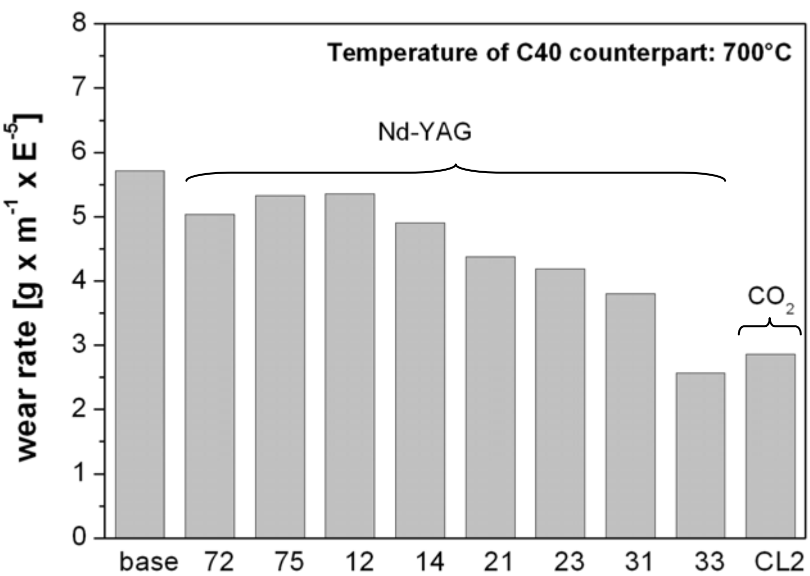

Figure 7: wear rate of untreated and laser hardend perlite cast iron measured with counterpart material induction heated at 700°C.

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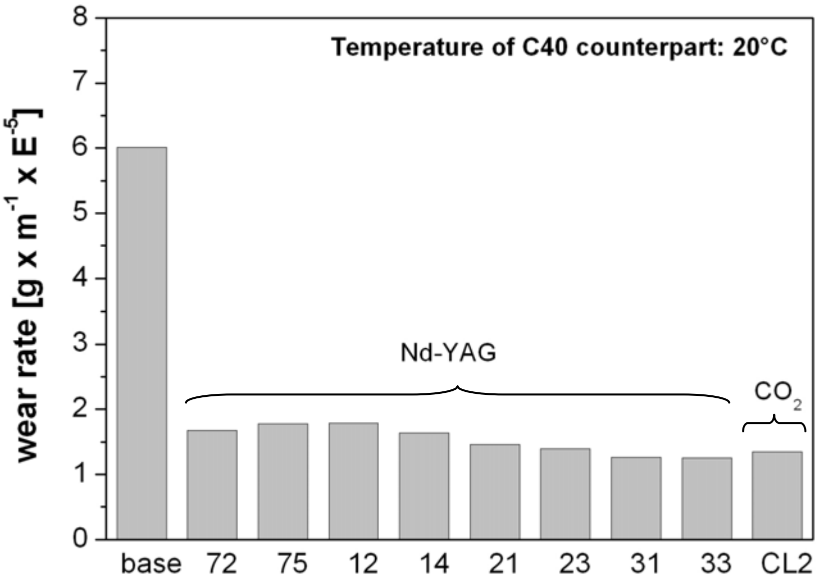

Figure 8: wear rate of untreated and laser hardened perlite cast iron measured with no heating of counterpart material.

A further consideration about the wear mechanism can be done looking at the mass loss curve of the C40 counterpart (Figure 9). Three samples (base PCI, Nd:YAG P12 and CO_2 CL2) were selected as representative for the behavior of all the materials investigated. Excluding the first test interval for sample CL2, during which a net mass loss is observed, a mass increase is observed during the rest of the test, highlighting the occurrence of material transfer form the roll to the counterpart disc. This observation is confirmed by a “load free” test which indicated that the mass gain of the C40 disc due to thermal oxidation i lower that that exhibited by the discs withstanding wear. The same results was also obtained during the testing of a laser hardened forged steel.(22)

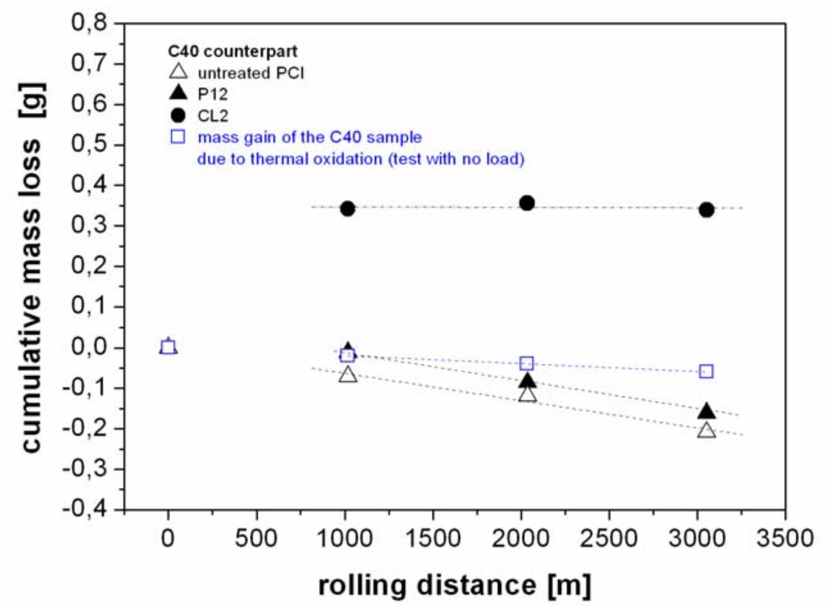

Figure 9: curve of cumulative mass loss of C40 counterparts.

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The friction coefficient recorded for the same three samples, is shown in Figure 10. Friction is almost steady for untreated cast iron and P12, samples showing very similar wear rate (Figure 7). After an initial transient, during about 10 minutes,[17] needed by the sample to reach the regime temperature (300°C), the friction coefficient remains almost constant. Just a minor increase is eventually shown within the three test intervals. This frictional behavior is similar to that displayed by high speed steels in a previous work,[17] which was ascribed to the occurrence of an abrasive wear mechanism. On the other side, CL2 evidences a transition: in the early stage of the test friction is low, suddenly increasing to higher values, in the same way same shown by high chromium irons.[17] This behaviour was ascribed to the occurrence of important oxidation phenomena during the tribological contact, which resulted in the formation of protective oxide layers.

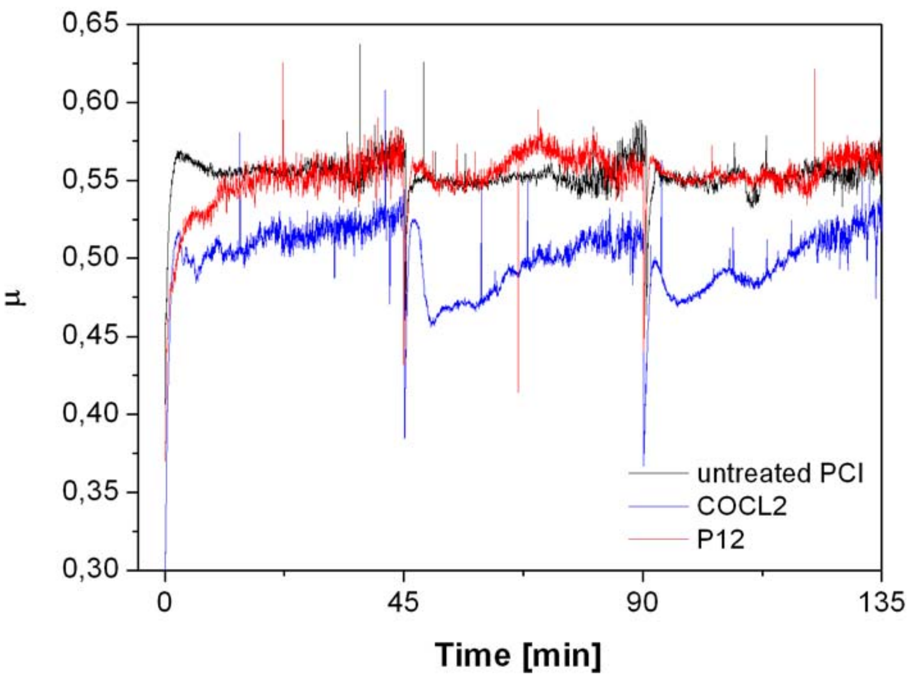

Figure 10: friction coefficient of untreated PCI, P12 and CL2 samples.

4 DISCUSSION

The wear resistance of materials with different microstructure (type and amount of eutectic carbides) generally increases with increasing hardness. It was demonstrated that using present test configuration at elevated temperature, as far as abrasion rules wear damage, high speed steels are more resistant than high chromium and indefinite chill irons, respectively.[17,20] The same could be also demonstrated considering a cast steel and a graphitic steel.[23] However, the opposite effect was observed considering the same material with different hardness: an increase in wear resistance occurs if hardness is reduced, e.g. due to overtempering producing a reduction of matrix microhardness.[17]
By specific test conditions used in this research, the higher matrix microhardness causes an increase in abrasion resistance. However, the increase at high test temperature (Figure 7) is much lower than that observed at low temperature (Figure 8), in view of the relatively lower contribution of abrasion with respect to triboxidation observed in the first case. As the temperature is diminished,

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triboxidation becomes more difficult, abrasion becomes the mechanism governing wear resistance and the improvement introduced by laser hardening is much more evident. As the temperature is raised triboxidation can occur, particularly if this is favored by the low hardness of the metallic matrix and the influence of hardness on the mechanism formation of wear protective oxide layer becomes more and more important.
A first confirmation for this is given by the wear rate of the untreated material, which is higher at low than at high temperature. This result is quite surprising, also in view of the opposite trend of laser treated samples, showing lower resistance at high temperature. In general, the thick and hard oxide scale on the C40 counterpart heated up to 700°C causes more intense abrasion at high than at low temperature, also because of the lower hardness of the samples. In the case of base PCI this is not. The morphology of the wear tracks highlight that, while no or poorly protective oxide layers are formed at low temperature, very compact glazes can form at high temperature (Figure 5 a), thus hiding the higher contribution of abrasion expected on the basis of the lower hardness.
The second experimental evidence is the poor improvement in wear resistance exhibited by laser hardened samples at high temperature. Again, the poor contribution of triboxidation (Figure 5b) is responsible for this, in spite of the higher abrasion resistance due to the very high surface hardness. The hard martensitic matrix produced by laser hardening is less favorable for the formation of protective oxide layers, for two reasons.(19) On one side, it counteracts the early formation of wear particles, the base elements of these layers. On the other side, it also prevents the entrapment and agglomeration of such particles because the cavities produced by the wear of the metallic matrix are much less deep than those in the untreated perlitic cast iron.
A further evidence is given by sample CL2, showing very good wear behavior at high temperature. This sample (like P33) is characterized by high fraction of retained austenite in the heat treated zone and relatively low hardness compared to the other Nd:YAG samples (Figure 4). The preferential wear of this soft phase satisfies both the above conditions for the formation of oxide layers, as confirmed by the lower friction coefficient (Figure 10) and the occurrence of the transition during the various test intervals.

5 CONCLUSIONS

Laser surface hardening is a valuable technique to improve wear resistance of perlitic cast iron. It allows the formation of a hard (700-800HV) martensitic layer for a total case depth comprised between 1.2-2.4mm, satisfying the target requirements of profiled hot rolls. The microstructure of the hardened zone was quite homogeneous and showed the partial graphitization of cementite during irradiation.
A marked improvement of wear resistance was demonstrated, particularly at low test temperature, when abrasion rules the damage of the roll. In this condition, the high surface hardness resulted in a reduction of material consumption of about 60%.
A significantly lower improvement was observed at higher temperature (300°C), carrying out the tests with auxiliary induction heating of the C40 counterpart to 700°C. In this condition, the soft perlite matrix of the untreated cast iron showed a comparatively better wear resistance than most laser treated samples, because of the protective action of oxide layers, hiding the higher abrasion due to the lower hardness. The contribution of triboxidation was poor in the case of laser treated

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samples, since a hard martensite matrix does not fulfill the two basilar conditions for the formation of protective oxide layers, i.e. the formation of wear particles and their agglomeration and entrapment in the tribological system. This result is confirmed by the relatively good wear resistance of samples showing high fraction of soft retained austenite.
Present results have to be considered in view of the specific test configuration, confirming (if necessary) that tribological properties are strongly system-dependent. Preliminary field tests on a rolling mill confirmed the improved surface durability of a roll treated using the laser parameters optimized on the basis of laboratory experiments here presented. During the first rolling campaign the roll consumption was about 50% lower than that of the base material.

Aknowledgements

This work was realized in the frame of the RFCS project (Research Found for Coal and Steel) “LASERHARD, Laser treatment of profiled rolls”, RFSR-CT-2006-00012

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