METALLURGICAL ASPECTS RELATED TO CONTACT FATIGUE PHENOMENA IN STEELS FOR BACK-UP ROLLS

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Abstract
The need of even longer rolling sessions is driving the improvement of back up rolls in terms of wear resistance. This is also aimed to reduce costs. In this paper the effect of steel chemical composition on contact fatigue phenomena, bringing to the macroscopic damage named spalling is reported. Results show that the removal by grinding operations of damaged portion of rolls surface should be not sufficient to restore the initial performances of material. Experimental tests showed that a portion of material below the damaged one keeps memory of the last fatigue cycle, and has to be removed.

1 Introduction
The worldwide increasing competition between steel producers, linked with emerging countries producers growth, requires the individuation of all possible solutions to save money and reduce production costs. The elongation of back-up rolls rolling campaign, reducing the number of plant stops, brings to a longer life of rolls, and represents one possible way of improvement.
Many papers have been published related to the metallurgical design and to the hot deformation behaviour of back-up rolls [1-7], but not so large research have been carried out about the relations between microstructure and surface fatigue phenomena. Some results are reported in literature showing that the finely precipitated carbides at different matrix during heat treatment process strongly influence mechanical properties of the backup roll. In particular, the spheroidized pearlite at the inner regions which consists of large globular or rod-like M_7C_3 and a little of small globular $M_{23}C_6$ shows increased toughness and fracture resistance properties than those of the lamellar pearlite with lamellar $M_{23}C_6$ and a little percentage of globular M_7C_3 [8].
In framework of the relations between microstructure and surface fatigue properties it is important to evaluate the effect of different metallurgical mechanisms (carbide precipitation, microstructure) [9-17] on surface fatigue phenomena, which are responsible of rolls surface damaging named spalling.
This paper reports the effect of microstructure on contact fatigue phenomena of back-up rolls rolling campaign duration and grinding operations.

2 Materials and experimental details
Back up rolls are manufactured by a forging process followed by a quenching and tempering (Q&T) heat treatment, aimed to obtain a target hardness of 450 HV in the surface. The component, after heat treatment, needs to be characterized by good toughness levels in the roll

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bulk and necks, and elevated wear /fatigue behavior on the barrel surface. Starting from 3%Cr steel for back up rolls (Steel A), the metallurgical design of new solutions for this kind of products is based on the introduction of some chemical composition variants aimed to activate different steel hardening metallurgical mechanism which could improve both surface fatigue resistance and toughness. Mechanism under considerations are the precipitation of V carbides (Steel B) which are known to be quite effective in enhancing wear resistance, and toughness improvement by lowering Mo content and raising Mn up to 1.5% (Steel C) (see **Table 1**).

Table 1 Steel chemical composition of the steels under investigation (other elements: N, S, P)

	Steel A	Steel B	Steel C
C, %	0.45	0.45	0.45
Si, %	0.35	0.35	0.35
Mn,, %	0.75	0.75	1.50
Ni, %	-	-	-
Cr, %	3.00	3.00	3.00
Mo, %	0.80	0.80	0.30
V, %	-	0.13	-

Steels were processed by thermo mechanical rolling followed by Q&T on pilot plant, in order to obtain the target mechanical strength.

Surface fatigue resistance was evaluated by a Ring-on-Ring tribometer. According to the experimental set-up, a ring is pressed against a cylinder, the two specimens rotating at assigned angular velocities. The two samples can be machined, treated, and finished in such a way to present the surface characteristics similar to the ones of the roll surface to be simulated. The normal load and the two velocities can be set within some limits imposed by the test machine. The tribometer is able to control the normal load from 0 N up to 5000 N and the temperature from 0 up to 1200 °C. The cylinder angular speed can be controlled from 50 to 1200 rpm, while the ring (counter part) angular speed can assume values from 0 to 500 rpm. The two axes can be moved depending on the sample dimensions. During these tests the diameter of test sample ring used was between 68 mm and 70 mm.

The parameters are controlled by a dedicated software. Rotation can have either the same or the opposite verses. In this investigation the tests have been performed at room temperature and with no lubrication. Normal load during tests is set to obtain a desired maximum Hertzian contact pressure, which ranged between 710 MPa and 1230 MPa during the test campaign. Air cooling has been ensured in order to prevent heating and uncontrolled oxidation phenomena on the contact track. Each material is characterized obtaining the equivalent “S-N surface fatigue” curve. Using as reference value the yield limit of the material, a first test load is chosen and the test is performed under pure rolling conditions or with a slipping percentage if required. After a certain amount of rolling cycles, the test is stopped and the sample made by the testing material is observed by SEM in order to evaluate the presence of surface fatigue damage. The test is stopped if, for instance, a dimension of 100 microns pitting is reached. A reduced test load is then fixed and the procedure repeated until enough points are available to trace the surface fatigue characteristic of the material. A reference ring is generally used as counterpart for all the tests; the diameter of the used ring is 76 mm.

Microstructure was analysed by Electron Back Scattered Diffraction (EBSD) technique. About 100 μm x 100 μm areas were scanned. From these measurements some microstructural characteristics of the material can be estimated, e.g. misorientations and types of grain

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boundaries, crystallographic orientations, etc., directly related to materials strength/toughness. EBSD is a very accurate method to measure the grain size, even for microstructures as fine as tempered bainite and tempered martensite. In this paper subgrains and packets were defined as microstructural features with misorientation lower than 5° and higher than 15°, respectively [18][19].

3 Results and discussion

Materials production and microstructural assessment

The three steels reported in **Table 1** were cast on laboratory scale. 80 kg weight ingots were cast and then hot rolled, simulating an industrial forging process. Hot rolled plates were then quenched and tempered. In order to identify the suitable tempering temperature to obtain the target hardness, materials were tempered in a wide temperature range (**Fig. 1**). Due to precipitation hardening, steel B requires higher tempering temperature in order to obtain the same target hardness, as expected.

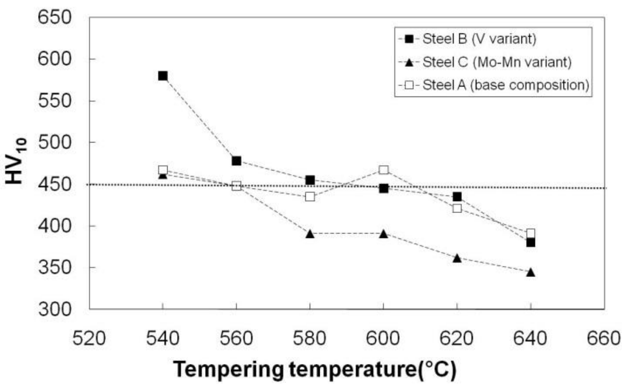
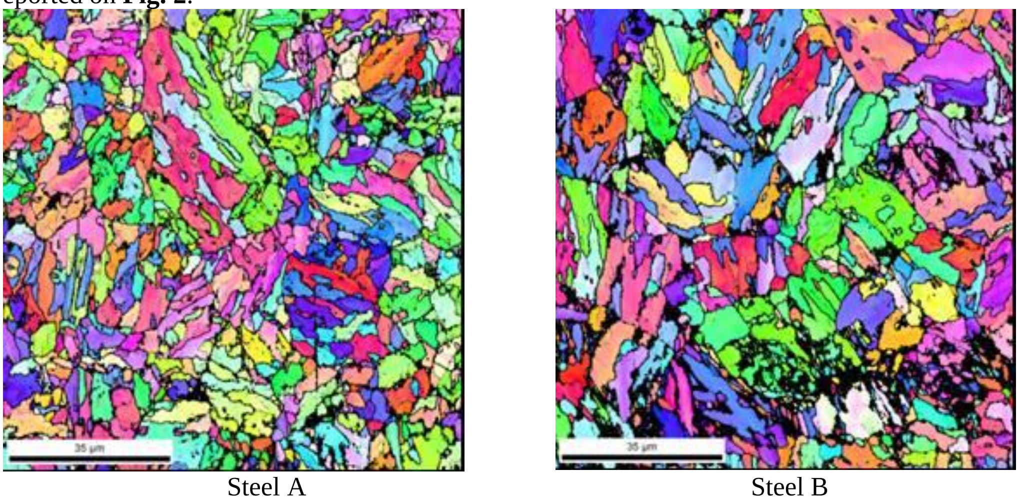


Fig. 1 Tempering behavior of the considered steels

Microstructures and relevant hardness profiles of the three considered steels after Q&T are reported on **Fig. 2**.



Steel A Steel B

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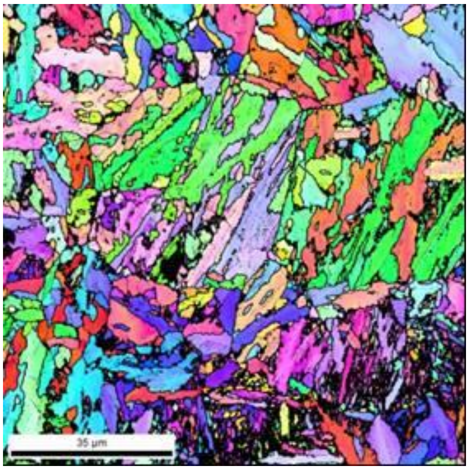
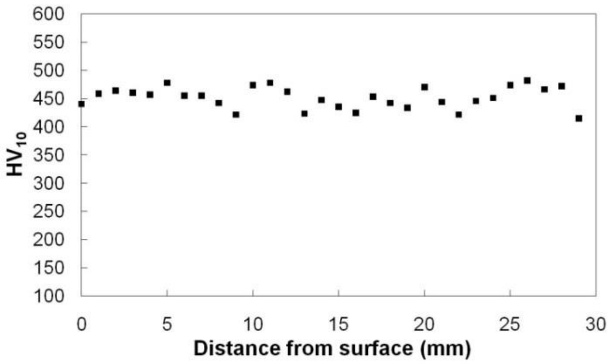


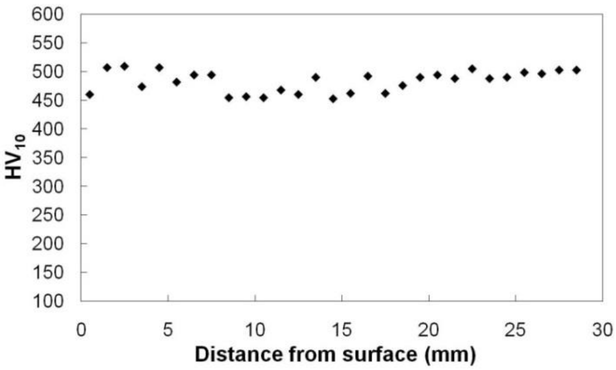
Steel C

Fig. 2 Microstructures of the considered steel after Q&T (EBSD results)

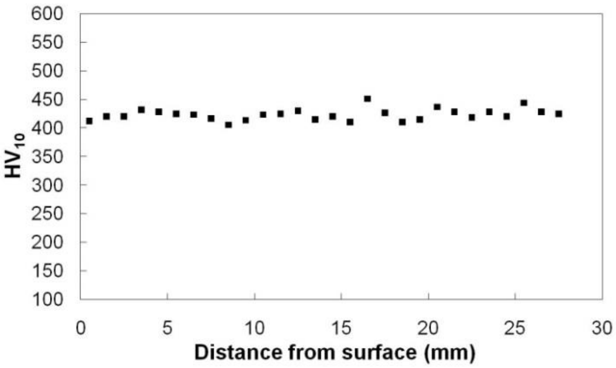
In all cases, a tempered bainitic microstructure was observed by EBSD. No differences in terms of packet/cell sizes are found between the three materials, so that similar tensile/toughness behavior have to be expected as obtained by different metallurgical mechanism hence process parameters (e.g. different tempering temperature). Moreover, due to the high intrinsic steel hardenability quite homogeneous through thickness hardness profiles were found (**Fig. 3**).



Steel A



Steel B



Steel C

Fig. 3 Through thickness hardness profiles of the considered steel after Q&T

Contact fatigue resistance

Steels reported in **Table 1** were tested by tribometer by means of a standard ring on ring test. Specimens were machined from each hot rolled steel and then tested in the tribometer using a reference counterpart ring of nitrided cromium steel. A first testing campaign was performed using sliding conditions, air cooling and three different load conditions (710 MPa, 897 MPa and 1230 MPa) in order to define a damage curve for each steel. The results of this test are summarized in **Fig. 4** and **Fig. 5**.

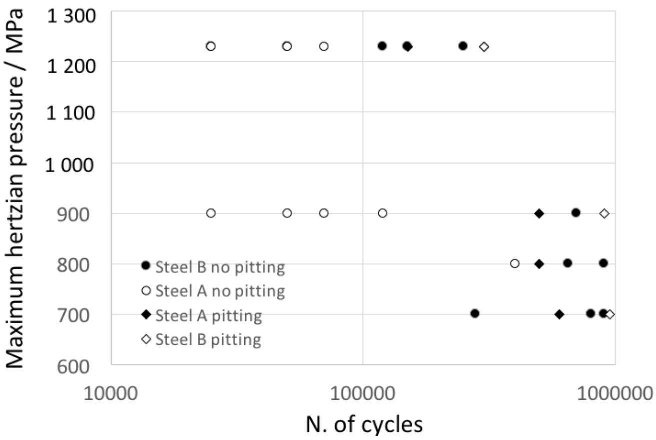


Fig. 4 Sequence of the results from the tribological characterization (comparison between steel A and steel B)

Fig. 5 shows the surface fatigue evolution at a constant test load per set of cycles. The damage (pitting) has been documented for each surface fatigue point.

Surface fatigue curves are reported in **Fig. 6**. The variant B, based on V carbides precipitation hardening, is quite more expensive than the basic composition, but the advantages in terms of test duration and contact fatigue resistance are repetitive and constant at all hertzian pressures tested.

The variant C, based on partial substitution of Mo by Mn content increase, which is cheaper than the basic composition, shows a very interesting behavior at low pressures but at high pressures has the same resistance to contact fatigue damages of the standard steel.

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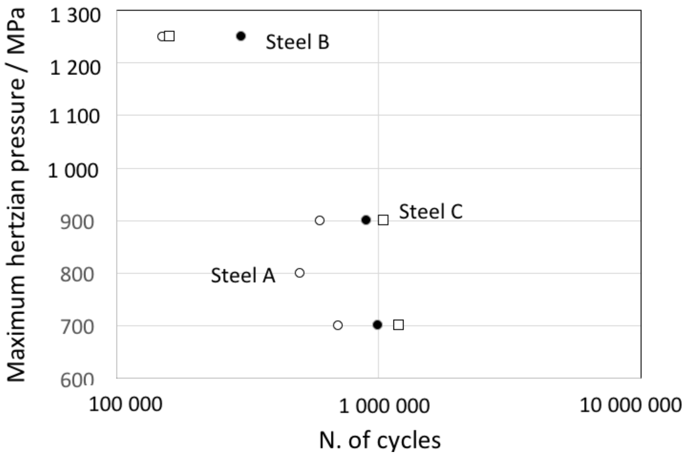
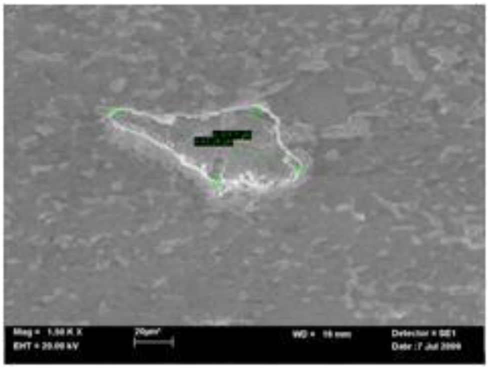
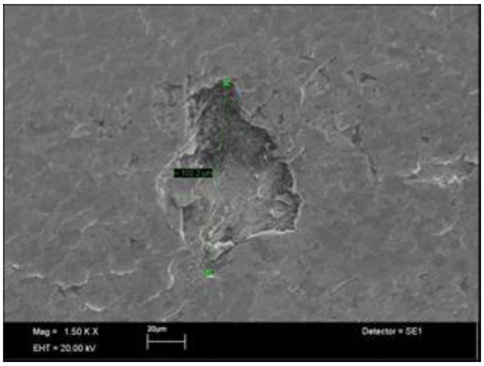


Fig. 5 Ring on ring results after first test campaign.

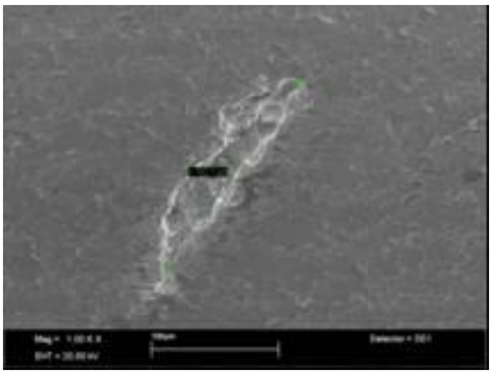
Examples of SEM analysis of specimen surfaces corresponding to pitting initiation are reported in **Fig. 6**.



Steel A after testing at 710 MPa for 8.00*105 cycles



Steel B after testing at 710 MPa for 1.04*106 cycles



Steel C after testing at 897 MPa for 1.04*106 cycles

Fig. 6 SEM image of a typical damage on ring surface (Steel B)

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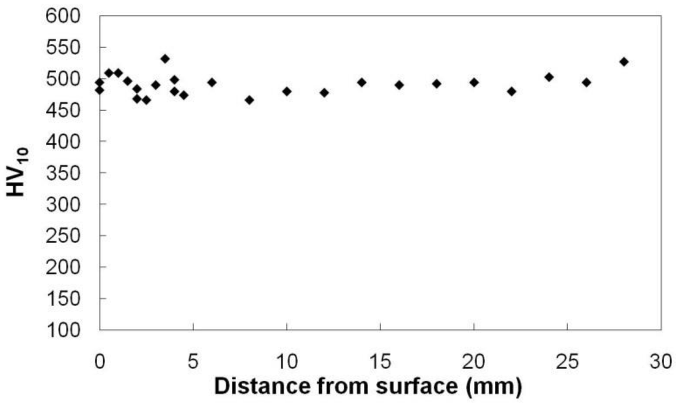
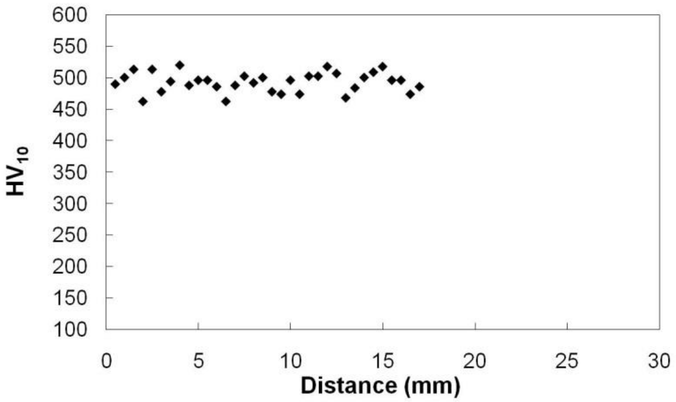
In order to understand the effect of machining on the wear resistance, steel A was machine grinded reducing the radius of 0.15 mm, 0.50 mm and 1.0 mm respectively, and then tested at 897 MPa of maximum Hertzian pressure (the intermediate value of the previously executed tests).
To evaluate if a 0.15 mm removal of material by grinding was sufficient to restore the initial condition of specimen, that means no pits on the surface and no residual surface hardening caused by previous tests, hardness measurements were performed on grinded samples (with 0.15 mm of removed material). No differences in terms of surface hardening were found by hardness measurements. Hardness profiles in the specimen bulk and in surface are reported in **Fig. 7**, showing that quite similar and homogeneous values are found.



Specimen bulk



Specimen surface

Fig. 7 Hardness profile in the specimen bulk and surface (steel B as example)

Results of Ring on Ring tests show a decrease of the damage resistance of the steel after machining: in **Fig. 8** a comparison of the effective number of cycles needed to damage steel A in different machining conditions is reported. This behavior has been observed also on the other two steels; the comparison between Steel A and Steel C in two conditions is reported in **Fig. 9** as an example (as received condition and radius reduced of 0.15 mm are shown). The test parameters were set to maintain an Hertzian pressure of 897 MPa in all trials.

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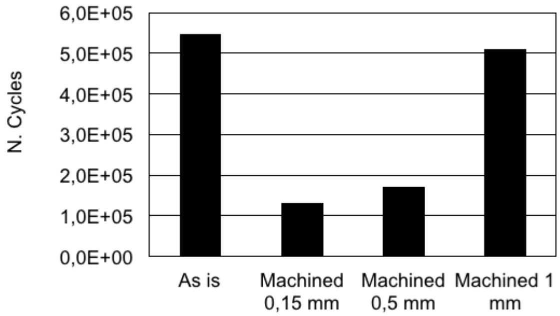

Fig. 8 Ring on ring tests on Steel A after machining

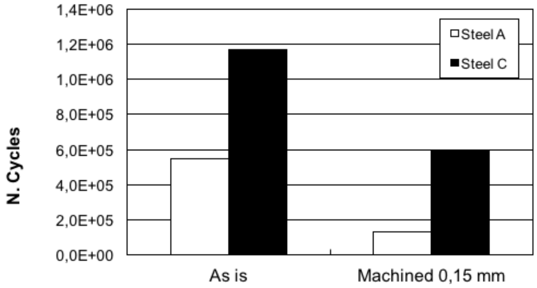

Fig. 9 Damage comparison before and after machining on Steel A and Steel C

Results can be explained considering that a portion of the thickness of the sample is affected from the rolling contact fatigue, and the machining of the component should be done with care in order to remove enough material to avoid the previous described phenomena. In fact, the yield stress of the steel is exceeded at a depth of almost 0.20 mm from the surface. The equivalent stress, taking in account the contribution of the shear, exceed the elastic limit close to the surface (for the effect of friction) and in the area in which the pressure reaches the maximum value [**20**][**21**]. Then there are two plastic zones: one immediately below the surface (depending on the value of the friction) the other one below this. The depth depends on the maximum working load and on the examined load condition: increasing the load the two areas can coalesce. An example of the distribution of the sub surface equivalent stresses [**18**] is reported in **Fig. 10**.

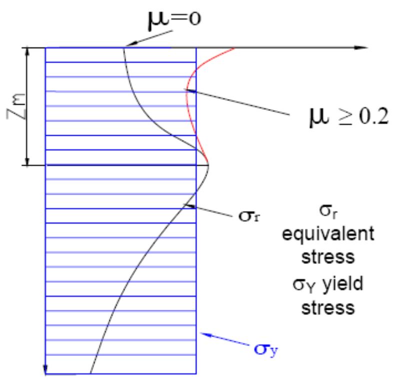

Fig. 10 Example of distribution of the sub surface equivalent stresses [4]

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The contribution of friction in the test is evidenced by the presence of pitting area whose depth is close to 10 μm. This means the highest equivalent stress is reached close to the surface. The other critical area is the one exceeding the yield stress below the surface. The machining of the sample at a depth including the extension of the plastic zone leaves a test surface with a damage memory of the previous working way. As a first approximation, the greater the cyclic plastic deformation, the easier the formation of fatigue cracks.

4 Conclusions

New steel variants for back-up rolls steels have been designed, aimed to improve rolls surface fatigue thus allowing elongated rolling campaign improving productivity and reducing costs. Starting from the basic 3% Cr steel chemical compositions adopted in SdF variants were designed. The effects of steel chemical composition on contact fatigue phenomena, that bring to the occurrence of macroscopic damages named spalling, have been evaluated. Both steel variants let to improve contact fatigue resistance even if with different behavior.

The variant B, based on V carbides precipitation hardening, is quite more expensive than the basic composition, but the advantages in terms of test duration and contact fatigue resistance are repetitive and constant at all hertzian pressures tested.

The variant C, based on partial substitution of Mo by Mn content increase, which is cheaper than the basic composition, shows a very interesting behavior at low pressures but at high pressures has the same resistance to contact fatigue damages of the standard steel.

These results show that the knowledge of the influence of different hardening mechanisms on the contact fatigue phenomena enables the design of the proper chemical composition and heat treatment, in terms of cost and performances, depending on the work conditions of the back-up rolls.

Moreover, the removal by grinding operations of damaged portion of rolls surface should be not sufficient to restore the initial performances of material. Experimental tests showed that a portion of material below the damaged one keeps memory of the last fatigue cycle, and has to be removed, in order to maintain quite constant the campaign duration along the whole back-up roll working life.

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