EFFECT OF ROLLING CONTACT FATIGUE ON THE ELASTIC-PLASTIC RESPONSE OF HADFIELD STEEL

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Abstract

The process of dynamic strengthening of Hadfield steel, currently widely used for cast railway frogs, was studied. Continual dislocation hardening up to the depletion of plasticity and creation of surface microcracks presents the specific limited state under rolling contact in this application. The narrow affected zone and intensive mechanical and structural heterogeneity on the loaded surface are restrictive for standard mechanical testing.

To study the different states of this process, instrumented indentation tests were performed. The results showed the possibility of comparative evaluation of the elastic-plastic behaviour of this steel, which is typical with high dynamic durability, but also with the significant sensibility to the ratio of normal impact loading vs. tangential slip. Because of this, an important parameter of fatigue life is the primary state of dynamic strengthening. The influence of explosion hardening, as a prospective way to improve the wear resistance of Hadfield steel, was included in the test. Each step of the degradation process was simulated using the special rolling contact stand at a defined loading condition. The measured hardness gradient of loaded surface layers displayed the depth and intensity of the induced changes. Martens hardness was measured in thus identified layers for each representative state of material. The elastic-plastic capacity of the surface layer was evaluated as a ratio elastic to the global energy of indentation. The metallography evaluation, focused on the contact surface, documented an increase of elastic response as a result of the dislocation hardening process.

Keywords: Rolling contact testing, Hadfield steel, surface layer, deformation hardening, indentation test

1. INTRODUCTION

Mat Material for rail applications, mainly for turnouts, is subjected to intensive dynamic contact loading, with variable contribution of cumulative plastic deformation, which leads to a specific limited state and wear of the surface layer. The combination of normal and tangential stresses acting between the rail and wheel surfaces is the source of incremental plastic flow or “ratcheting”. Sliding wear rate vs. the initiation of contact fatigue cracks and the rate of their propagation is decisive for operational safety [1]. Complex characterization of the surface layer's mechanical parameters influenced by plastic flow is an important precondition for the prediction of service life, mainly the determination of yield stress and work-hardening coefficient. The influence of a passing wheel mainly in contact with the turnout profile is very complex. Localised surface plastic deformation induces intensive structural and mechanical heterogeneity as a consequence of actual contact loading. The accumulation of plastic strain builds up residual stresses. The very low depth of the crucial effects does not allow the usage of standard uniaxial mechanical tests for precise determination of the required mechanical parameters. Because of that, studying the actual degradation state requires an evaluation of the elastic-plastic behavior of the surface layers. The standard hardness measurement partially reflects the intensity of surface dynamic hardening, but without giving detailed information about the elastic response of the material.

Austenitic manganese steel, known as Hadfield steel, is specially employed for the casting of railway crossings, because of its exceptional work hardening capacity and fracture toughness, proven by many experimental works [2]. Depending on the loading conditions, rapid deterioration of parts can occur if the wear is faster than the work hardening. Explosive hardening is therefore a promising way to improve service life.

In the presented study, the rolling contact fatigue (RCF) resistance of Hadfield steel was tested in two states - with and without explosive hardening. The experimental loading was adjusted to the actual operational ratio between normal loading and longitudinal slip. The strengthening effect of the surface layer was monitored in chosen loading stages and verification of the experimentally induced degradation process was based on structural analyses of the operationally induced process. The instrumented indentation test was employed for the evaluation of the elastic-plastic capacity of thin surface layers under the influence of rolling contact in compared states of Hadfield steel.

2. METHODOLOGY OF EXPERIMENT

2.1. Rolling contact simulation

Hadfield steel is characterised by its high sensitivity to the ratio between dynamic normal loading and longitudinal slip. Based on particular loading conditions, different degradation mechanisms can occur. Spalling of the surface layer represents a commonly observed consequence of excessive surface hardening due to dynamic loading; intensive wear of the contact profile results from the higher tangential force (and slip) in rolling contact.

Samples for the analyses of actual degradation mechanisms were cut out from a railway switch in position, where the contact track was 40 mm in width, i.e., in a position characterised by high dynamic operation loading. The chemical composition of the tested Hadfield steel was in full accordance with the standard EN 15689. The degradation process was simulated by a specialized wheel-test rig which enables rolling contact loading at a defined ratio between contact pressure and longitudinal slip. The contact was induced between a wheel 920mm in diameter and a special sample holder - a disk 136 mm in diameter. The principle of the test is displayed in **Fig. 1**. The tested samples can be pulled out from the holder during the test and can be subjected to complex material analyses in chosen stages of the fatigue test. The presented test focused on the degradation mechanism in defined stages of the rolling-contact loading, so the evaluation consisted of the following parameters: surface hardening (in HV10 hardness values), depth of the plastic zone, character and depth of the surface damage (i.e., the slope and depth of the surface microcracks) and wear rate, measured by the weight loss between defined steps of the loading. The test was performed at contact pressure P_{max} = 1140 MPa and relative longitudinal slip s = 1 %. The dynamic response of the Hadfield steel was evaluated in two conditions - after the typical fabrication process vs. after the explosive hardening process. The influence of explosive hardening on degradation mechanisms was assessed within this experiment.

Deformation hardening of surface layers was evaluated per 100-thou cycles; average values from 3 measurements of each of the 4 samples' surfaces are shown in **Fig. 2**. Intensive surface hardening was induced in the early stage of loading for both states of Hadfield steel. A sharp rise in hardness together with minimal wear appeared during the first 200-thou loading cycles. At about 300-thou loading cycles the biggest weight losses were ascertained for both compared states of the Hadfield steel, and earlier onset of intensive wear for material without explosion hardening. The tip of the observed wear progress was slightly moved to the higher loading cycles, and the global wear range of the steel after explosive hardening was lower compared to the material without prior hardening. A similar gradient of hardening depending on the number of loading cycles was ascertained up to approximately 800-thou cycles. Saturation of the hardening vs wearing processes occurred during subsequent loading cycles.

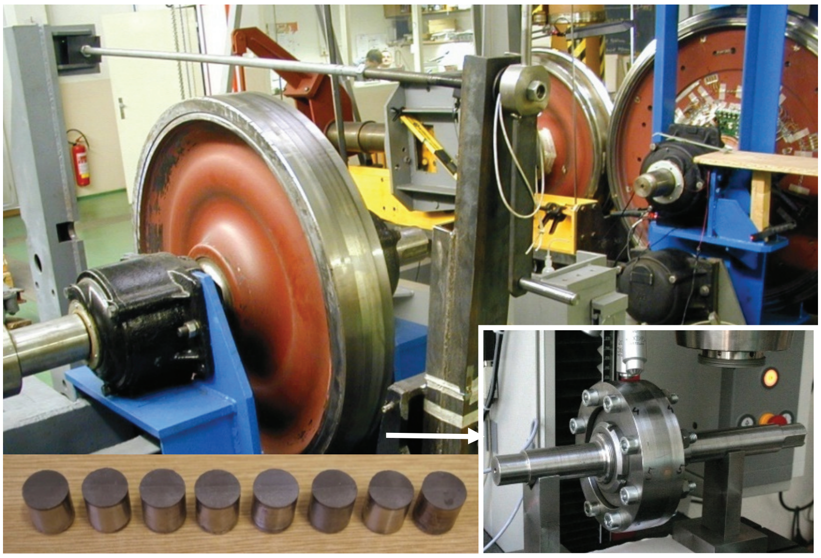

Fig. 1 Rolling-contact fatigue testing equipment, detail on holder for set of tested samples

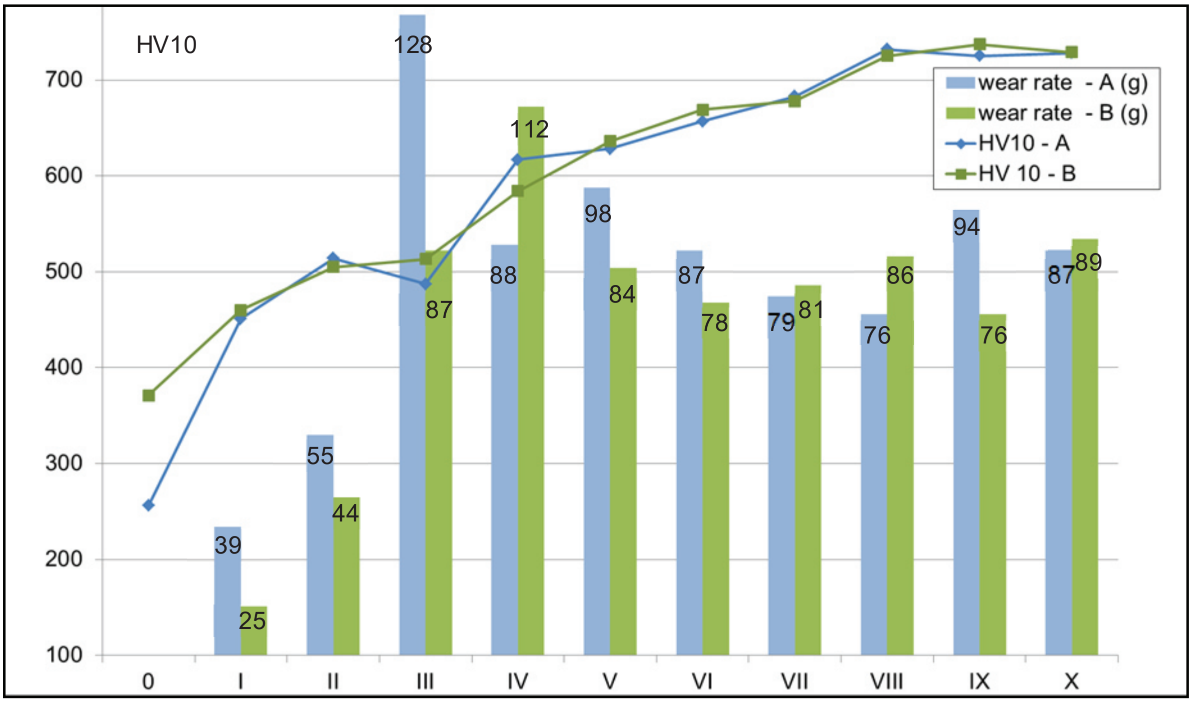

Fig. 2 Hardening process vs. wear rate induced by experimental contact loading, in HV10 values (A… samples without explosive hardening, B… samples after explosive hardening)

2.2. Structural Analyses of surface layers

The structural analyses were performed in the final state of the test, i.e., after 10^6 loading cycles. Intensive dislocation hardening to a depth of 700 µm was observed by metallographic analysis in cross sections directed according to the rolling contact (**Fig. 3**). Two different mechanisms of surface microcrack initialization were involved in the wear during the rolling contact.

The first one was the creation of a surface layer similar to "White Etching Layers" (WEL) typically formed in pearlitic railway steels. This name was derived from its white appearance, resulting from its higher corrosion resistance to metallographic etching. This cont0rast phase was created by simulated contact fatigue loading to a depth of 30 μm, and a different level of plastic deformation inside these layers was typical. Voids and microcracks were created directly in this layer approximately perpendicularly to the contact surface, apparently as a consequence of the fragility of these microvolumes. Surface hardness in those positions, measured to over 700 HV10, proved limited decrease in plasticity. Microcracks initiated at the interface with bulk material or in sublayers with less intensive plastic deformation typically propagated along the interface with different intensity of induced transformation. This tendency is pictured in detail in **Fig. 3** for the tested material without prior explosive hardening. Initiated microcracks propagated until wear flakes were formed at the surface. Based on continuous contact surface observation, this stage of the degradation process corresponds with the onset of increased wear rate at about 300 thou. cycles of experimental loading.

The differing degradation process was connected with ductile shear caused by the progressive shear deformation. Surface fatigue cracks were initiated and propagated by a low cycle fatigue mechanism, driven by cyclic plastic strain. While the orientation of microcracks due to "WELL" was subjected to the inhomogeneity of the deformation on the surface, the RCF cracks followed the plastic flow. In operational conditions, surface cracks due to RCF, known as a "Head check", are perpendicular to the running direction of the wheel.

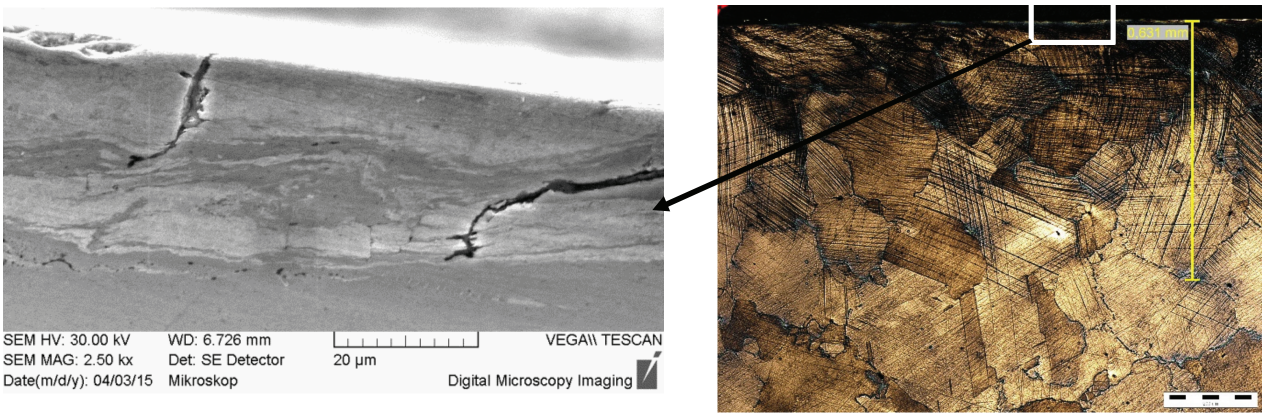

Fig. 3 Creation of "WEL" like surface layer

2.3. Indentation Tests

The macro range (i.e., over 2N) of the instrumented indentation test using a Vickers indenter according to standard ISO 14577-1 was used, so the measured parameters were not significantly influenced by the contact area or the actual shape of the indenter tip. The test procedure was force controlled. A continuous recording of the force and the relevant indentation depth was the result of the test. The results presented in **Table 1** are the mean values of 10 measurements. The higher standard deviation of the values after contact loading reflects the local differences in surface damage, i.e., the effect of repeated creation of surface hardened microvolumes up to the "WEL" state simultaneously with the uncovering of the "parent" material due to spalling of the layers. Martens hardness (HM) includes plastic and elastic deformation. The mechanical work during the indentation procedure (W_{total}) is only partly consumed as plastic deformation work. During the removal of the test force the remaining part is set free as the work of elastic reverse deformation W_{elast}. The relation η_{IT} (W_{elast} /W_{total}).100[%]) reflects the differing residual plastic capacity of the surface layer during rolling contact loading. The depth of the contact - fatigue strengthening needed to be determined for reliable measurements of the surface layer state. The gradient of experimentally induced surface changes was evaluated by hardness measurement directed perpendicularly to the loaded surface - **Fig. 4**. The maximal loading force was chosen according to the depth of the intensively hardened layer at a particular measured position. Comparative yield stress CYS [MPa] was determined by a cylindrical indenter 1.2 mm in diameter. According to hypothesis about the behaviour of the material during the extrusion of a cylindrical indenter [3], the constant 2.57 was used as the ratio of compressive stress applied by the indenter to shear yield stress.

Table 1 Parameters of elastic-plastic response at analysed states of Hadfield steel

state of steel	HV 10	HM [MPa]	h_{max} [μm]	W_{elast} [N.m]	W_{plast} [N.m]	W_{total} [N.m]	η_{IT} [%]	CYS [MPa]
A	256±7	1881	44.49	0.256	1.264	1.52	16.80±1.94	338
B	371±7	2542	46.38	0.212	0.998	1.21	17.54±0.57	609
C	732±10	4268	29.7	0.373	0.643	1.016	36.68±1.70	
D	725±9	3581	33.6	0.353	0.73	1.083	33.188±5.98	
X	708±14	4201	28.73	0.316	0.688	1.004	31.459±6.24	

(A - without explosive hardening /without contact loading, B - explosive hardened/without contact loading, C - without explosive hardening/after contact loading, D - after explosive hardening /after contact loading, X - representative surface state after operational exploitation)

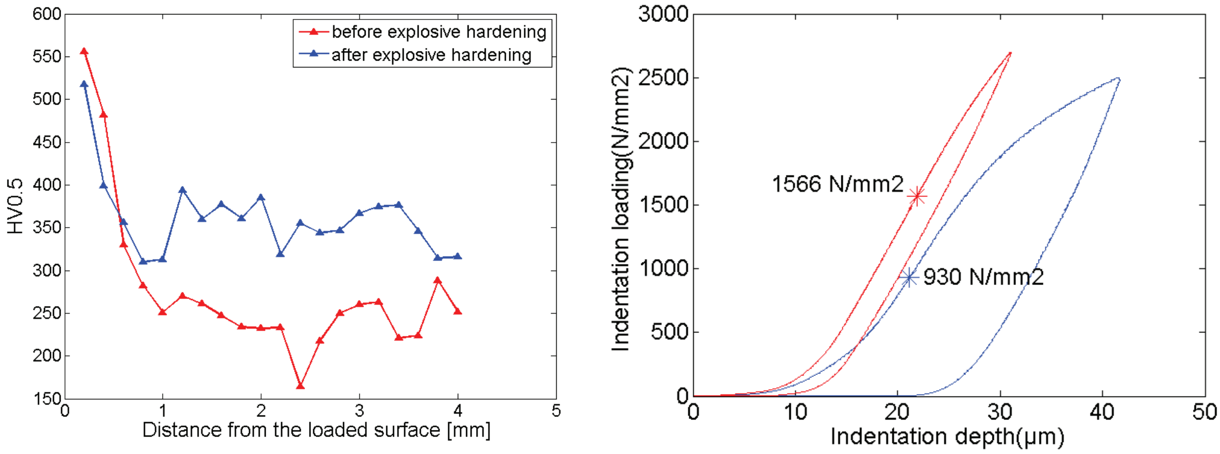

Fig. 4 Hardness gradient and indentation test record for compared stages of Hadfield steel

3. CONCLUSIONS

The degradation process in rail-wheel contact was simulated for Hadfield steel in two initial states - with vs. without explosive hardening. Based on the performed structural analyses and indentation test we can conclude that the used experimental process is able to simulate the actual degradation mechanism up to achieving a specific limited state of the surface layers of Hadfield steel. The used methodology enables evaluation of the degradation process in particular stages of loading.

Two interacting processes were observed. The formation of so-called White Etching Layers leads to the initialization of microcracks and surface spalling as the predominant wear process. Some delay in the onset of intensive wear was ascertained for the explosively hardened samples, with a very similar gradient of subsequent dynamic hardening and wearing process compared to material without prior explosive hardening. The higher overall wear rate of samples without explosive hardening can be associated with the earlier onset of spalling, more intensive hardening during the first stage of loading and mainly with sharper hardness contrast at the interface between the hardened surface and the bulk of steel.

Opinions about the substance and source of formation of WEL differ. For example, Takahashi [4] reported that martensite is formed due to frictional heating in rail-wheel contact areas. Contrary to that, nano-ferrite crystallization caused by repeated severe plastic deformation was discussed [5]. It needs to be mentioned that the origin and mechanism of the formation of WEL is still the subject of scientific interest, and reported results are related to pearlitic steels as a typical material for rails and wheels. Despite these uncertainties, the presence of WEL was proven to be detrimental to fatigue life through the mechanisms of crack initiation [6]. The performed test showed the formation of WEL-like layers in Hadfield steel, i.e., in the initial fully austenitic microstructure. The results indicate the predominant influence of dynamic hardening up to the "dynamic destruction" of the primary microstructure. As a validation, the operationally induced changes were analysed using the same methodology, i.e., structural change evaluation, hardness and elastic-plastic capacity measurement of samples taken from actual loaded track. The same process as the experimentally induced process was observed in parts of the turnout with high dynamic loading. These results support the hypothesis that severe dynamic strengthening leads to WEL formation, contrary to the mentioned martensitic transformation after rapid austenitization as the potential origin of WEL.

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