SPHERICAL INDENTATION APPROACH TO DETERMINE MECHANICAL PROPERTIES OF HADFIELD'S STEEL

KAYA Utku[1], SCHMIDOVA Eva[2]

[1] *Jan Perner Transport Faculty, University of Pardubice, Pardubice, Czech Republic, EU,* utkukaya63@gmail.com

[2] *Jan Perner Transport Faculty, University of Pardubice, Pardubice, Czech Republic, EU,* Eva.Schmidova@upce.cz

Abstract

Hadfield's steel has been widely used for railway switch and frogs because of its desirable mechanical behaviour under high load applications. Austenitic Hadfield´s steel containing approx. 1.2 wt. % of C and 12 wt. % of Mn is known for a high resistance to impact wear caused by rapid cold work hardening.

In this study, several methods have been performed to examine the mechanical properties of Hadfield's steel. Dislocations and white etching layers were observed during metallographic analysis. Besides that, indentation method was applied for evaluation of the elastic-plastic response of the surface. In addition to our previous studies, the spherical indentation method was introduced to obtain more accurate results for rough (uneven) surface. Force-Indentation depth graphs were examined by the specific method, moreover, real rail sample, with or without explosive hardening samples were compared by means of the new method.

Keywords: Hadfield steel, metallography, spherical Indentation test

1. INTRODUCTION

Hadfield steels are widely used for the high load railway applications. Impact load of switches and crossings is very high while the wheels have to pass from one rail to another therefore, it is necessary to use extremely resistant material against wear and another environmental condition. Hadfield steel has been commonly used for these conditions because of its exceptional work hardening capacity and fracture toughness which has been proved by many experimental works [1].

Explosion hardening is one of the ways to improve the mechanical properties of Hadfield steel by shockwave [2]. In this study, the effect of explosive hardening as a source of different elastic-plastic behaviour was observed by several experimental methods. Measuring of Hadfield´s steel mechanical behaviour by the cylindrical indentation was introduced in our previous study [3]. In this paper, the new approach using the spherical indentation and its advantages will be introduced. Besides that, mechanical behaviour of the operationally loaded samples vs. experimentally loaded samples will be compared by means of the new method.

2. EXPERIMENTAL AND RWAULTS

Samples were prepared to perform the metallographic analysis before applying indentation test. The sample for analysis of real degradation mechanisms was cut out from railway switch the cross section was 50 mm in the width of contact track. The degradation process was also simulated by specialized wheel-test rig (**Figure 1a**), which enables the rolling contact loading at a defined ratio of the contact pressure and longitudinal slip. The contact was induced between the wheel with 920 mm in diameter and special sample holder - disk with 136mm in diameter. The tested samples may be pull-out from the holder during the test and can be subjected to complex material analysis in chosen stages of the fatigue test. The experimental procedure, i.e.

the loading level and evaluation principle, simulated the standard operational conditions. The test was performed at contact pressure P_{max}= 1140 MPa and relative longitudinal slip s = 1 % until 1mil.of loading cycles. Several samples in the final stage of loading were prepared for metallography analysis. Intensive dislocation hardening was observed near the surface. Dislocations resulted to the high loading hardening (**Figure 1b**), as well as local destruction of the surface layers similar to so-called White Etching Layers (WEL). WEL are typically formed in the pearlitic railway steels; they were observed in very local surface layer (20 -100 µm in width) within currently performed experiment.

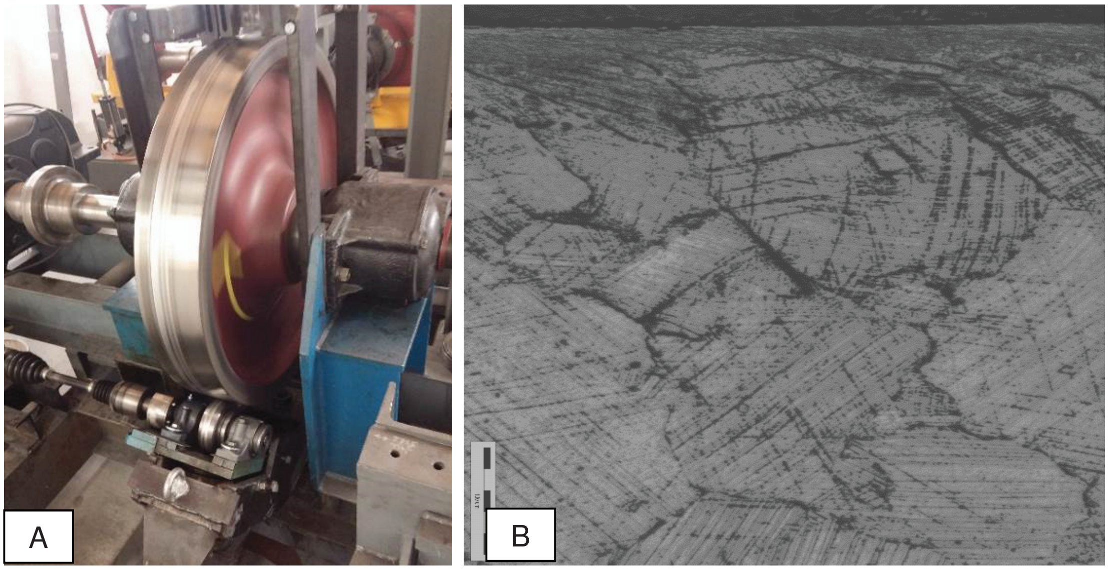

Figure 1 Surface dislocation hardening after rolling contact test

2.1. Indentation test

We used the cylindrical indentation to determine comparative yield stress CYS [MPa] in our previous study. Cylindrical indenter with diameter of 1.2 mm was applied to obtain indentation depth corresponding to linear force to examine the effect of explosive hardening [3].

In this paper, spherical indentation method is introduced. Because of intensive operational damage of surface layers together with a typical material heterogeneity of Hadfield steel, the standard evaluation by cylindrical indentation is limited. Spherical indenters give better results even for rough surfaces and also results are less affected by micro-cracks, grain boundaries, and typical micro-casting defects. Besides that, spherical indentation methods let us a direct surface measurement without cutting off samples. Unlike pointed indenters, elastic-plastic, and fully developed plasticity regime of material can be determined by spherical method because spheres possess the unique ability to transition through perfectly elastic to fully developed plasticity zone. Cylindrical indenter's sharp edges behave like Vickers indenter (as seen in **Figure 2**) which results in exceeding of the elastic regime by small forces.

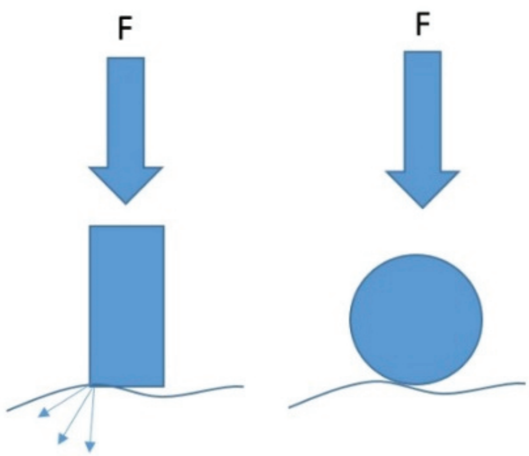

Figure 2 Effects of cylindrical and spherical indenter for uneven surface

Numerous investigators have proposed methods to measure the yield strength of metals using instrumented indentation experiments performed with a sphere. Brinell was one of the investigators who brought simple approach for indentation method in 1990. It was the first widely used and standardized hardness test in engineering and metallurgy. Indentation diameter is measured by the optical system. However, indentation diameter can't be easily determined because of piling up (pile-up) or sinking in (sink-in) caused by the plastic flow of the material surrounding the ball indenter as seen in **Figure 3**.

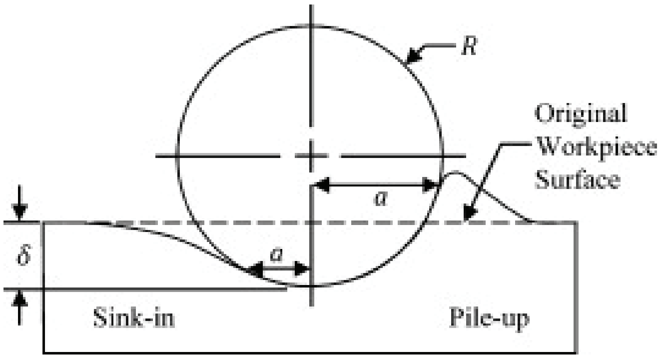

Figure 3 Indentation diameter affected by pile-up or sink-in effect [4]

Application of instrumented indentation methods enables the evaluation based on loading force/ indentation depth, even the study of material response at a particular stage of loading. Typical spherical indentation depth and force graph can be seen in **Figure 4.** Curve's deflection between indentation (blue), and relaxation curve (red) was examined for several samples. These deflections seem to be more narrow (cover less area) for hardened sample. However, it is more expanded behaviour for unhardened samples (as seen in **Figure 5**), because increasing rate of indentation depth corresponding to the force is more compared to hardened sample. The mathematical expression of deflection can be calculated with equations below. Each P value determines the variation of indentation depth corresponding to the force. We named curve energy deflection change as ''P_{mean} value''.

$P_1 = X_2 - X_1$ (P_2, P_3, P_4, ... P_N can be calculated as P1) (1)

$$P_{mean} = \frac{P_1+P_2+P_3+P_4+\cdots\ldots+P_N}{N} \quad (2)$$

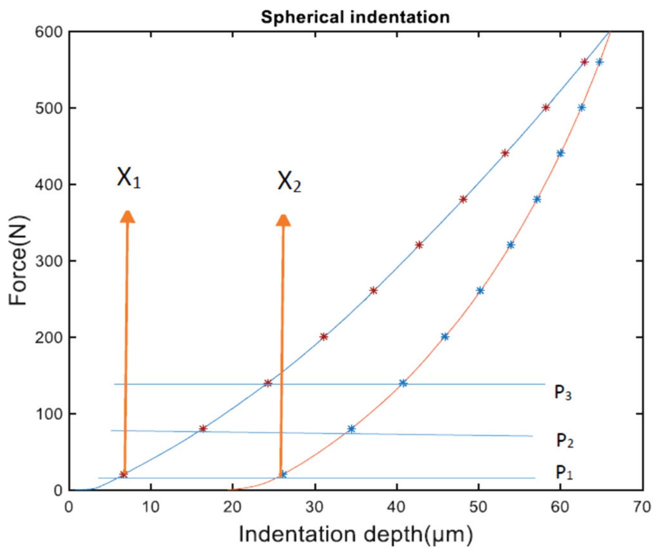

Figure 4 Mathematical calculation of deflection between indentation and relaxation curve

We applied 2000 N for 4 different samples by using 5 mm indenter. After the removal of the indentation force, the diameter of the indentation was measured. Contact diameter is influenced by mentioned undesirable effects (**Figure 3**), so at least 5 measurements should be performed in every position. Effect of explosion hardening changes both "Brinell hardness" and "**P_{mean}**" values. There is a reverse ratio between P_{mean} and hardening effect as **Table 1** demonstrates. The harder surface has a narrow graph, low P_{mean} values, and high Brinell hardness (as expected in **Figure 6** and **Table 1**).

Table 1 Effect of explosion hardening expressed by used mathematical parameters

Samples	Force (N)	P_{mean}	Contact diameter (µm)	Brinell hardness
After explosive hardening	2000N	22.16	984	274
Before explosive hardening	2000N	36.16	1213	165
Real switch sample - surface	2000N	21.93	907	313
Real switch sample - middle	2000N	36.92	1200	177

2.2. Comparison of operational vs. experimental loading effect

To validate the experimental loading system the indentation measurements were performed in the next positions:

- Real rail sample (after operational loading) beyond the effect of contact loading,
- The surface area of the real rail sample (after operational and explosive hardening) - **Figure 5**,
- The surface area of the samples with and without explosive hardening (after applied rolling contact test in the laboratory).

The explosive hardened surface of rail samples presented the state of dislocation hardening due to rolling - contact and shock hardening process.

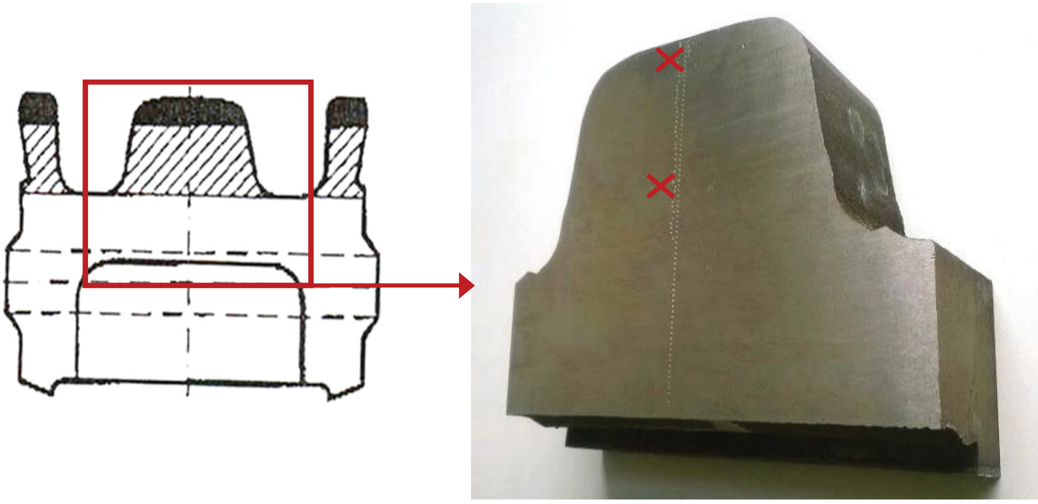

Figure 5 Measurement positions for the real rail sample

Because of the hardening effect of rolling contact and explosive hardening, explosive hardened sample (also after experimental loading) displays almost the same mechanical behaviour as the real rail sample (measured near the surface). We calculate P_{mean} values as $\mathbf{P_{Realrailsurface}} = 21.93$, $\mathbf{P_{Afterexphard}} = 22.16$. These values are unsurprisingly very close and tendencies of curves are narrow compared with unhardened samples **(Figure 6**).

We also compared samples without explosion hardening (experimental loading) and real rail sample (middle point).These samples are less affected by operation loading and explosive hardening. For this reason, curves of these samples have more expanded tendency compared with hardened samples. This curve behaviour can be explained by means of P_{mean} values ($\mathbf{P_{Beforeexphard}} = 36.1$, $\mathbf{P_{Realrailmiddle}} = 36.92$). These samples display almost the same mechanical behaviour.

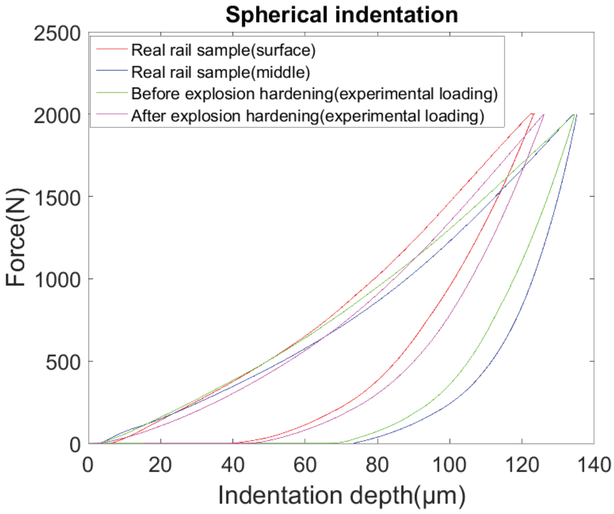

Figure 6 Comparison of indentation curves tendency

3. CONCLUSION

Explosive hardening methods were proved as a perspective way to extend the service life of steel by dislocation hardening of the surface layers. Creation of dislocations can be observed also due to operational loading because of work hardening. The residual plastic capacity of surface layers is decisive for material resistance to the rolling contact loading. Depletion of plasticity, as an incremental effect of the hardening process, is a typically limited state of the railway steel in rail- wheel contact.

Different stages of the hardening effect were observed by metallographic analysis after experimental loading. Besides that, the spherical indentation was applied in order to evaluate the mechanical behaviour at different loading conditions and results were analysed by a specific method. Four types of measurements were performed; real rail sample (i.e. after operational loading and also after explosive hardening) was evaluated inside the affected surface layer and beyond this layer. Experimentally loaded samples in the both stages (with and without explosive hardening) were also measured by suggested method. Loading force-indentation depth graphs were examined and curve tendency was expressed by the simple mathematic method. Effect of hardening was compared between each sample and expected results were also verified by "P_{mean}" value.

The comparison of the results has shown the possibility of suggested way for easy monitoring of the elastic-plastic response of the surface. This evaluation can be used as a comparative method for estimation of the residual plastic capacity of the steel. The introduced way of evaluation can be used also as a validation of experimental simulation of the both processes - load fatigue and explosive hardening.

REFERENCES

[1] HARZALLAH, R., MOUFTIEZ, A., FELDER, E., HARIR,I S., MAUJEAN, J.- P. Rolling contact fatigue of Hadfield steel X120Mn12. Wear, 2010, vol. 269, pp. 647-654.

[2] NORMAN, A. M. Method of hardening manganese steel, US patent no. 2703297, 1955.

[3] HAVLÍČEK, P., ZBOŘIL, T. Wear of the railway turnout Crossings Made of Explosive Hardened Hadfield Steel. In Metal 2013: 22nd International Conference on Metallurgy and Materials. Ostrava: TANGER, 2013, pp. 415-420.

[4] ANDERSON, D. D., WARKENTIN, A. A., BAUER, R.R. Simulation of Deep Spherical Indentation Using Eulerian Finite Element Methods. ASME. J. Tribol., 2011, vol. 133, no. 2, pp. xx-xx..