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THE INFLUENCE OF NONMETALLIC INCLUSION ON STRAIN HARDENING CARBON STEEL

Summary. On a fragment of the rim of a railway wheel removed from service, the volume of the metal with non-metallic inclusions located near the tread surface was investigated. The use of the microhardness measurement technique made it possible to establish the nature of strain hardening of carbon steel near non-metallic inclusions. It showed that with a normal orientation of the plastic flow relative to the inclusion surface, the metal volumes undergo hardening. In proportion to the appearance of a fraction of the tangential component of the deformation near the nonmetallic inclusion, a decrease in the degree of hardening of the metal was observed.
Keywords: deformation, steel, railway wheel, microhardness, non-metallic inclusion

1. INTRODUCTION

Improving the operational safety of railway wheels is achieved through different qualitative technological solutions [1]. Purposeful development of proposals for changing the chemical and phase composition of steels for the manufacture of railway wheels [1, 2], explaining the influence of dispersion and morphology of structural components on the complex of properties [3], including after

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thermal hardening [3, 4], is impossible without explaining the mechanism behind the formation of damage to the metal on the rolling surface [5]. From the interaction with the rail, the resulting non-uniform distribution of plastic deformation of the metal over the rolling surface of the wheel [5, 6] receives an additional gain from the presence of non-metallic inclusions [7, 8].

The assessment of the level of internal stresses that are formed in the metal close to the particles [9] indicates the total effect not only of size, shape and distribution but also the nature of the origin of non-metallic inclusions. Indeed, as shown in [7, 10], differences in the type of crystal lattice, the ability to thermally expand, etc. metal matrix and particles of non-metallic inclusions, leads not only to a change in the magnitude of residual stresses but their sign as well [11, 12, 13].

2. MATERIALS AND METHODS

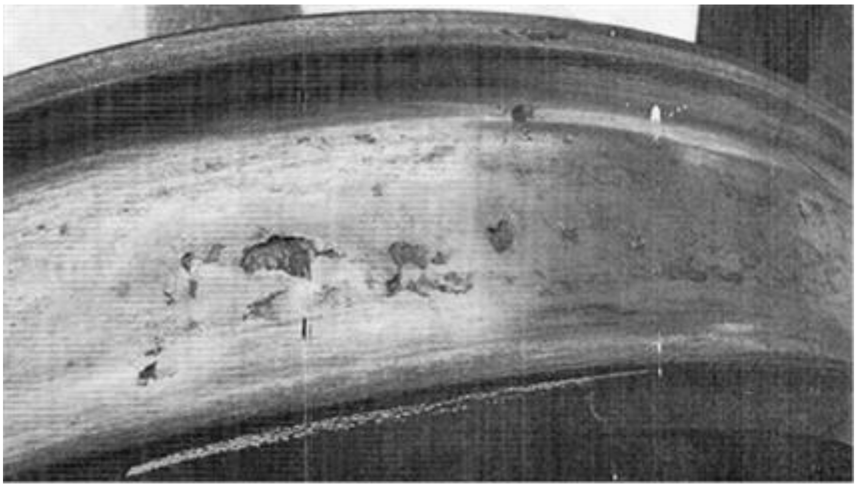
As an object of study, a fragment of a whole-rolled railway wheel was taken out of service due to damage to the rolling surface above regulatory restrictions. The chemical composition met the requirements in the redistribution of steel grade used for the manufacture of railway wheels: 0.62% C, 0.78% Mn, 0.30% Si, 0.031% S, 0.029% P, 0.09% Ni, 0.14 % Cr, 0.15% Cu. The selection of blanks for the manufacture of the object of study for the microstructure was carried out from areas of the rim with detected damage to the rolling surface.

The microstructure was studied under a light microscope. Sample preparation for the study was carried out in accordance with the methods of structural analysis. In order to prevent distortion of the field of residual stresses in the metal, after the grinding operation, the work-hardened layer was removed from the surface of the sample using the electrolytic dissolution technique [14]. To identify the microstructure of the metal, the samples were etched with nital. As a characteristic, to assess the hardening of metal micro volumes, microhardness (H_{μ}), measured by a PMT-3 type instrument, was used with an indenter load of 0.49 N.

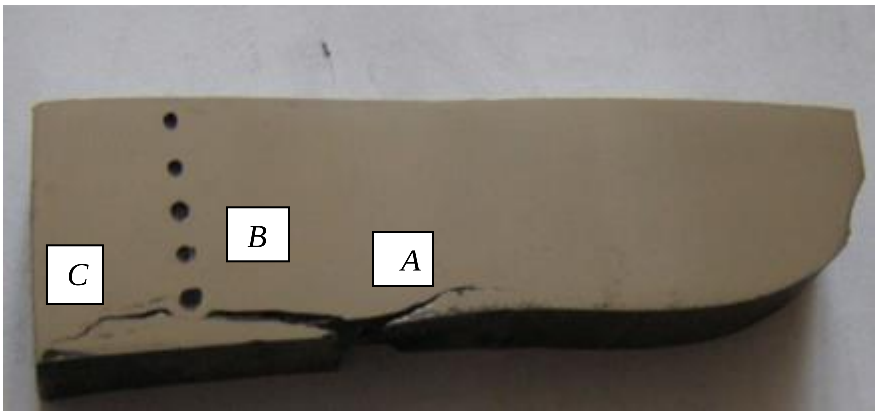
3. RESULTS AND DISCUSSION

In addition to the influence of carbon content in steel and the degree of thermal hardening on the damageability of the rolling surface, there is a definite dependence of the formation of the number of local metal absence on the rolling surface in the presence of non-metallic inclusions [15]. Figure 1a shows the rolling surface of a railway wheel with typical damage in the form of local metal absence, which was removed by machining when the profile of the rim was restored. The formation of local metal absence with the orientation of growing cracks inside the rim (Fig. 1b, designation *AB*), is one of the reasons for removing the railway wheel from operation as it is unfit for future use.

As a result of the layer-by-layer removal of metal from the surface of the rim fragment, the effect of a nonmetallic inclusion particle in the change in the direction of a growing crack was found (Fig. 1a, symbol *B*). This confirms the given growth sequence, the magnitude of the divergence the crack faced, which is maximum in point *A* and minimal in point *C* (Fig. 1b). Considering the cyclical nature of the change in the effective stresses in the wheel-rail contact area, the normal component of the deformation should ensure the metal hardening from the development of the deformation hardening processes. With increasing distance from the rolling surface, the damped effect of strain hardening is accompanied by a decrease in residual stresses in the metal [16]. From the formal analysis, it follows that when the particle is located on the path of propagation of plastic flow, distortion would arise in the monotonous nature of the metal work hardening. Moreover, the higher the particle hardness compared to the metal matrix, the more its effect in the change in the strength characteristics of the metal. For the case under study, the immutability of the particle shape (Fig. 1b) indicates that the nature of the effect on the metal matrix should be classified as non-deforming inclusions [9, 17].



a

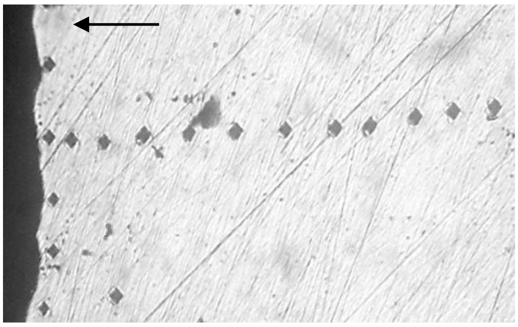


b

Fig. 1. Appearance of damage to the rolling surface of the railway wheel (a) and fragment of the rim of study (b)

Considering the differences between the metal lattices and the inclusion, the formation of internal stresses from the phase hardening should contribute to the initiation of a crack at the interface. However, the observed crack growth trajectory (point *B*, Fig. 1 b) indicates that the plastic flow in the bulk of the metal between the rolling surface and the non-metallic inclusion is most likely due to the formation of compression stresses. Indeed, if it is assumed that the strain hardening of the metal near the particle surface is ensured by the action of the normal component of stress from the wheel-rail interaction, it becomes clear that there is no effect of reduced resistance to crack growth along the interface. The distribution of the indenter prints across the thickness of the metal layer enclosed between the crack and the inclusion surface (symbol *B*, Fig. 1b) and the corresponding pattern of change H_μ depending on distance (*L*) with distance from the particle are shown in Fig. 2.

The extreme nature of the ratio $H\mu \sim f(L)$ indicates the effect of hardening the metal from the normal orientation of the plastic flow relative to the particle surface. Despite the fact that the metal interlayer between the surfaces of the particle and the crack (Fig. 1b, designation *B*) is in the glued-up state to a hardness level of 3.6-3.75 GPa, the magnitude of the increase still reaches 2 times. According to external signs, the presented dependence is similar to that observed during thermal effects on the metal. However, when the occurrence of internal stresses in the metal close to the particles is the result of differences only in the coefficients of thermal expansion, in the absence of texture, the stresses are oriented radial relative to the inclusion surface [14]. Based on this, the cyclic change of the stages of heating and cooling the railway wheel during operation is already accompanied by an increase in internal stresses near the interfacial interfaces [5, 6].



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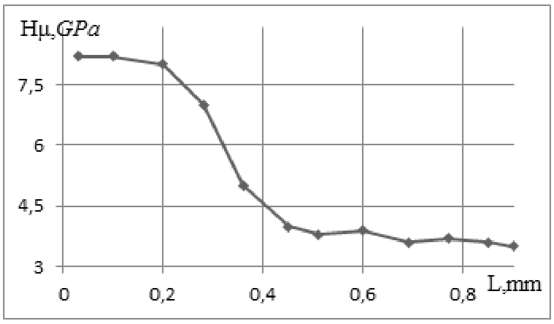


b

Fig. 2. The location of the indenter hardness tester is perpendicular to the inclusion surface (indicated by an arrow) (a) and the corresponding values H_μ (b) as they move away from the particle

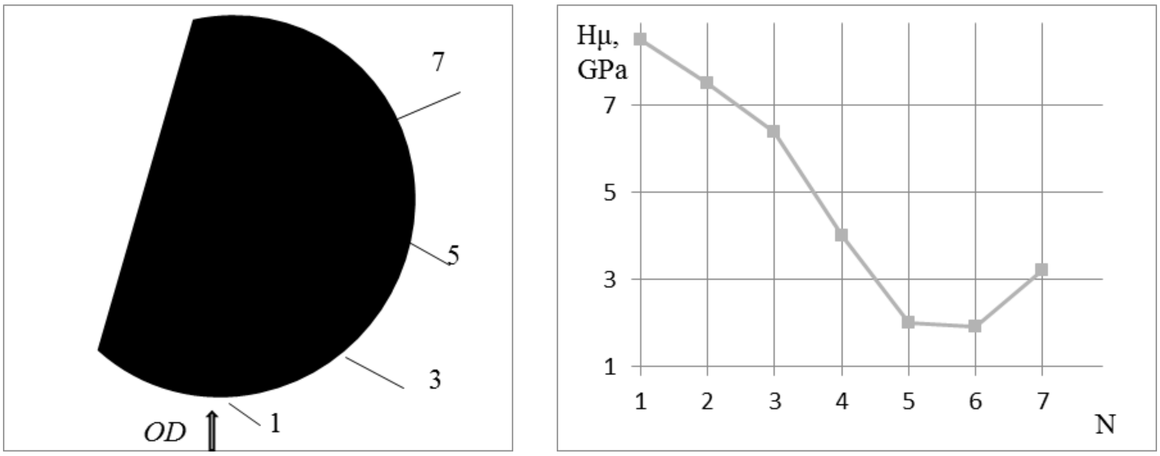
In the case of propagation of plastic deformation during the work hardening of the metal over the rolling surface, the picture is somewhat different. Considering that the interfacial interface is capable of performing the functions of both the nucleation and annihilation sites of dislocations [14], the presence of the inclusion should inevitably lead to a violation of the conditions of uniformity of plastic flow propagation. Based on this, depending on the degree of plastic deformation, the volumes of the metal near the particles should be enriched to a different degree by defects in the crystal structure (dislocations, vacancies, etc.).

With the frontal orientation of the flow relative to the interfacial surface, after exhaustion of the resource of accumulation and annihilation of dislocations, the number of inhibited crystal structure defects should increase when approaching the particle, which is confirmed experimentally (place N = 1 measurement H_μ, Fig.3b). On the other hand, in the neighbouring micro volumes of the metal, where the influence of the particle is reduced or absent, the process of accumulation of these defects should be different. As a result, we should expect a change in the field of residual internal stresses and, as a consequence, the nature of the distribution of the metal microhardness along the contour near the particle of a nonmetallic inclusion (Fig. 3).

Experimental data H_μ when measuring along the interfacial surface (Fig. 2a) indicate a change in the nature of the strain hardening of the metal when it deviates from the frontal orientation of the deformation. Indeed, an increase in the proportion of deformation with a tangential component is accompanied by a gradual decrease H_μ (Fig. 3b), reaching minimum values (points 5.6). The result obtained indicates the existence, at least, of a qualitative dependence of the level of residual stresses in the metal layer (Fig. 2 b) on the contact phenomena in the interaction of the wheel and the rail. Moreover, in the area of maximum tangential stresses (N = 5.6), a decrease H_μ was found to 1.8 GPa, which is lower than the minimum values H_μ (Fig. 2b).

Based on this, it can be assumed that the closer the inclusion is to the incline, the greater the distortion that must be made in the field of metal deformations in volumes close to the rolling surface of the wheel. Given the current trend of increasing the strength characteristics of railway wheels, we should expect a decrease in the crack resistance of the metal from the non-uniform stress distribution in the micro volumes of the metal close to the non-metallic inclusions. One evidence of this is the result of the study of causes of reduction in cyclic crack resistance of high-strength wheels during operation [19]. The observed effect of non- metallic inclusion particles is in fact much more complicated if one considers the effects of a thermal nature [2, 5, 7, 20].

In addition to the work hardening on the rolling surface, changes are expected in the metal structure from successive stages of intense heating during deceleration of the rolling stock and accelerated cooling of the wheel rim from the incoming airflow. The structural state of the steel will be determined by the ratio in the development of qualitatively different mechanisms of structural transformations from diffusion to shear [4, 19]. Therefore, the complex processes of redistribution of defects in the crystal structure near the particles can lead to unpredictable changes in internal stresses in the metal of the railway wheel.



a b

Fig. 3. Layout of locations *(N)* of measurement $\boldsymbol{H_\mu}$ close to non-metallic inclusion (a) and the corresponding values $\boldsymbol{H_\mu}$ depending on *N* (b); the direction of plastic deformation (*OD*) is indicated by an arrow

4. FINDINGS

1. The character of the strain hardening of carbon steel near non-metallic inclusions was investigated.
2. In the case of normal orientation of the plastic flow relative to the inclusion surface, the metal volumes were subjected to hardening.
3. The growth of the share tangential component of the deformation near the non-metallic inclusion was accompanied by a corresponding decrease in metal hardening.

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References

1. Soares H., T. Zucarelli, M. Vieira, et.al. 2016. “Experimental characterization of the mechanical properties of railway wheels manufactured using class B material”. *XV Portuguese Conference on Fracture PCF.* 10-12 February 2016, Paço de Arcos, Portugal. *Procedia Structural Integrity* 1: 265-272.
2. Walther F., D. Eifler. 2004. “Fatigue behaviour of railway wheels at different temperatures”. *Mater. Test.* 46(Lm): 158-162.
3. Vakulenko I.O. 2016. “Influence of cooling rate on the strength of the rims of railway wheel”. *Materials Science* 6: 839-842.

4. Ahlström J., B. Karlsson. 1999. "Microstructural evaluation and interpretation of the mechanically and thermally affected zone under railway wheel flats". *Wear* 232: 1-14.
5. Vasauskas V., Z. Bazaras, V. Capas. 2005. "Strength anisotropy of railway wheels under contact load". *Mechanika* 1: 31-38.
6. Vakulenko I., A. Kawalek, L. Vakulenko, S. Proiydak. 2018. "Influence of perlite dispersion of carbon steel on the fatique". *Metal Forming* 3: 243-252.
7. Gubenko S., Y. Proidak, A. Kozlovsky, et. al. 2008. "Influence of nonmetallic inclusions on micro breaks formation in wheel steel and railway wheels". *Transport Problems* 3: 77-81.
8. Kosicka E., Kozłowski E., Mazurkiewicz D. 2015. „The use of stationary tests for analysis of monitored residual processes". *Eksploatacja i Niezawodnosc – Maintenance and Reliability* 17(4): 604–609. DOI: http://dx.doi.org/10.17531/ein.2015.4.17.
9. Kuslickiyj A.B. 1976. *Nemetallicheskie vklyucheniya i ustalostj stali*. [In Ukrainian: *Non-metallic inclusions and steel fatigue*]. Kiev: Tekhnika.
10. Gubenko S., Y. Proidak. 2012. "Investigation of wear mechanism of tread during operation of railway wheels". *Transport Problems* 3: 119-125.
11. Finkelj V.M., O.P. Esina, V.A. Zrayjchenko. 1968. "Nemetallicheskie vklyucheniya i prochnostj stali*"*. [In Russian: „Non-metallic inclusions and steel strength"]. *Dokl. AN SSSR* 3: 576-579.
12. Malinauskas K., V. Ostaševičius, R. Daukševičius, V. Grigaliūnas. 2012. „Residual stress in a thin-film microoptoelectromechanical (MOEMS) membrane". *Mechanika* 3: 273-279.
13. Gao M.X., H. Song, J. Yang, L.J. Fu. 2019. „Study on residual stress and strain during rail rolling contact of straight U75V rail". *Metalurgija* 58(3-4): 203-206.
14. Boljshakov V.I., G.D. Sukhomlin, N.Eh. Pogrebnaya. 2001. *"Atlas struktur metallov i splavov".* Dnepropetrovs, Ukraine: Gaudeamus.
15. Kabo E., A. Enberg. 2002. "The influence of defects in rolling contact fatigue". Brescia: *Proc. Workshop Jointly Organized ICF & University Brescia.* 15 nov. 2002: 85-93.
16. Knott J.F. 1973. "*Fundamentals of fracture mechanics"*. London, UK: Butterworths.
17. Chepil R., Vira V., Kharchenko Y., Kulyk V., Duriagina Z. 2018. „The peculiarities of fatigue process zone formation of structural materials". *Diagnostyka* 19(4): 27-32. DOI: doi:10.29354/diag/94754.
18. Babich V.K., Yu.P. Gulj, I.E. Dolzhenkov. 1972. *Deformacionnoe starenie stali*. Moscow: Metallurgiya.
19. Andreyjko I.M., V.V. Kulik, V.I. Prokopecj. 2011. "Doslidzhennya poshkodzhuvanosti poverkhni kochennya zaliznichnikh koli". *Mashinoznavstvo* 2: 30-33.
20. Maruschak Pavlo, Sergey Panin, Ilya Vlasov, Olegas Prentkovskis, Iryna Danyliuk. 2015. „Structural levels of the nucleation and growth of fatigue crack in 17Mn1Si steel pipeline after long-term service". *Transport* 30(1): 15-23.

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