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# INFLUENCE OF NONMETALLIC INCLUSIONS ON MICROBREAKS FORMATION IN WHEEL STEEL AND RAILWAY WHEELS

**Summary**: It is well known that formation of defects of many types during railway wheels service somehow or other is connected to nonmetallic inclusions in wheel steel. Microbreakes connected with nonmetallic inclusions have different origin. The first one is "deformational", the second is "thermal" and the third is "hydrogenous". The objective of this work is the study of nature of microbreaking in wheel steel relative to nonmetallics. Mechanisms of microbreaking of all types near different nonmetallics had been investigated and their influence on safety threshold of railway wheels had been analyzed herein.

# ВЛИЯНИЕ НЕМЕТАЛЛИЧЕСКИХ ВКЛЮЧЕНИЙ НА ФОРМИРОВАНИЕ МИКРОРАЗРУШЕНИЙ В КОЛЕСНЫХ СТАЛЯХ И ЖЕЛЕЗНОДОРОЖНЫХ КОЛЕСАХ

**Аннотация.** Хорошо известно, что образование дефектов различных типов в процессе эксплуатации железнодорожных колес, так или иначе, связано с неметаллическими включениями в колесной стали. Микроразрушения, связанные с неметаллическими включениями имеют различную природу: деформационные, термические и "водородные". Исследованы механизмы образования всех типов микроразрушений вблизи различных неметаллических включений, а также влияние неметаллических включений на надежность железнодорожных колес.

## 1. MATERIALS AND PRINCIPLES OF INVESTIGATION

Standard samples of wheel steel produced at Nizhnedneprovsky Tube-rolling plant had been selected for examination. Samples had been subjected to plastic deformation with use of IMASH-5C unit at temperature ranging from $25^0$C up to $1200^0$C. The development of steel matrix deformation near nonmetallics as well as mechanism of microbreaks formation had been studied. Railway wheels after exploitation had been investigated in order to analyze damages occurred near inclusions. Moreover, wheel steel samples had annealed in hydrogen medium at temperatures $650^0$C and $1100^0$C with different gas pressure.

## 2. INVESTIGATION RESULTS AND DISCUSSIONS

During the hot deformation of wheel steel, billet and then wheel on process stages, varying in deformation method and thermal forced influences through different deformability of inclusions and steel matrix deformational stresses concentrated near them. These stresses cause three types of microbreakes: voids or ductile cracks on interface inclusion/steel matrix, brittle cracks inside nonmetallic inclusions, cracks in steel matrix near inclusions [1-3].

In many respects, the quality of wheel steel and mechanical properties level is determined by processes that are running during plastic deformation.

Steel deformation at temperature ranging from $25^0$C up to $700^0$C is accompanied with development of intragrained sliding. At first, sliding traces occurred in ferrite and then in perlite, plates of which is then bended. First of all, microbreaks occur on ferrite-perlite interfaces. It is significant that signs of intragrained deformation occur at $600^0$C – $700^0$C conducting widening of boundaries. At $740^0$C steel is in ferrite-austenite condition distinctive by variability of grains. It should be emphasized that steel being in such condition has low plasticity. Temperature range from $900^0$C up to $1200^0$C corresponds to hot deformation modes during wheel manufacturing. At such temperatures on initial stages of deformation ($\varepsilon$~2-4% is critical) rapid growth had started as a result of dynamic collective recrystallization. In practice, deformation rate should be sufficiently high in order to pass rapidly this dangerous interval of deformation levels. Mechanism of hot deformation of steel is connected not only with development of intragrained sliding and twinning, but also with intensive sliding along grain boundaries which is associated with moving of grain -boundary dislocations as well as with engaging of lattice dislocations by grain boundaries with its further delocalization and moving in boundary flat. Inside of grains dynamic substructure is developed which is related to hardening processes during formation of cellular and fragmentary dislocation substructure and softening in the result of dynamic return and recrystallization during reconstruction of dislocation substructure and dynamic migration of grain boundaries.

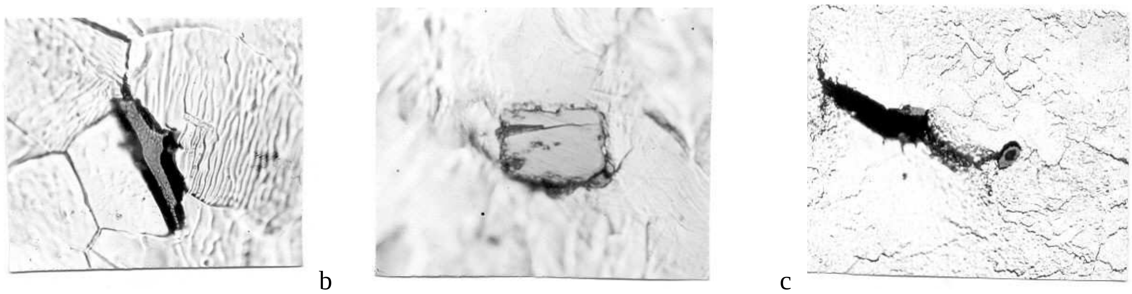
Parts of inclusions and grain boundaries promote concentration of stresses under loading and relaxation process of plastic yielding is a result of correlative behaviour of moving defects of crystal structure or elementary actions of plastic deformation near stresses concentrators which are applied and spread in metal in the form of continuous oscillating front.

During hot deformation microbreaks can occur near grain boundaries and parts of nonmetallics, i.e. where max deformations are located and matrix plasticity margin is exhausted. Near inclusions of oxides, nitrides, sulfides, silicates at all temperatures deformation localization in matrix had occurred nature of which dependant from inclusions plasticity level and temperature. Near rigid inclusions of oxides and nitrides matrix deformation values are higher than near plastic sulfides and silicates, at that, the latter are controlling the matrix deformation magnitude. It is significant that at temperatures from $900^0$C up to $1200^0$C, in addition to higher deformation area of matrix deformation "peaks'' connected with sliding development had observed directly at interface inclusion-matrix in all cases with rigid, plastic and fused inclusions. Value of such deformation peaks are increasing in proportion as temperature, plasticity level and inclusion size correspondingly.

Three types of microbreaks of deformable origin observed near nonmetallics were as follows: voids (ductile cracks) – as a result of decohesion along interface inclusion-matrix, cracks in inclusion and matrix near inclusion.

Mechanism of microbreaks development is distinguished by the type of inclusion, ratio of cohesive resistance, matrix and interface inclusion/steel matrix and conditions of deformation (Fig. 1).

Voids had been observed near rigid inclusions of such oxides as $Al_2O_3$, $MnO \cdot Al_2O_3$ at all temperatures. Such silicates as $MnO \cdot SiO_2$, $FeO \cdot SiO_2$ at temperature ranging from $25^0$C to $900^0$C are inductile and brittle cracks occur in them. At higher temperatures silicates are ductile and cracks in them are occurred more rarely. Such sulfides as FeS, (Fe, Mn)S are ductile at all temperatures and cracks in them had been observed in the range of $25\text{-}600^0$C, but voids, occurring as a consequence of difference between plasticity of inclusions and steel matrix, had been observed at different temperatures. It should be emphasized that sulfides had been fused at temperatures $1030\text{-}1050^0$C and nature of voids had not been deformable, but other nature; at that, deformation localization of matrix near inclusion became sharper. Each type of microbreaks occurred while reaching certain deformation level – critical $\boldsymbol{\varepsilon}_{kp}$, which value depends on temperature and connected with plasticity level of system inclusion-matrix. It is significant that during temperature raising $\boldsymbol{\varepsilon}_{kp}$ value is increasing for all types of inclusions and microbreaks, but for sulfides, where at temperatures higher than $1030^0$C red brittleness occur as a result of inclusion fuse, $\boldsymbol{\varepsilon}_{kp}$ value is decreasing sharply.



a b c

Fig. 1. Microbreaks near nonmetallic inclusions after plastic deformation; x600
Рис. 1. Микроразрушения вблизи неметаллических включений после пластической деформации; x600

Microbreaking growth rate is defined by its nature and temperature.

Microbreaks near inclusions have three stages of development: nucleation, growth and integrating in mainline crack. Leading role of nonmetallic inclusions in developing of breaking is clearly shown from investigation of fractures surfaces (Fig. 2).

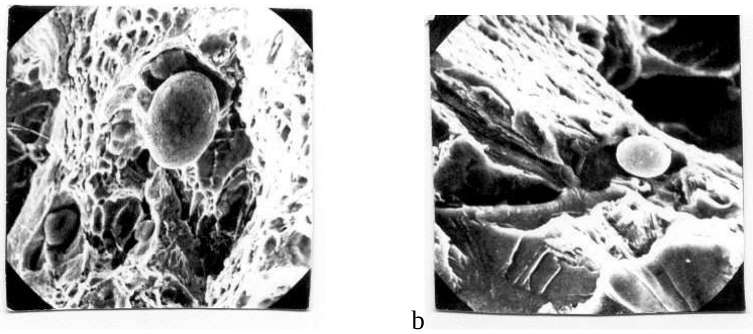


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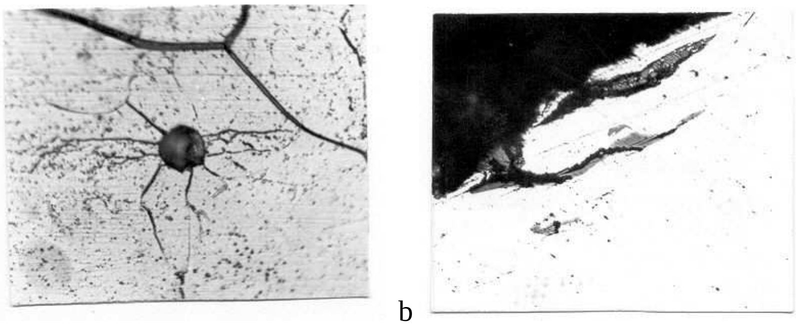
Fig 2. Fractures of wheel steel with nonmetallic inclusions; x2000
Рис. 2. Изломы колесной стали с неметаллическими включениями; x2000

In such a way, nonmetallic inclusion and matrix represent the system of stressed (inclusion) and plastic layers (matrix) shared by interface. Zones of nonlinear collective strongly excited states that generate different deformational defects occur due to concentration of deformational, contact and thermal stresses near inclusion at adjacent areas of matrix. Plastic deformation near inclusions is generated as a result of max concentrations of stresses at these areas as a local kinetic structural transformation and extends into grain by means of defects movement. Elementary action of plastic deformation considered as relaxing waving process going with local stress drop. Mechanism and nature of deformation depend on deformation conditions. Deformation localization near inclusions is observe at all stages of its development. Inclusions accumulate defects becoming the sources of long-distance stress fields which are connected with local bend of lattice due to incompatibility of deformation. Nonmetallic inclusions in steel constitutes a set of stresses concentrators which magnitude and way of relaxation depend on type and size of inclusion, thermal-speed and baro-mechanic conditions of deformation and correlation between physicochemical properties of inclusion and matrix. Relaxation of deformational stresses near inclusions goes with localization of dissipative structures witnessing processes of self-organization in system inclusion-matrix. For deformation of microbreaks near inclusions (as one of the way of stresses relaxation) it is necessary to generate deformation waves which length is comparable with inclusion size. Influence of nonmetallics on steel fracture development is varying along with temperature and deformation level, yet level of inclusion risk for different mechanisms of steel fracture is distinct.

Thermal microbreaks (voids or ductile cracks) are generated either during steel cooling after hot deformation of wheel steel or wheel cooling during thermal hardening. This phenomenon is associated with difference in thermal compression coefficient between inclusion and matrix that generates thermal stresses near nonmetallic inclusions (Fig. 3a). The same factor is significant during formation of thermal stress fatigue and, as consequence, microbreaking of wheel in service thermal cyclic loads.

Plastic shifts near tread surface are developing during wheel service and if inclusions are located in this area they cause cracks and wear parts formation. These are also microbreaks of deformational origin. Ready to use wheels inherit inclusions distribution from ingot. During service life wheels are running in severe loading conditions, undertaking alternating loads, subjecting to impacts from higher or lower and frequently cyclic changing temperatures. Reliability and durability of railway wheel are connected with its resistance for cracking incipiency and development. Near inclusions, in conditions of alternating, cyclic and constant loads and temperatures, local stresses field occurs inevitably, and its magnitude depends on the type of loading, size and form as well as inclusions interference. For example, under cycling loading, stresses near inclusions reach the value of steel yield stress. Process of accumulation of such stresses causes the incipiency of cracks fatigue near inclusions (Fig. 3b).



a b

Fig. 3. Thermal stresses near nonmetallic inclusions (a) and wear parts near nonmetallic inclusion (b); x 600
Рис. 3. Термические напряжения вблизи неметаллического включения (a) и частицы износа вблизи неметаллических включений (b); x 600

Thermal structural stresses promote generation of thermal voids at the boundaries of inclusions with matrix being finished stress centers.

In view of influence on structural strength inclusions are considered to be defects for which size and form are important. Based on data of $K_{1C}$ value for different steels it is necessary to distinguish critical size of inclusions. Relative to form the most adverse are acute and platelike inclusions. Near tread surface, running in the conditions of contact stresses, fatigue cracks are developing near inclusions. At that, fatigue cracks are generated in 100% oxide and silicate, 21% hydrosulfide, 48% nitride and 4% sulfide inclusions. Risk coefficient of inclusions from the point of view of fatigue breaking for alumina, alumina-silicate, nitrides, silica, sulfide, calcium silicate and hydrosulfides of cerium based inclusions is equal to 13, 10, 8, 6, 4, 2, 1 accordingly. It is significant that for different types of steel such coefficients are different and may be applied for comparison.

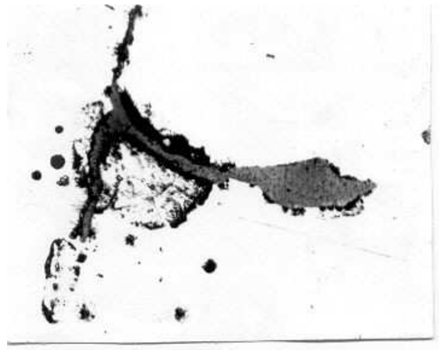
Railway wheels running in conditions of friction are inevitably subjected for wear. During wear wheel tread surface are undertaking plastic shifts and parts of wear are generating on the surface which specificity is determined by type of wear. Inclusions located near surface facilitate formation and breaking of wear parts.

Moreover, fatigue cracks occur on inclusions during wear and then extend to steel matrix.

The so-called "hydrogenous" cracks are associated with hydrogen content in the wheel steel that causes flake generating. In fact, inclusions are always observed in flake zone, mostly sulfides (Fig. 4).

During running of steel products in hydrogen content media inclusions play the role of hydrogen collectors, since interfaces inclusion-matrix having microdiscontinuities can occlude hydrogen. Series of studies shown that inclusion as it is has no relationship with hydrogen, thus, work as its sufficient

a



b

Fig. 4. “Hydrogenous” cracks near sulfides in wheel steel; x 600
Рис. 4. “Водородная” трещина вблизи сульфидов в колесной стали; x 600

traps due to microhollows. According to this, hydrogen, having accumulated at interface and affected by internal pressure from reaction of its molization causes microbreaking near inclusions. Nature of such microbreaks depends on size of inclusion and steel matrix content determined level of its plasticity and provided either brittle or ductile opening of microcracks.

Thus, concept of no relationships between hydrogen and inclusion substance needs clarification, since series of works shown ambiguity of influence of inclusion type on hydrogenous cracking. Analysis of flakes contained in steel had shown sulfides accumulation in defected area and practically had not discovered oxide and silicate inclusions. Issue pertaining to the sulfides influence on flake generating is still open. All inclusions are capable to occlude hydrogen, but as was showed during the study, microbreakes are generated only near sulfides under different temperatures and hydrogen pressure that needs not only stresses concentration but also thermal tensile stress formation.

## 3. CONCLUSIONS

Nonmetallic inclusions are the centers of initiation of microbreaks in wheel steel having different nature, thus, their role in determination of reliability and durability level of railway wheels depends on critical parameters of inclusions itself and wheel service conditions.

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