Transactions of the VŠB – Technical University of Ostrava, Mechanical Series
No. 2, 2012, vol. LVIII
article No. 1915

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INFLUENCE OF THE SURFACE CONTACT PHENOMENA ON THE STRUCTURAL CHANGES AND NANO-LAYERS GENERATION

VLIV KONTAKTNĚ ÚNAVOVÝCH JEVŮ NA STRUKTURNÍ ZMĚNY VE VAZBĚ S MECHANISMY VZNIKU NANO-VRSTEVNÝCH OBLASTÍ

Abstract

This work is dealing with a study of the micro/structure transformation that is induced by rolling contact friction and adhesive wear, respectively, in the rail-wheel/rail system. Several small rail-surface samples, we term them as the "chips", as well as a railway wheel samples were chosen for the analyses of the surface changes on the rail/wheel surface. A multitude of different experiments were carried out in order to analyse the microstructure changes at the surface and the near-surface region of the material samples and, thus, to contribute to the understanding of the complex rail/wheel rolling contact phenomena - and mainly, its degradation mechanisms. The formation of nano-structured martensite and carbides on the rail and wheel surface causes the extremely high microhardness valuees and the strong corrosion resistance of the so called White Etching Layers (WEL).

Abstrakt

Mechanismy probíhající v soustavě kolo-kolejnice způsobují v určitých režimech jízdy kolejového vozidla (rozjezdy, brzdění) koncentraci napjatosti, úměrně velikosti smykových napětí v dané vzdálenosti od povrchu, resp. v jeho určitých oblastech. Pokud stupeň deformace v dané oblasti dosáhne kritické hodnoty, dochází nejprve k rozštěpení lamel cementitu v uvažované povrchové vrstvě na jednotlivé hrubé segmenty. Posléze pak, v průběhu provozem indukovaného cyklického zatížení, jsou lamely cementitu separovány na jemnější částice, které nakonec dosahují morfologie velice jemnozrnných částic, řádově o velikostí několika nanometrů. Jak dokládá TEM-analýza těchto oblastí, byla zde pozorovaná i velice vysoká hustota dislokací, odpovídající enormnímu stupni plastické deformace v kontaktním regionu. Zde popisované bíle naleptané vrstvy (White Etching Layers) lze ovšem identifikovat nejen na kontaktně zatížených površích železničních kol / kolejnic, ale i na celé řadě dalších komponent, jako jsou např. pístní kroužky, ozubená kola, resp. během obráběcích procesů (technologie řezání, broušení), jakož i vlivem různých provozních podmínek (např. mechanismy tření).

1 INTRODUCTION

There is no doubt, that an increased service life and reliability of rail/railway wheel materials is a highly topical issue, considering the current trend of increasing the number and modernisation of rolling stock, and increasing axle loads and travel speeds on railroads. Added to this is the situation of the Czech Republic ascending to the highly developed European environment, which is closely related to building high-speed railroad corridors which run across the country and represent the main

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transport routes among a number of European countries. The geographic and geopolitical position of the Czech Republic calls for the need for joining the transportation infrastructure to the European network in such an extent and quality that will allow operation of domestic and transit transportation at an internationally recognised level of quality.

In the conditions of the Czech Republic, road and rail transport continue to play the key role as they will serve the majority of transportation needs that the society will have. From this point of view, it is the reliability translated into service life and safety of individual components in the vehicle-rail system that represents one of the prime factors that affect the function of an advanced rail transportation system.

The present era and its matching level of scientific knowledge and technical expertise undoubtedly require that a systemic approach be applied towards the analysis and realisation of these facts. A systemic philosophy and theory are required for a structural description of the characteristic properties which, by means of components and relationships in the wheel-rail system, result in certain processes and states in the system of interest (Janicek P. 2001).

As such, the experimental part of the study presented herein focused on the study of structural changes in the surface layers of the rails, with a primary emphasis of the mechanisms of occurrence and the structural characteristics of the "White Etching Layer". The methods of X-ray diffraction analysis, light microscopy and transmission electron microscopy (TEM) were used to analyse segments from rails deteriorated by operation. The segments were collected as they exhibit specific surface defects with the possibility of a "White Etching Layer" (hereinafter referred to as "WEL").

2 SURFACE LAYER AND ITS DEGRADATION IN THE RAILWAY WHEEL / RAIL CONTACT REGION

Synergy of degradation processes in the surface layers of the contact areas is closely related to the study of mechanisms of structural modification in those locations. Research activities have been focusing on this issue on a rather major scale; however, the processes have not been clarified entirely which during operation of the rails lead to structure modifications in the surface or subsurface area of wheel and rail contact. Another important consideration in the matter is the effort towards reduction of the financial burden that includes the costs for manufacturing and operation of rail vehicles and the tracks, as well as the requirements for maintenance of the vehicles and rail superstructure. The results of our own research and study of literature on the subject suggest that the area of the wheel and rail contact, being exposed to operation and long-term variable load and wear, exhibits major macro- and microstructure changes. These are especially related to occurrence of corrugation on the rail head (so-called "*riffels*") and to occurrence of so-called *White Etching Layer* ("WEL") on the corrugated rail surface. As WEL is characterised by a high level of hardness and, therefore, by notable fragility, these layers represent a critical location for occurrence of cracks or release of a part of the material separated by cracks, known as *spalling*. A system thus degraded generates considerable vibration and background noise; this is incompatible with the European concept of a "silent railroad", currently subject to frequent discussion. Furthermore, periodical grinding of damaged rails is associated with considerable expense.

In general, the structure components that are subject to varied contact load are subject to degradation mechanisms known as *contact fatigue*. This refers to damage the evidence of which can be the cracks that occur either on or below the surface, depending on the nature of stress. The topic of contact fatigue is rather complicated as it always includes rotation of the major stresses (Wang L. 2002). What is more, there are many other mechanisms (e.g. wear, degradation by corrosion, corrugation of the surface) each of which needs to be considered in prediction of the *fatigue life* of the entire system. A typical example of a contacting pair matching this concept is the wheel-rail system. As axle loads and travel speeds in the railroad industry are constantly rising and, in the global view, all railroad administration bodies are striving for more effective methods of prevention of wear of the rail head and the wheel, the issue of *rolling contact fatigue* ("RCF") in the wheel-rail system represents a major concern, see Tournay and Mulder (Turnay H. 1994) or Clayton (Clayton J. 1994). The subject of these analyses is quite complex and many of the aspects have not yet been theoretically explained in full. The rail head is the rail component which is exposed to the highest load and wear. Higher operating load is caused especially by the dynamic forces between the wheel and the rail by heat effects of wheel slip both while braking or transmitting power from the axle to the rail. These factors are subsequently multiplied by the ever-increasing weight load per axle and by the continuous application of higher and high speeds. It is evident that the observed damage of the rail head (*fatigue cracks*) may be initiated both on the surface or in the areas immediately below the surface, see Gallier et al. (Galliera G. 1995). It may also be inferred that the mechanisms leading to occurrence of these are highly varied and depend on the operational, material, and geometrical conditions of the contact. In consideration of movement of the heat source in the wheel-rail contact, the following may be inferred: The observed defects identified by the ČD (Czech Railways) regulation S-67 in force, see (CD S 67 1997), type: "areas in the zone of travel ground by recurring slippage of the driving axle" (referred to as *wheel-burns* in English terminology), occur at low speeds of vehicle travel relative to the rail.

In order to explain both these phenomena it is necessary to monitor the relative speed of the wheel relative to the rail, in the area of contact. That of the two monitored surfaces which is moving at a higher rate of speed produces friction heat that is dissipated equally into the rail and into the wheel. It is obvious that the heat source remains longer above the surface that is moving more slowly (in the case of a blocked wheel it is the wheel itself, in the event of slippage, it is the rail). The result is that the surface moving at the lower rate of speed absorbs much more heat that is generated at the point of contact, with the risk of exceeding the transformation temperature of the material. However, once the heat source moves outside the area of contact, the subject location of the surface layer is abruptly cooled by subsequent radiation of heat into the cold mass that surrounds the monitored area of contact. This translates into structure modifications which result in degradation of the layer on or below the surface on the rail head or on the active area of the wheel.

3 DESCRIPTION OF THE WHITE ETCHING LAYERS ON THE RAIL HEAD

The requirements for material characteristics of rail steel, caused by the increasing rate of travel speeds of rail vehicles and the higher axle loads, are constantly rising. The changes of material structure of the rail retroactively affect the mechanisms of rail degradation. While in the past two decades the main criterion for rail service life has been its resistance to abrasive wear (application of Series 75 ČD rails in the Czech Republic), the current prevailing trend is the requirement for resistance to occurrence and propagation of contact-wear defects (i.e. defects such as *head-checking, riffel* and *shelling*) that occur on or near the surface of rails with higher strength characteristics. These defects differ in the mechanism of occurrence, yet one of their properties is universal - occurrence and propagation of cracks with subsequent separation (flaking, release) of material from the rail surface which, in an extreme situation, may lead to rupture across the entire rail section. Each year, considerable amounts of funds are spent in the world for elimination of these defects and of their consequences.

Therefore, explanation of the acting mechanisms and effective factors represents a crucial task towards reduction of occurrence of the contact-fatigue defects in rails mentioned above. When viewed in a microscope, the cross-section of an operated rail (**Fig. 1**) shows *riffle bands*, (surface corrugation of the rail head) in a layer approximately 10-100 μm thick, without a structural contrast, which is resistant to etching of metallographic samples and shows a white colour after etching with Nital. This layer is often considered or identified as martensite. As this area exhibits exceptional fragility, propagation of defects known as *squat* or *shelling* and occurrence of defects is observed in the rail head. All of the above result in background noise when the wheel travels along the rail and exhibit a detrimental effect on the service life of the rail and of the wheel axle (Lojkowski W. 2001).

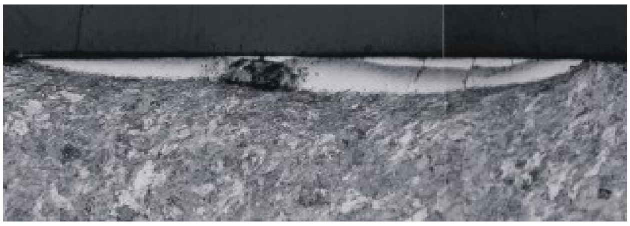

Fig. .1 White Etching Layer (WEL) on the surface of the rail (Wang L. 2002). NITAL, magn.100x.

Therefore, a number of studies have focused on the origin of these WEL (Clayton P. 1994, Galliera G. 1995). Until recently, the predominant theory claimed that WEL is caused by the rise of temperature in the wheel-rail contact during enormous friction, or slippage, processes during wheel travel along the rail (Baumann G. 1996).

Standard rail steel has a predominantly pearlitic structure with a nearly eutectoid content of carbon and fine plates of pearlitic cementite. Some authors claim that the temperature in the wheel-rail area of contact may extend the boundaries of transformation temperature for generation of austenite (Kout J. 2001, Mitura K. 1980) while the subsequent rapid cooling may be the cause for modification into martensite (Jergéus J. 1992) in a closely delimited area corresponding to the surface.

Although this may, in extreme situations, provide conditions for generation of martensite on the rail surface (heating to the transformation temperature and subsequent rapid cooling), it has been established that this is not the only possible mechanism of WEL occurrence (Djahanbakhsh M. et. al). This discussion was initiated by Newcomb and Stoobs (Newcomb J. 1984) who used TEM surface analyses of rail surfaces and suggested the so-called model of low-temperature solution of carbides. These authors consider the influence of high contact pressure in the wheel-rail system in the order of GPa, which causes solution of carbides in temperatures as low as 100 °C; this process leads to much higher density of dislocations and to segregation of carbon atoms in the cores of such dislocations. Furthermore, they suggest a process of progressive propagation of WEL that differs from the initially accepted single-stage process of WEL occurrence.

This concept has recently received considerable support, especially based on recent findings on the so-called mechanical alloying process (Lojkowski W. 2001). These findings have established that experimental processes may lead to generation of structures analogous to the discussed WEL only by mechanical spreading of metallic dust from pearlitic steel under high pressure at temperatures lower than the transformation temperature required for generation of austenite (Djahanbakhsh M. et. al). Baumann (Baumann G. 1996) does not regard the white etching layers to be “traditional” martensite either, in reference to Liebelt (Liebelt S.B. 1984) who suggests that the maximum temperature limitation of the processes occurring in the wheel-rail contact is temperature increment by 400K; this value is not sufficient for austenitisation of pearlitic material and for its subsequent quenching into the martensite region.

For a long time, WEL were regarded as amorphous materials as the development of laboratory equipment at the time did not allow identification of their microstructure. The structure is similar to that of the Beilby layer that is used in polishing and grinding of polished sections in metallography. Based on the high hardness and fragility of the material, studies of WEL have observed the occurrence of cracks and crumbling of material from the rail surface with subsequent generation of dappling in the rail head area (Baumann G. 1998).

4 SELECTED RESEARCH AND ITS METHODOLOGY

The main goal of the experimental section of this study was to analyse microstructure changes in the rail head caused by wheels contacting the rail especially in locations with frequent starts of rail driving machinery and on track curves. As indicated in the introduction of this paper, it is an extremely complex tribology system in which the friction and wear processes lead to degradation of material and cause occurrence of critical defects.

The samples collected from rail sections where occurrence of WEL was assumed (*samples taken from take-off track sections before semaphores or from areas around train stations*) were subject to metallographic analysis and transmission electron microscopy (TEM). In order to provide comparison of the degradation mechanisms being analysed, the selection of experiment material was extended by segments from Mn-austenitic steel used for the crossing elements of rail switches, and by samples taken from the travel surface of the rail wheel rim.

After demonstration of the existence of the white etching layer (WEL) that is clearly connected with the initiation and propagation of defects on the rail head, a hypothesis was proposed and subsequently verified for elimination of WEL by cumulative tempering under air at temperatures of 150 °C, 200 °C, 250 °C and 300 °C, each for a period of 4 hours. Classification of the structure changes after each of the four-hour cycles required that the samples be documented using the light microscope, SEM, and a diffraction plot to record the progressive change in the microstructure characteristics of the studied sample volume.

5 METALLOGRAPHIC ANALYSIS OF RAIL CHIPS

The main purpose of the particular experiment (metallographic analysis) was to use a standard polished section (a cross-section of the selected chip) for assessment of the microstructure changes observed after application of low-temperature tempering in comparison to the initial condition of the chip. The selected chip sample consists of heterogeneous layers that are the result of intensive and locally varied plastic deformation with a dominant influence of tangential shear components in the area of contact. Mutual dislocations of the layers are delimited by thin oxide layers in the boundary regions and, in some cases, by pores arranged in rows or by more consistent cracks. The potential defects possess a high degree of variability; this is logically attributable to the random nature of the observed states and their random dynamic causes.

The analyses performed show that the WEL itself consists of several sub-layers; this suggests gradual generation of the layer during operational exposure (see **Fig. 2**). The figure also shows a tendency to layer delamination along the boundary with unaffected mass in the sub-surface area of the rail head, which is the result of a high hardness gradient and, therefore, of local stress conditions acting on both sides of the boundary area. The cumulative effect of the tangential shearing components in the area of contact causes separation of material masses from the rail head and is the cause of occurrence of the studied defects on the surface.

Fig. 2. Microstructure of the rail-segment after annealing on 250°C / 4hrs. Etched in NITAL, magn. 250x and 50x, resp.

The selected chip showed a characteristic feature in the locally homogeneous microstructure which may be used to derive one of the possible mechanisms. High local dynamic stress and the resulting plastic deformation have caused, in the final effect, local heating up to the transformation levels $\alpha Fe+M_3C \Rightarrow \gamma Fe_C$. The maximum temperature was high enough - it is necessary to consider transformation hysteresis at the realistic rate of heating, including the possibility of M_3C dissolving in austenite. The subsequent abrupt cooling of the austenite saturated with carbon resulted in athermal martensitic transformation. The quantity of carbon dissolved in austenite (0.3 - 0.5%) was sufficient for transformation of lath martensite (triangular elements).

The registered condition of the initial microstructure suggested that this case was the final condition of the chip as the martensitic structure mentioned above showed no subsequent plastic deformation. The state of an identical area has been documented in various cumulated modes of tempering for an assessment of the effect of secondary application of heat in temperatures ranging from 150 to 300 °C to the initial structure. Tempering of lath martensite at 150 °C usually does not yield recognisable changes in the microstructure under application of optical microscopy equipment. As the tempering temperature increases, the characteristic triangular arrangement of martensite laths gradually loosens and nearly disappears after heating at 300 °C. It is replaced with a structure which is known as “sorbite” in carbon steels. **Table 1** shows the microhardness value of HVm 50 which is determined by puncture into the influenced side of the chip before and after annealing at 300 °C / 4 hours.

Table 1: Microhardness values HVm 50 in the surface layer of the influenced rail-chip, before and after annealing 300 °C / 4 hrs.

	Surface layer with the “nanostructure” component	
	Measurement average 1	Measurement average 2
Before annealing (initial state)	721±13	841±14
After annealing 300 °C / 4 hours	405±11	364±12

After etching, the overall character of the sorbitic structure exhibits relief both by nature as per the initial orientation of the martensite laths and secondarily by the orientation and local clusters of the carbidic precipitate. The described decomposition processes of lath martensite correspond to the measured microhardness in the respective areas and, to a large degree, to the results of the X-ray diffraction analysis.

6 RESULTS OF TEM-ANALYSIS OF A SAMPLES FROM THE SURFACE OF RAIL STEEL

Selected analyses in a transmission electron microscope (TEM) were performed in two samples of chips from the subject rail: the samples were identified as “initial state” and “state after tempering at 300 °C / 4 hours”. The following methods were applied in preparation of thin films from the segments taken from the rail surface for TEM observation: the discs were spherically ground on the inside using the *One Side Dimpling* method; then they were thinned with ion polishing in a Gatan PIPS *(Precision Ion Polishing System)* machine. The thinning operation was performed, for the most part, on the inside so that the distance of the studied area from the rail surface was approximately 1 (m. The subsequent observation used a Philips CM12 transmission electron microscope under 120 kV of acceleration voltage.

Morphology of the samples was a typical microstructure of highly deformed steel with a high density of dislocations. Selective electron diffraction from an area with a diameter of approximately 6 µm shows uninterrupted rings, which suggests a very small grain size. Grain size ranges approximately from 20 to 200 nm. Therefore, the microstructure may be identified as nanocrystalline (see **Figure 3**), highly homogeneous; the grains are of irregular shape and are separated by clusters of dislocations. Annular diffractions (**Figure 3**) show that only ferrite is present in the material; presence of carbides may be expected; however, the diffraction sensitivity in the situation is not sufficient as to show carbides in the image. Presence of austenite has not been demonstrated. The deformation level of the structure is so strong that the carbide contrast in normal images is obstructed by the contrast from a dislocation clusters.

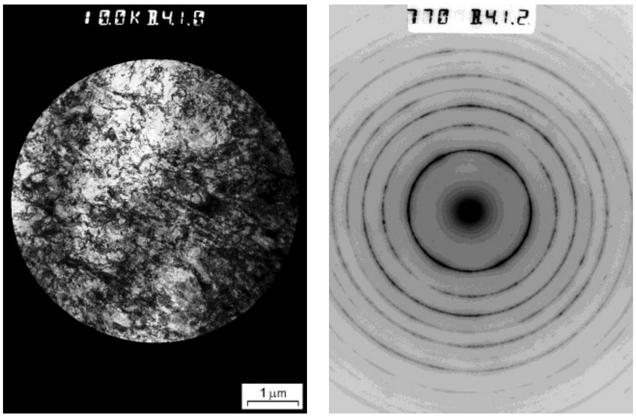

Fig. 3. TEM-image of the region where the selected electron diffraction was carried out; the obtained annular diffraction pattern proved that the microstructure consists of very small ferrite grains with random orientation.

The density of dislocations cannot be quantified in such a highly deformed state - compared to the publication by Lojkowski et al. (Lojkowski W. 2001) where an analogous case showed a numerical representation of dislocation density; however, it was only shown in samples collected from the rail surface at a distance of more than 50 µm from the rail head. After annealing at 300 °C / 4 hours, materials recovery occurs, the density of dislocations declines and the boundaries of individual grains are defined more clearly.

7 CONCLUSION - APPLICATION TO THE RAILWAY TRANSPORT

The processes occurring in the wheel-rail system lead to concentration of stress during certain modes of rail vehicle travel (take-off, braking); stress is concentrated in certain distances from or in certain areas within the rail head surface. Whenever the degree of deformation in a given area exceeds the critical point, the first event is cracking of the cementite lamellas into coarse particles within the assumed surface layer. Subsequently, during the cyclic load, the cementite lamellas separate into finer segments which, in turn, achieve the morphology of extremely fine particles in the size of several nanometers. As the TEM analysis of these areas suggests, very high density of dislocations has been observed here as well. At the same time, the effect of the discussed heat source in the wheel-rail contact results in heating required for austenitisation of the mass element in the rail head. However, the time interval of the contact between the wheel and the rail is too short, and cementite cannot dissolve completely. The effects of the transmitted load result in considerable deformation of the austenite. The subsequent cooling transforms the austenite in the areas into ultra-fine martensite. Therefore, the structure of the white etched layer includes this ultra-fine martensite, nanocrystalline cementite and residual austenite.

The white etched layers (WEL) described here may be identified on the surface of worn rails and railway wheels, as well as in a range of other components such as piston rings, gears, during machining processes *(cutting and grinding technology)*, and in various operating conditions *(e.g. friction mechanisms).* This topic has been covered by many experimental and simulation studies. Nonetheless, there are differences in the individual observed mechanisms which lead to occurrence of various types of these layers. Therefore, the results obtained by the analyses presented herein may only be compared or applied to WEL which occur in similar material types and under similar load conditions. From the application (transport engineering) point of view, there is generally known, that the discussed considerable heat-affection of subsurface materials layers, and consequently risen quenched microstructures with high hardness level, can be indicated as an origin of heat and/or fatigue cracks, as well as the contact fatigue and falling of the material out from the railway wheel/rail tread, mostly in case of railway vehicles with disk brakes.

However, the mechanism of conditions resulting in microstructure changes in a rail and railway wheel material is not hitherto explicated in satisfactory way, and that is why the presented research is to be significantly applied in the railway-operation and practice, specially as a prevention and diagnostics. Moreover, we cannot discount an idea that the rising thermally-induced cracks following the circumferential direction of the wheel surface can change their orientation into radial direction, with a possible catastrophic failure (brittle fracture) of a wheel and imminent derailment of a railway vehicle, or a train. These problems are of particular interest since the increase of axle loads in freight traffic as well as increase of velocity in passenger trains within recent years led to an increase of wear of the rails that appeared e.g. in an increase of frequency of structure modifications and defects in the surface layer. From the fracture mechanics point of view, the catastrophic brittle fracture of a rail and wheel can occur when reaching the critical size of these defects (radial cracks). There is therefore necessary to study these white etching layers, their characteristics and mechanisms of origin, as well as the “thermal effects” on principle and to clarify the causes of its generation in order to achieve the higher safety of railway operation.

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