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Microstructural transformation of a rail surface induced by severe thermoplastic deformation and its non-destructive monitoring via Barkhausen noise

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ABSTRACT

The paper presents a new concept for evaluation of surface damage of rails subjected to long-term cyclic loading. A rail cyclically loaded during 20 years of traffic was examined by combination of several non-destructive techniques with high sensitivity to surface damage, namely positron annihilation spectroscopy, X-ray line profile analysis and magnetic Barkhausen noise. The parameters of magnetic Barkhausen noise were correlated with the parameters describing the rail surface integrity, i.e. thickness, hardness, stress state and microstructure of the damaged layer. Good correlation between these parameters was observed and it has been demonstrated that thickness of the damaged layer can be measured non-destructively by the magnetic Barkhausen noise technique. Cyclic loading of the rail introduced a high density of dislocations into the sub-surface region and also vacancies which agglomerated into small clusters. Phase analysis of the rail surface revealed that repeated severe plastic deformation induced multiple phase transitions.

1. Introduction

The large axle loads of trains usually cause serious wear and structure transformations to the rails. The near-surface region of a rail surface appears white under metallographic observations [1–3] due to the resistance against conventional Nital etching. For this reason, this region is named the white etching layer (WEL). The origin of the WEL has been widely discussed. Newcomb and Stobbs reported that the WEL is initiated by repetitive and severe plastic deformation [4]. Alternatively, phase analyses reveal retained austenite, which indicates that WEL formation is a thermally initiated process when the near-surface region undergoes heating above the austenitising temperature, followed by rapid self-cooling [1–3,5]. Such a process hinders the full transformation of austenite to pearlite and a certain volume of austenite is retained in the WEL. Various techniques were employed to identify the stress state, phase composition, chemical and other alterations of the WEL [1–5]. An overview of railway wheel and rail fatigue under rolling contact and thermal loading was reported by Ekberg and Kabo [6]. Their study outlined the mechanism behind the various phenomena, means of prediction, influencing parameters and possible means of prevention. Pal et al. [1] reported that the WEL is a product of rolling-contact fatigue caused by the alternating stresses associated with rolling contact bodies. Jirásková et al. [7] carried out a microscopic investigation of surface layers on rails by the use of various techniques and found that the decomposed initial pearlite structure is accompanied by surface oxidation, defect formation, carbon clustering, precipitation of nanosize carbides and austenitisation of the material.

Positron annihilation spectroscopy (PAS) [8] is a non-destructive technique with a high sensitivity to open volume defects as vacancies, vacancy clusters, dislocations and so on. In the present work, PAS was employed for the characterisation of defects created in a rail by cyclic loading during the long-term operation. Three complementary PAS techniques were used: (i) positron lifetime (LT) spectroscopy [8], which enables the identification of defects and determination of their concentrations; (ii) coincidence Doppler broadening (CDB) spectroscopy [9,10], which carries information about the local chemical environment of defects and (iii) variable energy positron annihilation spectroscopy (VEPAS) [11,12], which enables the determination of the depth profile of defects.

Magnetic Barkhausen noise (MBN) is a non-destructive technique

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employed for monitoring components made of ferromagnetic materials. This technique is sensitive to the microstructure and stress state [13–18]. On this basis, this study utilises the sensitivity of the MBN technique for such a purpose. MBN originates from irreversible and discontinuous Bloch wall (BW) motion during cyclic magnetisation. The main reason for the sensitivity of MBN to the microstructure can be viewed by the pinning strength of variable microstructure features interfering with BWs in motion. Irreversible and discontinuous BW motion produces acoustic and electromagnetic pulses. Electromagnetic pulses propagate towards the free surface and can be detected by the use of a suitable pick up coil. It is well known that MBN is a function of stress state and microstructure. However, the stress state mainly affects the domain and corresponding BW alignment, whereas the microstructure affects the free path of BW motion [14]. The microstructure of the matrix can be expressed in many terms and it is worth noting that BWs interfere with all crystalline defects. Therefore, in many studies MBN is studied as a function of dislocation density [16], carbide precipitation [17], grain size or the presence of non-ferromagnetic phases [14]. Transformations in the WEL are very complex and fully change the character of the matrix. Thus, MBN could be a promising technique for monitoring the surface state of rails in operation. However, it is necessary to carry out an investigation of the microstructure and stress state for a true interpretation of MBN signals and a deeper understanding of BW interactions with microstructural features. For these reasons, conventional destructive techniques also have to be carried out. It is noted that a short communication focused on this topic was previously reported [19]. MBN has already been used in the rail track studies in other cases. Santa-aho [20] provided the review of the magnetic methods and their utilization in rail studies. Takacs [21] investigated the grain size in the ball milled as well as operated rail surfaces and reported that MBN measurements may be utilized to investigate the formation mechanism of surface corrugation in rails or pre indicate the corrugation process [22].

It is well known and clearly evidenced that the WEL structure is very defective. The operation of rails containing WEL regions may be risky with respect to the possible rail macro cracking initiated by micro cracks in the WEL. Furthermore, rails are subjected to a grinding process in order to remove the damaged layer, as well as surface asperities [3]. For these reasons, a suitable non-destructive method would be beneficial for revealing the surface damage degree and the thickness of the damaged layer. Therefore this paper deals with MBN technique employed for such purpose.

2. Experimental

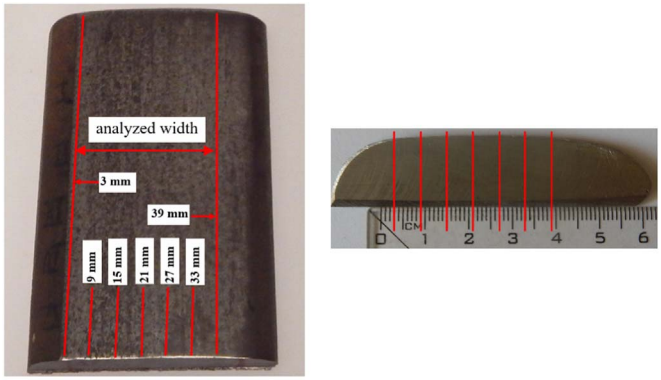
The experimental study was carried out on hot rolled rail steel R220 (strength 785 ± 50 MPa, hardness 215 ± 35 HB) with the chemical composition indicated in Table 1.

The rail was subjected to 20 years of accumulated passing tonnage of ~0.8 million tons per year. Fig. 1 shows a photograph of the rail profile with an indication of the analysed zone. The rail surface was measured and analysed within the whole rail width, in which the valuable contact of the rail and wheel can be expected. Metallographic observations, microhardness testing, X-ray diffraction (XRD), MBN measurements and PAS studies were carried at certain points regularly distributed within the rail width (the distance between the neighbouring points was kept at 6 mm).

MBN was measured by the use of a RollScan 350 apparatus and analysed by μScan 500 software (magnetizing voltage 5 V, magnetizing

Table 1
Chemical composition of rail steel R220 in wt%.

Fe	C	Mn	Si	Cr	Ni	Cu	P
bal.	0.60	1.05	0.21	0.12	0.13	0.07	0.02



a) Analysed rail width (36 mm) b) Cross section of the rail

Fig. 1. Analysed rail and its cross section with an indication of the measured regions. Bulk measurements were performed 15 mm below the rail surface.

frequency 125 Hz, sensor type S1-18-12-01, frequency range of MBN pulses in the range from 10 to 1000 kHz). MBN values were obtained by averaging ten MBN bursts (five magnetizing cycles). MBN refers to the rms (effective) value of the signal. The estimated sensing depth of the MBN signal is ~50 μm [23,24]. The magnetisation of the rail surface was carried out in the direction of traction. In addition to the conventional MBN parameter (rms value of the signal), the *peak position* of the MBN were analysed. The peak position of MBN refers to the position of magnetic field in which the MBN envelope attains the maximum (it corresponds to the magnetic hardness of the body).

Phase analysis was performed by XRD carried out on a X'Pert PRO diffractometer using Cr-Kα radiation. The average sensing depth of the XRD measurements was ~5 μm. The residual stress was determined from shifts of the 211 reflection by the $\sin^2\psi$-method. The X-ray line profile analysis was performed by employing the whole powder pattern refinement method [25–29]. The computer program MStruct [29] was used for the fitting of the measured XRD patterns. The X-ray line profile analysis revealed the details of the real structure of the investigated material, i.e., the size of coherently diffracted domains and the dislocation density.

To reveal the microstructural transformations induced by severe plastic deformation, 10 mm long pieces were routinely prepared for metallographic and scanning electron microscopy (SEM) observations (etched by 3% Nital for 8 s). The microstructure was observed in the direction longitudinal to the track direction.

Vickers microhardness (HV) testing was conducted by a Zwick Roel ZHm microhardness tester by applying a force of 50 g for 10 s. The microhardness was determined by averaging three repeat measurements (three microhardness profiles spaced at 0.1 mm). All measurements were conducted at seven points within the rail surface region indicated in Fig. 1. The first position was placed 3 mm from the left side. The following positions were spaced 6 mm from each other (the bulk structure was also investigated).

PAS investigations were performed using a ^{22}NaCl positron source with an activity of ≈1 MBq deposited on a 2 μm thick Mylar foil. A digital spectrometer [30] with a time resolution of 145 ps (FWHM of the resolution function) was employed for LT spectroscopy. At least 10^7 positron annihilation events were collected in each LT spectrum, which was subsequently decomposed into exponential components by a maximum likelihood code [31]. The source contribution to the LT spectra determined using a well annealed α-Fe reference sample consisted of two components with lifetimes of 368 ps and 1.5 ns and corresponding relative intensities of 9.5% and 1.2%, respectively. These contributions come from positrons annihilated in the ^{22}Na source spot and the covering Mylar foil.

The CDB studies were carried out on a digital spectrometer [32] equipped with two high purity Ge detectors. The energy resolution of