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Synchrotron and neural network analysis of the influence of composition and heat treatment on the rolling contact fatigue of hypereutectoid pearlitic steels

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ABSTRACT

A series of experimental hypereutectoid pearlitic steels were tested under rolling contact sliding conditions using a lubricated twin-disc setup to study the influence of different chemical compositions and heat treatments on rolling contact fatigue life. Tested samples were then characterised using microscopy and synchrotron measurements as a function of depth from the contact surface. Results, analysed through neural networks, indicate that the most influential factor in lengthening the number of cycles to crack initiation of hypereutectoid steels is hardness, attained by increasing the cooling rate from the hot rolling temperature, but adequate alloying additions can enhance it further. The harder, fast-cooled samples displayed less plastic flow at the surface than the softer slow-cooled ones. With regard to chemical composition, silicon was found to strengthen the ferrite thus reducing strain incompatibilities with the cementite, preventing in this way the fragmentation and eventual dissolution of the lamellae. This is beneficial since larger depths of cementite dissolution were found in samples with lower cycles to crack initiation for a given cooling rate (hardness). Samples containing vanadium lasted longer and displayed less plastic deformation at the surface than those without, at a similar hardness.

1. Introduction

Hypereutectoid rail steels (0.8–1.0 wt% C) are attractive for heavy haul applications as well as mixed traffic networks due to their higher resistance to wear and gross plastic deformation that derives mainly from their higher hardness in comparison to eutectoid C-Mn steel [1]. Despite many counterexamples [2–4], higher hardness in rail steels has been linked to a greater wear and rolling contact fatigue (RCF) resistance [5–8], which are the main degradation mechanisms of railway tracks during service. Nevertheless, head hardened rails of such a high carbon content can contain proeutectoid cementite, which has been shown to be detrimental to rolling contact fatigue life, fracture toughness, elongation, and wear resistance in rail steels [9–11]. The proeutectoid phase at the rail-wheel contact locations can be mitigated through controlled cooling (>2.5 °C s^{-1}) from the finish rolling temperature [12] or a silicon addition in excess of about 0.8 wt% [9]. Silicon alloying has been recognised as a more reliable alternative to preventing grain boundary cementite since accelerated cooling rates may not be achieved by direct air impingement on rail heads, are depth dependent, or may lead to martensite formation in the heavily segregated web region for cooling rates greater than 4 °C s^{-1} [9]. In addition to carbon and silicon, high performance ultra-high carbon steels (UHC) can contain elements such as Mn, Cr, Ti, and V, whilst restricting others like N, P, and S, to achieve improved properties even in the relatively soft as-rolled condition (~370 HV), challenging the hardness based approach [9]. Such improvements have been attributed to interlamellar spacing refinement, increased cementite volume fraction, solid solution strengthening of ferrite [1,9], and precipitation strengthening through V/Ti carbides [13]. Since the improvements brought about through alloying are additive to the known benefits from higher cooling rates to increase hardness through refinement of interlamellar spacing, these steels can be heat treated to endure more demanding service conditions.

The aim of this work is to understand the specific role that each alloying addition or heat treatment (normal or accelerated cooling) has in determining certain microstructural parameters (hardness, interlamellar spacing, cementite volume fraction, ferrite lattice parameter) and identifying those most responsible for the overall wear and rolling contact fatigue performance of the alloy with the aid of numerical

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Table 1
Chemical composition of twin-disc samples, wt%.

Grade	C	Mn	Si	Cr	V	Al	P	S	N	Ti	Others
AR + 0.3Cr	0.92	0.96	>0.40	0.32	0.004	0.002	0.008	–	–	–	Mo <0.005, Ni 0.031, Co 0.015, Cu 0.025, Sn 0.002, Pb <0.004
AR + 0.8Si + 0.1 V	0.92	0.88	0.79	0.06	0.14	0.005	0.012	0.007	0.011	0.013	
HT + 0.8Si + 0.1 V	0.92	0.88	0.79	0.06	0.14	0.005	0.012	0.007	0.011	0.013	
HT + 1.0Si + 0.1 V	0.94	0.84	0.96	0.05	0.13	0.006	0.011	0.005	0.009	0.013	
HT	0.99	1.09	0.56	0.21	–	<0.005	0.015	0.017	0.006	0.013	
Wheel	0.56	0.76	0.36	0.14	0.003	0.036	0.006	0.004	–	0.009	Mo 0.013, Ni 0.08, Cu 0.11, Nb 0.001, Sb 0.015, Sn 0.009

Table 2
Results from twin-disc testing and microstructural characterisation showing average values and standard error with a 95% confidence interval.

Rail sample	Cycles to initiation/10^3	Hardness rail / HV30	Hardness wheel / HV20	True interlamellar spacing rail / nm
AR + 0.3Cr	30	314 ± 1	228 ± 4	181 ± 32
AR + 0.8Si + 0.1V	130	336 ± 3	223 ± 3	203 ± 32
HT + 0.8Si + 0.1V	170	401 ± 2	225 ± 2	104 ± 11
HT + 1.0Si + 0.1V	160	410 ± 2	207 ± 5	121 ± 11
HT	150	409 ± 2	225 ± 2	130 ± 25

regressions in the form of neural networks. In order to do so, five different experimental ultra-high carbon rail steels have been tested under twin disc rolling contact fatigue and characterised using hardness, microscopy, and high energy synchrotron X-ray diffraction, which allows the study of solid solution strengthening as a function of the ferrite lattice parameter [14] and precipitation strengthening as a function of the phase volume fractions for increasing depths from the contact surface.

2. Experimental methods

2.1. Material, heat treatment, and sample preparation

The chemical composition of the different experimental ultra-high carbon rail steel grades used in this study are listed in Table 1. These alloys were hot rolled into 30 mm thick plates at *TATA Steel UK* and experienced a similar cooling rate to that of rail heads on cooling beds after rolling [9]. The plates were either slow cooled in still air (as-rolled, AR) or fast cooled using compressed air (heat-treated, HT) to form pearlite. Rail disc specimens, 56 mm in diameter with a contact thickness of 7 mm, were then cut out ensuring their rotational axes were perpendicular to the length of the plate to pursue constant microstructural properties such as grain size and inclusion content. The specimens were then machined to achieve a surface roughness, R_a, at the contact surface of 0.4 μm. The same process was followed for the wheel disc specimens, but using one single pearlitic grade with composition described in Table 1, a diameter of 112 mm, contact thickness of 7 mm, and surface roughness of 0.4 μm, according to the British standard BS 970: Part 1:1983 [15].

2.2. Twin-disc RCF testing and microstructural characterisation

One sample of each grade was tested at room temperature in a twin-disc testing rig using a load of 900 MPa, a nominal slip of 5%, and water as lubricant to ensure RCF crack generation but minimal wear. Identification of crack initiation is performed by stopping each run every 10,000 cycles, removing the disc from the testing apparatus, and inspecting visually using an optical microscope. Any clear RCF crack, irrespective of size, is considered a failure so the run is terminated and the cycles recorded. In case of ambiguity, the feature in question is marked and the sample is tested for another 10,000 cycles. If the feature developed into a distinct crack, then failure by crack initiation is recorded as the previous cycle count.

After testing, radial cross sections were cut from the rail discs, mounted in bakelite, ground, polished to 0.25 μm, etched in 5% nital, and metallographically characterised using a *FEI Nova NanoSEM* (scanning electron microscope). Images of the surface were acquired for wear and rolling contact fatigue assessment, as well as from the subsurface at high magnifications for interlamellar spacing determination [16,17]. Further analysis was performed using transmission electron microscopy (TEM) with similar preparation as in [18] by first cutting 1 mm thick samples, grinding them down to ~ 80 μm using silicon carbide paper, punching discs 3 mm in diameter, and electropolishing them using a *Struers TenuPol 5* twin jet polishing machine and a solution of 80% ethanol, 15% glycerol, and 5% perchloric acid at 19.5 V and 7 – 10 °C. TEM samples were observed in a *JEOL 200CX* microscope using a *Gatan Orius* camera and an accelerating voltage of 200 kV. The chemical composition of precipitates in the matrix of the samples was studied using energy dispersive X-ray spectroscopy (EDS) in a *FEI Tecnai Osiris* in scanning electron transmission microscopy (STEM) mode using

a)

b)

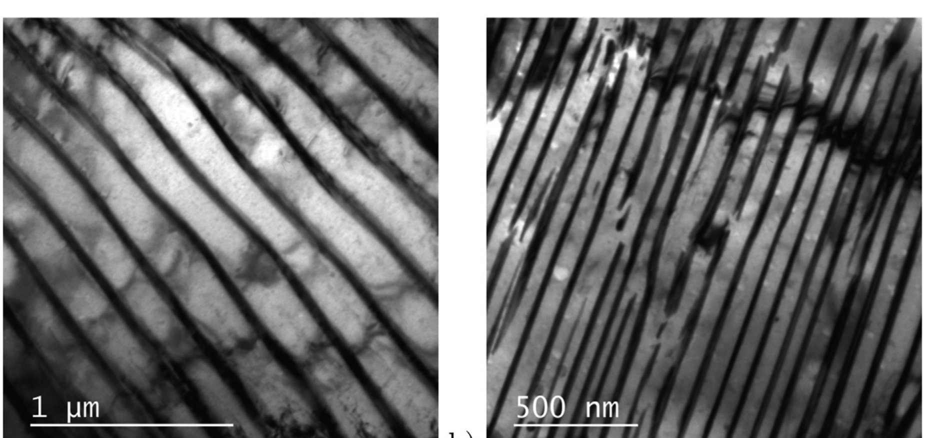

Fig. 1. TEM images of samples: (a) AR + 0.8Si + 0.1V (as-rolled, slow cooled) and (b) HT + 1.0Si + 0.1V (heat-treated, fast cooled).