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Degradation of nanostructured bainitic steel under rolling contact fatigue

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ABSTRACT

The consequences of rolling contact fatigue on a carbide-free nanostructured bainitic steel intended for bearing applications are presented for the first time. Tests performed at various intervals followed by mechanical, microscopical, and crystallographic characterization lead to the conclusion that the degradation mechanism is ductile void formation at interfaces, followed by growth and coalescence into larger voids that lead to fracture along the direction of the softer phase. This is different from the conventional damage mechanism that involves crack initiation at inclusions and propagation, for example in typical bearings steels such as 52100. The huge density of interfaces in the nanostructure allows the formation of a large dispersion of voids, and ultimately cracks, at depths consistent with the maximum orthogonal shear stress below the contact surface. This study should prove useful for the eventual usage of nanostructured bainitic steels in rolling bearings.

1. Introduction

It is possible that nanostructured bainite, which consists of incredibly fine platelets of bainitic ferrite dispersed in matrix of carbon-enriched retained austenite [1,2], may prove suitable for the manufacture of bearings. The steel in its transformed condition can have a hardness in the range 600–670 HV, strength exceeding 2 GPa, and toughness levels of around 30–40 MPa $m^{1/2}$; the available information on such mechanical property data is summarized in recent reviews [3–5]. The material is commercially available as armor but it also exhibits excellent abrasive and rolling–sliding wear resistance [6–14]. When the austenite content exceeds the percolation threshold, the structure resists the penetration of hydrogen [15]. The fatigue resistance in a variety of uniaxial tests has been proven to be excellent [11,14,16]. However, in the context of bearings, the stresses involved in fatigue due to repeated contact stresses are quite different from uniaxial loading, a close approximation being a combination of mean, uniaxial compressive-stress and torsion that are in phase with respect to their maximum values [17,18]. The purpose of the present work was therefore to investigate the rolling contact fatigue phenomena associated with nanostructured bainite. The damage mechanisms have never before been reported and are unlikely to be identical to common bearing steels due to the complete absence of carbides and the work hardening mechanism associated with the retained austenite.

2. Experimental methods

2.1. Material and sample preparation

The alloy was produced by Tata Steel UK as an ingot subjected to electroslag remelting, vacuum arc remelting, annealing, cold straightening, smooth turning, and rolling to a shaft 180 mm in diameter with the composition described in Table 1.

Long cylindrical samples for rolling contact fatigue testing with a diameter of 9.53 mm and a length of 120 mm were cut out along the longitudinal direction of the shaft using a band saw, turned, ground, and polished to a 1 μm finish.

2.2. Heat treatment

Samples were wrapped in four layers of steel foil and austenitized in a Carbolite RWF1200 box furnace at 930 °C for 30 min, cooled in air to 250 °C which took around 6 min, introduced to an oven for isothermal heat treatment at 200 °C for 10 days, and cooled in air. In order to corroborate that the heat treatment was successful, one of the samples was cut along the radial cross-section and prepared for metallographic characterization and macrohardness testing using a Vickers Limited HTM 8373 hardness machine with a load of 30 kg and a dwelling time of 5 s.

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2.3. Rolling contact fatigue (RCF) testing

Testing of the cylindrical samples was carried out on a Delta Research Corporation BR-4 Ball-Rod Rolling Contact Fatigue machine [19]. In this machine, the load is applied by three 12.7 mm in diameter balls, placed inside a bronze retainer, so that the balls push against the rotating cylindrical test specimens through two tapered bearing cups held at a certain distance of each other by adjusting the length of three springs, as seen in Fig. 1. Testing was performed at room temperature without transient conditions or hydrogen charging of the specimens that would accelerate, but might also alter the microstructural degradation process.

Before every test, three new 52,100 balls with a surface roughness of 0.013 μm, the bronze retainer, and the rod specimen were ultrasonically cleaned for 5 min first in a mixture of 50% isopropanol-50% water, then in acetone, and finally in isopropanol. The tapered loading cups were changed every four tests and turbine oil BP2380 was used as a lubricant at room temperature and a rate of 10 drops min^{-1}. This oil was filtered and recirculated. Vibration levels were monitored through an accelerometer, which automatically stopped tests if the thresholds were surpassed, caused normally only by flaking or spalling. All tests were performed at a rotational speed of 3600 rpm (the design of the test rig allows ~2.4 stress cycles per revolution) and a Hertzian pressure of 3.5 GPa (191 N of load). The nominal values and depths of the maximum unidirectional and orthogonal shear stresses induced by such Hertzian pressure are presented in Table 2. However, the actual stresses experienced are likely to be somewhat smaller given groove formation (larger contact area). The nominal thickness of the 3D elastic contact area is 0.635 mm as given by [22]

$$2a = \frac{\pi p_0 R^*}{E^*} \tag{1}$$

$$\frac{1}{R^*} = \sqrt{\frac{1}{R_1^2} + \frac{1}{R_1 R_2}} \tag{2}$$

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \tag{3}$$

where p_0 is the maximum contact pressure of 3.5 GPa, R_1, E_1 and ν_1 are the radius, Young's modulus, and Poisson's ratio of the ball and R_2, E_2 and ν_2 of the cylindrical sample. Young's modulus of both samples was taken as 210 GPa and Poisson's ratio as 0.3.

Table 2
Maximum shear stress, τ_{max}, acting at $\pm 45^\circ$ with respect to the surface, and orthogonal shear stress $\tau_{xz,max}$, acting parallel or normal to surface, and their depths, for a 3-D contact area. The values assume frictionless and elastic Hertzian contact p_0=3.5 GPa where $r_0 = (3p_0 R_{eq}/4E^*)^{1/3}$ and $R_{eq} = (R_1^{-1} + R_2^{-1})^{-1}$ [22].

	τ_{max}		$\tau_{xz,max}$	
	GPa $0.31p_0$	Depth/μm $0.48r_0$	GPa $0.25p_0$	Depth/μm $0.25r_0$
Circular contact	1.09	190	0.88	99

Table 1
Chemical composition, wt%, of the steel studied.

C	Mn	S	P	Si	Al	Cu	Cr	Ni	Mo	V	Nb	Ti	B
0.8	2.03	0.006	0.006	1.51	0.057	0.03	0.22	1.05	0.377	0.004	0.007	0.019	0.0007

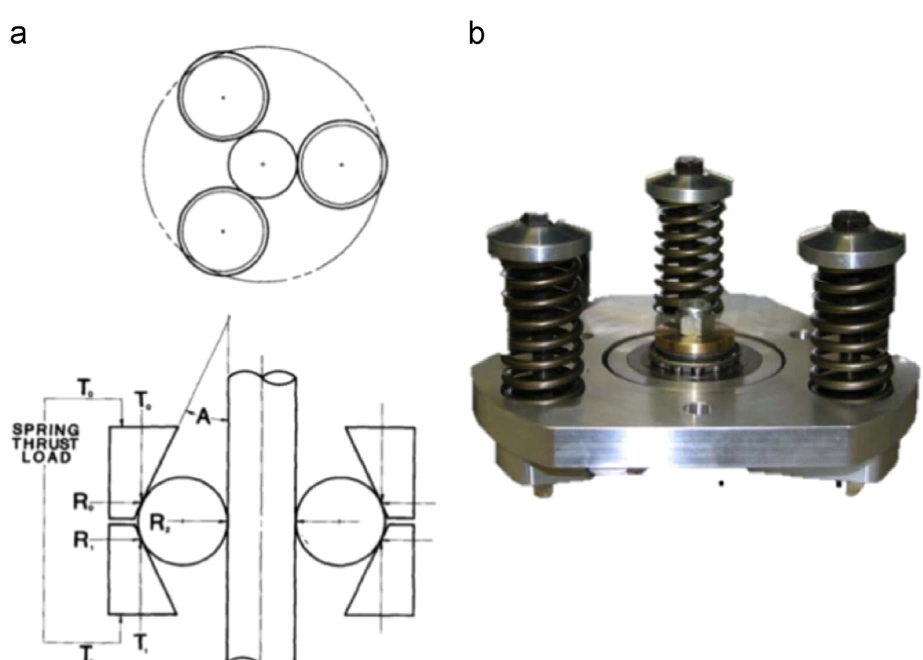

Fig. 1. (a) Rotating cylindrical specimen stressed by three radially loaded balls, which are thrust loaded by three compression springs [20] and (b) individual retainer plate during the load-setting configuration showing the three compression springs around three calibration bolts. After [21].