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Improved rolling contact fatigue life for an ultrahigh-carbon steel with nanobainitic microstructure

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In the present work, the influence of nanobainite on the rolling contact fatigue (RCF) performance of an ultrahigh-carbon steel has been studied. The results show that nanobainite can effectively improve the RCF life of the steel. In particular, the L_{10} life of specimens with 21 ± 1 vol.% nanobainite is approximately 3.3 times longer than that of specimens without nanobainite. The improvement in the RCF life of the steel is attributed to the nanobainite, which can delay the crack initiation and propagation.

Keywords: Nanobainite; Rolling contact fatigue; Ultrahigh-carbon steel; Hardness

In recent years, a novel steel grade with extremely high strength (2.5 GPa) and toughness (30–40 MPa m$^{1/2}$) has been developed according to phase transformation theory for the bainite reaction [1–8]. In these steels, a nanobainitic microstructure, which consists of extraordinarily slender ferritic plates (20–40 nm) separated by carbon-enriched austenite films, is obtained by austempering at temperatures as low as 125–300 °C [1,7]. The excellent strength of the new ferrous alloy is associated with the ultrafine grains of ferritic plate, while the high toughness is due to the stabilized austenite film [7]. One of the typical features of these steels is the high content of silicon [4,5,8], which retards cementite precipitation from austenite. The austenite is thus enriched by carbon and can be stabilized down to room temperature [1,6]. Recently, a number of studies on steels with high aluminum and low silicon (1.5 Al + 0.5 Si) have proved that nanobainite can also be obtained when the steels are austempered at low temperatures [9,10]. It is believed that aluminum slows down the formation kinetics of cementite and reduces its thermodynamic stability [9]. On the other hand, aluminum is a ferrite formation element, which can increase the bainite transformation driving force and hence increase the transformation rate of the nanobainite [11].

It has been demonstrated that traditional 1C–1.5Cr-bearing steel in the lower bainite condition exhibits an enhanced rolling contact fatigue (RCF) performance in a contaminated lubricating environment [12,13]. However, the influence of a nanobainitic microstructure on the RCF performance has rarely been studied. The hardness of the commercial bearing steels is normally between 700 and 800 HV30 [14], which is higher than that of traditional nanobainitic steels, the hardness of which is usually less than 650 HV30 [15]. In the present study, a mixed microstructure composed of nanobainite, martensite, retained austenite and undissolved spherical carbides was designed to achieve a sufficiently high hardness. By adjusting the austempering time periods, the amount of nanobainite can be readily controlled. It is well known that, if bearings are well assembled, lubricated and loaded, RCF is the main type of failure [16]. Accordingly, the evaluation of the resistance to RCF is of paramount importance for bearing steels [17]. The purpose of the present work is to study the influence of nanobainite on the RCF performance of a steel.

The chemical composition of the designed alloy (wt.%) is 1.26C–0.49Si–0.49Mn–1.56Cr–1.37Al and balance Fe. The martensite start (Ms) temperature was measured by a Gleeble 1500D thermal simulated test machine, and a value of Ms = 147 °C was obtained. Specimens for RCF tests, with dimensions of 40 mm in outer diameter, 16 mm in inner diameter and 10 mm in thickness, were machined from the spheroidizing annealed steel bars.

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These specimens were then subjected to austenitizing at 880 °C for 15 min, followed by austempering at 270 °C for 15, 30 and 45 min, respectively. Afterwards, the specimens were quenched in oil to room temperature. During austenitizing at 880 °C, 1.02 wt.% C was dissolved in the austenite matrix and 2.78 vol.% of carbide particles was retained, as calculated by Thermal-Cal in conjunction with the database TCFE6. For comparison, specimens without an austempered microstructure were austenitized at 850 °C for 15 min and then quenched in oil immediately, as based on the standard heat treatment process of SAE 52100 bearing steel. All specimens used in the RCF test were tempered at 160 °C for 2 h to eliminate the quenching stress and improve the toughness of the martensite [18]. The effect of such tempering on the nanobainite was negligible [19]. Finally, the surfaces of all specimens were ground to a roughness of 0.5 μm.

The RCF tests were carried out by using a flat washer-type RCF testing machine similar to that used in Ref. [20] (see Supplementary Fig. 1). Data about the RCF lives of 12 specimens under each heat treatment condition were acquired and used in a Weibull distribution.

Samples used for optical microscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) examination were prepared by standard techniques (see the Supplementary "Sample preparation"). Quantitative X-ray diffraction (XRD) analysis was used to determine the volume percentages of retained austenite in the samples before testing, using the integrated intensities of the (200)γ, (220)γ and (311)γ peaks, together with those of (200)α, (220)α and (211)α [4,21]. The carbon content in the retained austenite was calculated from the lattice parameters using the Dyson and Holmes equation [22,23]. The volume percentages of nanobainite were estimated by Image-Pro-Plus software on the optical images of untempered samples, within which the nanobainitic microstructure was darker than other phases (see Supplementary Fig. 2). The hardness and impact toughness of the specimens were measured using a Rockwell hardness tester (150 kg) and a Charpy impact tester (150 J), respectively.

Figure 1 shows the optical images of the designed alloy austempered at 270 °C for various time periods. As can be seen, the amount of bainite increases with the increasing austempering time. The microstructure of the specimens austempered for 0 min is composed of fine martensite, undissolved spherical carbides and retained austenite (Fig. 1a). The presence of undissolved spherical carbides can improve the wear resistance of the steel [24] and inhibit the austenite grain growth [25] (see Supplementary Fig. 3). It has been claimed that fine austenite grains can accelerate the overall bainite reaction kinetic [2]. The phases in specimens austempered at 270 °C for 15, 30 and 45 min are identical except for the quantity of each phase (Fig. 1b, c and d, respectively).

Figure 2 shows an SEM image of a bainitic area of the designed alloy austempered at 270 °C for 30 min. It can be seen that a multiphase microstructure comprising martensite, nanobainite, blocky austenite and undissolved spherical carbides is developed. The nanobainite was confirmed by TEM and a representative image of specimens austempered for 30 min is shown in Figure 3, which presents the typical microstructure of nanobainite

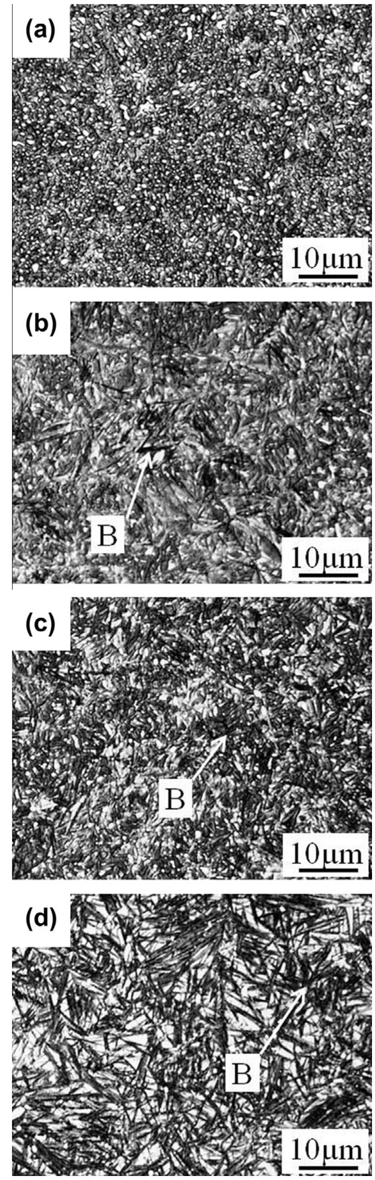

Figure 1. Optical images of the studied alloy austempered at 270 °C for (a) 0 min, (b) 15 min, (c) 30 min and (d) 45 min, then tempered at 160 °C for 2 h; B represents bainite.

composed of nanoscale bainitic ferrite and austenite film. The nanobainitic microstructure in the present study is similar to those in Refs. [1,3,4]. The formation of nanobainite in the studied alloy is due to the high carbon content, together with the presence of Si and Al, which prevent cementite precipitation [4,9]. On the other hand, it should be noted that the nanobainite is uniformly distributed in the martensite matrix and, compared with martensite, the nanobainite is soft [26]. It is believed that the presence of soft phases embedded in a hard matrix is conducive to improving mechanical properties [2].

Table 1 shows the volume percentages of nanobainite (V_{NB}) and retained austenite (V_γ), the average carbon content in the retained austenite (C_γ) and the mechanical properties of specimens austempered at 270 °C for different time periods. It is evident that the V_{NB}, V_γ, C_γ and impact toughness all increase, while the hardness decreases, as the austempering time increases. Here, the amount of retained