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Microstructure evolution of carbide-free bainitic steels under abrasive wear conditions

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ABSTRACT

The idea of carbide-free bainitic (CFB) microstructure, a mixture of bainitic ferrite and retained austenite (RA), in high-silicon steels has been recently thoroughly investigated by numerous researchers. In this research, two medium-carbon steel grades were tested in a wear tumbling machine to investigate microstructural changes under wet sliding abrasive wear conditions and to benchmark their performance against conventional tempered martensitic steels. The nature and type of defects responsible for material removal were analysed using scanning electron microscopy. To observe microstructural evolution of heavily deformed top layers of test specimens, special layer-by-layer X-ray diffraction methodology was applied. This technique allows accurate quantification of the volume fraction of RA transformed into untempered martensite at different depths from the worn surface. The results suggest that better performance is achieved in specimens heat treated to carbide-free bainitic microstructure containing higher volume fraction of RA, however with blocks of RA thermally stable at room temperature. The improved wear resistance is due to the increased surface hardness caused by stress-induced transformation of RA into untempered martensite during wear, while maintaining good toughness in the subsurface zones, which prevent brittle cracking.

1. Introduction

1.1. Carbide-free bainite

Carbide-free bainitic (CFB) microstructure of steel contains only two phases, bainitic ferrite and retained austenite (RA). In comparison to conventional lower bainite, any carbide precipitates are not present. First experiments regarding low temperature CFB and discussing this kind of structure were published in early 1980s [1–3]. Since then, the knowledge about its nature and morphology has been greatly improved, but there are still many scientific issues to resolve [4,5]. Even though the development of CFB steels is still in progress, few applications have been found, i.e. rails [6–8] and armours [9], but there are few other application possibilities, which are investigated by researchers (i.e. railway wheels [10], ball bearings [11,12] and elements for the automotive industry [13]).

Suppresion of cementite precipitation is achieved by increasing the content of silicon in alloy composition. It is commonly assumed that 1.5 wt% addition of Si is enough for complete cementite suppression [14–16]. It is important to stress, that this suppression is effective only on cementite precipitation from retained austenite, but does not influence carbide precipitation from within bainite ferrite [17] or martensite [4,18], and does not stop to other kinds of precipitates, i.e. transition carbides, from nucleating [2].

Technological realisation of the heat treatments to obtain carbide-free bainite is achieved by isothermal holding in the range of 200°–400° C, but above the M_S temperature, or continuous cooling to room temperature after austenitization step. The method and temperature used may influence overall time and output of transformation, but the transformation mechanism is always the same [17]. Elimination of carbide precipitation results in carbon supersaturation of both, bainitic ferrite and retained austenite, after the transformation. Consequently, bainitic ferrite plates can be refined, in some cases down to nanoscale.[1] However, this also significantly retards the transformation, so it can take up to several days for high carbon steels to be fully transformed into carbide-

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[1] In case of high carbon steels, bainitic ferrite plates can achieve thickness below 100 nm threshold and may be called superbainite or nanobainite.

free bainitic state. This feature can be utilized for treating steel in bulk volumes [19].

Carbide-free bainitic steels are well known to achieve superior mechanical properties. Hardness of almost 700 HV30, with tensile strengths in excess of 2200 MPa, and compressive strength up to 3000 MPa have been reported [20]. Alloys with varying carbon content can reach maximum elongation varying between 5% up to 30% [20], but also combinations of high UTS of over 2 GPa together with 12% elongation are possible [21]. Importantly, the described microstructure offer superior toughness values without sacrificing other properties, i.e. hardness. For medium-carbon steels values in excess of 120 J were obtained for Charpy impact tests [3,10,22], whereas for higher carbon contents fracture toughness K_{1C} values up to 45 MPa $m^{1/2}$ can be achieved [20]. Better toughness is produced by isothermal treatment at higher temperatures, as the microstructure contain more RA [23,24].

1.2. Role of retained austenite

The crucial feature of retained austenite in bainite is its morphology. There are two forms:

- film-like retained austenite - very thin (down to few nm in thickness) regions of austenite trapped between two parallel sub-units or plates of bainitic ferrite;
- blocky retained austenite - volumes of austenite restricted by T_0 composition.

Blocky RA is found to be the determinant for mechanical properties [3], due to the possibility of its transformation to martensite when stressed. On the other hand, it has been found that film-like RA is too stable for transformation to occur. High strain resultant from the bainite transformation, high carbon supersaturation, as well as fewer nucleation sites for martensite transformation, improve its mechanical stability [25], whereas blocks of retained austenite does not poses the same stability due to lower carbon content and larger scale. Therefore, for more stable microstructure a higher level of bainitic transformation is desirable, as the overall volume of blocky RA will decrease and higher carbon content can be achieved in this phase. Thermodynamically, this can be done by the optimisation of the chemical composition, so moving T_0 line to higher carbon contents, by lowering overall carbon content or by depressing the austempering temperature [26].

Carbide-free bainitic steel with lower carbon content (i.e. less then 0.4 wt%) in some cases shows instability of blocky RA even at room temperature [27]. Additional stabilisation of the austenite can occur when newly created martensite is sub-dividing the regions of austenite into smaller size [28]. Refinement of the RA grains can improve its stability and strength in further exploitation. The effect of austenite stabilisation is also very important to stop crack propagation. Around the tip of any microcrack, high strain energy is being delivered to a small volume of RA, which will result in transformation to martensite [8]. It has been found that the decomposition of retained austenite develops in the most controlled manner, when the microstructure consists of wide range of sizes of retained austenite and if it is regularly distributed throughout the volume of material [29].

1.3. Wear resistance of carbide-free bainite

The ultimate performance of CFB steels in abrasive conditions is believed to be mainly dependent on work hardening and microstructure evolution. Transformation to martensite from retained austenite introduces compressive stresses which inhibit propagation of damage [30] and have a grain refinement effect [31]. The thickness of a hardened layer is related to overall pressure applied during wear and it thickens with increased number of stress cycles [32]. Hardened layers can reach from 20 μm [32,33] to 50 μm deep [28]. This value is reliant to work-hardening capabilities of the microstructure [28] and may be related to RA volume fraction.

The clear correlation between RA fraction and wear resistance has not been found. It was reported [34] that CFB specimens with the same hardness, but prepared using different heat treatment parameters showed better wear resistance with higher RA volume. The author concluded, that the positive result was due to higher plasticity and good toughness of carbide-free bainite. This work contradicts the findings of Yang et al. [31], where small amount of RA showed better wear resistance mainly due to higher hardness. In other cases where CFB steel outperformed pearlitic and martensitic structures, is was related to substantial decomposition of RA during wear, i.e. from 44 vol% to less than 20 vol% [8,9].

The mechanism of damage taking place during abrasive wear in CFB steels was reported to be a combination of localized micro-cutting, micro-ploughing and some micro-fatigue, due to the random motion of particles in the contact [34], with relatively minor pitting also present. In contrast, the dominating mechanism in hard martensite is cutting [9]. As a result, surface cracking, indentations, as well as accumulation of oxidized wear debris on the surface occur. In final stages of surface degradation, delamination of thin layers can be observed. Moreover, newly created oxides are embedded into surface as a debris, which contributes to a very high friction coefficient and strong adhesion [33]. Created grooves are narrower than grooves visible in damaged benchmark martensitic steel, but can be significantly deeper [9].

Overall, despite slightly lower hardness, carbide-free bainitic microstructure exhibits better wear resistance than quenched and tempered steels [31], including widely used boron containing steels [35]. Additional surface treatment, i.e. laser hardfacing [36] or laser cladding [35], which can increase surface hardness by almost 200 HV30, do not enhance wear resistance. Therefore, hardness should be adjusted by controlling bainitic ferrite lath thickness, carbon content and RA volume fraction, with the respect to steel cleanliness [30].

2. Materials and experimental procedures

The chemical compositions of the alloys used in this study are listed in Table 1. Both alloys were delivered by the manufacturer, Ovako Sweden AB, in a rolled and spheroidized condition. Flat bars, before the heat treatment, were roughly cut to rectangular blocks. The complete list of heat treatments performed together with measured hardness values are presented in Table 2. Carbide-free bainitic samples were treated with previously chosen parameters and their hardness was checked. Subsequently, martensitic samples of each grade were tempered with temperature high enough to guarantee approximately the same level of hardness as

Table 1
Chemical compositions of tested grades.

Alloy	Chemical composition [wt%]						
	C	Si	Mn	Cr	Mo	Ni	Other alloying elements
0.3C	0.32	1.64	0.85	0.20	–	1.17	V 0.01 B 0.004
0.4C	0.39	1.60	0.61	0.72	0.33	1.66	V 0.06