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Dry rolling/sliding wear of nanostructured bainite

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ABSTRACT

The abrasive wear of carbide-free bainitic steel under dry rolling/sliding conditions has been studied. It is demonstrated that this nanostructure, generated by isothermal transformation at 200 °C, has a resistance to wear that supersedes that of other carbide-free bainitic steels transformed at higher temperatures. The experimental results in combination with a theoretical analysis of rolling/sliding indicate that, under the conditions studied, the role of sliding is minimal, so that the maximum shear stresses during contact are generated below the contact surface. Thus, the hardness following testing is found to reach a maximum below the contact surface. The fine scale and associated strength of the structure combats wear during the running-in period, but the volume fraction, stability and morphology of retained austenite play significant roles during wear, by work-hardening the surface through phase transformation into very hard martensite.

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1. Introduction

The wear behaviour of bainitic steels subjected to rolling and sliding conditions has been studied for a variety of circumstances [1–9]. In many instances, the results have indicated that this microstructure does not in general outperform pearlite with similar hardness and loading conditions [3,10–13], the exception being a 0.04 wt%C bainitic steel that had a lower wear rate (rolling–sliding) than less-ductile pearlite of similar strength [2]. The greater wear resistance of pearlite is attributed to the ability of the microstructure to deform during rolling and sliding [12], the work-hardening of the ferritic component [13,14] and the significant presence of hard cementite at the wear surface. In contrast, the interpretation of the response of bainite to similar loading tends to be complicated by the smaller fraction of cementite normally associated with bainitic microstructures, and the presence of residual phases such as martensite and retained austenite [3].

Some of these issues have been reviewed [15, pp. 382–389], but the purpose here is to consider a relatively new two-phase, carbide-free nanostructure consisting of exceptionally fine plates of bainitic ferrite embedded in carbon-enriched retained austenite [16–18]. There now exist many different alloy compositions that lead to similar nanostructures, and given hardness levels in excess of 600 HV, and good combinations of strength, toughness and ductility, there has been considerable activity in exploring the wear resistance of the structure, under many different conditions, Table 1 [8,9,19–21]. While strict comparisons are difficult, there is a general impression from all this research that the nanostructure described above holds promise. Reasons offered for this include the fine scale of the nanostructure [8,9,19–21], and the role of the austenite in preventing crack propagation during sliding [20]. A general conclusion is that the finest structures generated by transformation at the lowest temperatures have the best resistance to dry sliding wear [21]. A recent set of three-body abrasion tests that compared the nanostructured bainite, pearlite and martensite in the same steel indicated quite different wear and surface-damage mechanisms for the three structures, with the bainite being the only one that leads to a hardening of the affected surface [22].

The aim of the present work was to develop a deeper understanding of the dry rolling–sliding wear resistance of nanostructured bainite, using high-resolution characterisation methods combined with mathematical modelling. The steel studied is identical to that in our earlier work on three-body abrasion using silicon carbide particles [22].

2. Experimental procedure

2.1. Alloy and heat treatment

The steel was produced as a part of a larger programme of work on the development of nanostructured bainite for commercial

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Table 1
Wear data on the hardest, fine mixtures of bainitic ferrite and austenite reported, focusing on the lowest transformation temperatures used to generate the bainite. The Vickers hardness is also listed, and the chemical compositions are given in wt%. 'NA' stands for not available. The units of the data quoted from Table 6 of [23] have been corrected here.

C	Si	Mn	Cr	Mo	Ni	Al		Hardness	Test	Outcome	Ref.
0.89	1.43	0.19	0.47					697	Dry sliding friction, cylindrical-end against disc	Comparable wear to martensite of unspecified hardness	[19]
0.19	0.57	1.77	1.37	0.33	0.42	1.35	Carburised	625	Dry sliding friction, cylindrical-end against disc	Comparable wear to martensite of similar hardness	[20]
0.61	1.72	0.75	0.35	0.04	0.12			627	Rolling–sliding (5%) counter-rotating discs	Specific wear rate 1.0 to 1.6×10^{-4} $mm^3\,N^{-1}m^{-1}$	[8]
0.83	1.56	1.37	0.81			1.44	0.87W	685	Dry sliding friction, cylindrical-end against disc	Much greater wear resistance than harder tempered-martensite	[21]
0.99	1.50	0.76	0.46					660	Rolling–sliding (5%) counter-rotating discs	Specific wear rate 1.1×10^{-4} $mm^3\,N^{-1}m^{-1}$	[9]
0.98	2.90	0.77	0.45					630	Rolling–sliding (5%) counter-rotating discs	Specific wear rate 0.9×10^{-4} $mm^3\,N^{-1}m^{-1}$	[9]
0.90	1.65	0.79	0.48					693	Rolling–sliding (5%) counter-rotating discs	Specific wear rate 0.4×10^{-4} $mm^3\,N^{-1}m^{-1}$	[9]
0.68	1.60	1.25	1.50					589	Rolling–sliding (5%) counter-rotating discs	Specific wear rate 1.0×10^{-4} $mm^3\,N^{-1}m^{-1}$	[9]
0.99	2.47	0.74	0.97	0.03				650	Rolling–sliding (5%) counter-rotating discs	Specific wear rate 8.6×10^{-6} $mm^3\,N^{-1}m^{-1}$	[23]
0.67	1.67	1.31	1.73	0.15			0.12V	NA	Rolling–sliding (5%) counter-rotating discs	Specific wear rate 1.2×10^{-5} $mm^3\,N^{-1}m^{-1}$	[23]

Table 2
Chemical composition (wt%), heat treatment and resultant hardness.

C	Mn	P	S	Si	Al	Cu	Cr	Mo	V	Co	Sn	Nb
0.83	2.28	0.011	0.008	1.9	0.044	0.12	1.44	0.24	0.11	1.55	0.019	0.023

Heat treatment	Vickers hardness
930 °C 1 h, air cooled to 200 °C, held for 10 days, air cooled	622 ± 13

engineering-applications. Nine tonnes of material were continuously cast in round sections of 150 mm diameter with the chemical composition listed in Table 2. Cylindrical discs for wear testing were cut from the cast material using wire-electro-discharge machining, the edges of which would be subjected to rolling contact. The edges were therefore machined to a final average roughness of ~1 μm. The discs were then heat treated in a sealed tube furnace maintained with a positive pressure of argon. Details of the heat treatment and resulting hardness are also given in Table 2. Low transformation temperature with prolonged heat treatment time helps to achieve uniform microstructure across the wear rings which is essentially free from any residual stress.

2.2. Wear tests

Rolling/sliding tests were performed in a UTM 2000 twin-disc machine using 10 mm thick cylindrical discs of 45 ± 0.1 mm diameter. The two discs, when made to contact at their edges during rotation, develop a rectangular area of contact. Because of the surface roughness and geometrical/dimensional tolerance, full contact over the entire length of overlap was never made possible. Theoretically, the contact should first be made between the highest asperities and should gradually increase as the wear progresses. A roll-slide parameter, equal to $\xi=0.95$, was introduced by administering differential velocities between the discs.[1] This would influence the two normal stress and the shear stress component in plane stress condition. The tests were conducted in a controlled environment (~25 °C, 23% humidity) without any lubrication. Experiments were conducted for three pairs of discs for 30,000 cycles at a rotational speed of 100 rpm and 95 rpm with an externally applied load equal to 300 N. Weight losses were measured for three pairs of discs and normalised against load and wear length.

2.3. Metallography

Heat treated samples were characterised using scanning electron (Jeol 5800 LV) and transmission electron (Jeol 200 CX) microscopy depending on the resolution and information required out of the microstructure. For scanning microscopy, the metallographically ground and polished samples were etched with 2 vol% nital. Thin foils for transmission electron microscopy were prepared by cutting ~200 μm thick samples using a SiC blade from which discs of 3 mm diameter were machined out using spark-erosion. The discs were then ground down to 50 μm thickness using 2500 and 4000 grit SiC abrasive papers successively and foils were prepared by electro-polishing at −4 °C in an electrolyte comprising 5% perchloric acid, 15% glycerol and 80% methanol by volume.

Light optical interferometry under vertical shift mode, which is used for irregular surfaces having step heights of the order of few millimetres, was adopted to measure the roughness of the surfaces before and after the wear tests.

2.4. Nanoindentation tests

Knoop indenters often fail to measure the hardness of the surface and the sub-surface layer after abrasion because of the presence of severe microstructural gradients that require finer resolution than the scale of the indenter [24,25]. Constant-depth nanoindentation was therefore used to characterise changes on cross of the wear samples, prepared by polishing with 200 nm colloidal silica for 5 min. This polishing achieves a surface roughness less than the maximum depth of penetration made by the

[1] The parameter is calculated from the difference of circumferential velocities of the two discs. Mathematically, it is 1−(% slip/100).

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