Wear 358-359 (2016) 80–88

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

The scratch and abrasive wear behaviour of a tempered martensitic construction steel and its dual phase variants

Xiaojun Xu [a], Sybrand van der Zwaag [a], Wei Xu [b,a,*]

[a] Novel Aerospace Materials Group, Faculty of Aerospace Engineering, Delft University of Technology, 2629HS Delft, The Netherlands
[b] State Key Laboratory of Rolling and Automation, Northeastern University, 110819 Shenyang, China

ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form
4 April 2016
Accepted 6 April 2016
Available online 12 April 2016

Keywords:
Abrasion resistance
Tempering
Martensitic steels
Scratch test
Failure mechanisms
Dual phase steel

ABSTRACT

An experimental investigation of the scratch and abrasive wear behaviour of a lean C–Mn construction steel in its tempered fully martensitic (TM) state is presented. The scratch resistance and the corresponding failure mechanisms as a function of the tempering temperature (200–500 °C) were evaluated using a multi-pass dual-indenter (MPDI) scratch test applying different loading conditions. Results show that the scratch resistance depends not only on the tempering temperature, but also on the load applied during scratching. The optimal tempering temperature depends on the applied load. For both low and high loading conditions, the dual phase (ferrite–martensite) variant with an optimised martensite volume fraction and morphology yields an even better combination of scratch/abrasion resistance and hardness. The scratch resistance at different loading conditions is linked to the strength coefficient K in the Hollomon equation ($\sigma = K\varepsilon^n$). The scratch behaviour in the MPDI scratch test at a low load correlates quite well with the standard ASTM G65 multi-particle abrasion test.

1. Introduction

Lowly alloyed martensitic steels are used widely as cost-effective materials for applications requiring a high-abrasion resistance because of their high hardness [1–3], which is supposed to lead to a higher abrasion resistance [4,5]. In order to improve the wear resistance, such steels are generally tempered to modify the balance between the various mechanical properties, and in particular to improve the toughness/ductility [6–8] while keeping a relatively high hardness. The wear behaviour of (tempered) martensitic steels has been studied extensively as a function of many main factors, such as carbon concentration [9,10], tempering temperature [11–13] and working conditions (such as applied load and sliding speed) [14–16]. The work reported by Xu et al. [9] and Moore [10] showed that the wear resistance of martensitic steels can be improved by increasing the carbon content. However, if the carbon concentration exceeds a critical level, the wear resistance decreases although the hardness increases. The change in behaviour is because the ductility and toughness decrease dramatically and the resulting microstructure becomes susceptible to crack nucleation and brittle delamination, especially under harsh conditions [17–19]. Studies on the effect of the tempering temperature on wear resistance [13,20–22] showed that with increasing tempering temperature both the hardness and wear resistance decrease. In contrast, El-Rakayby, et al. [11] and Fu, et al. [23] showed that for their steels the wear resistance first increases and then drops with the temperature rises and they attributed this dependence to the carbide precipitation during tempering. Finally, many studies reported that the wear rate displays a linear relationship between the abrasion rate and the work conditions in particular applied load and sliding speed [14,15,24]. However, Rai, et al. [16] reported that the wear rate first increases with applied load or sliding speed up to a transition value beyond which the wear rate decreases as a result of oxidative wear. While the relationship between microstructure, load conditions and abrasion resistance is not yet very clear and unambiguous, the situation becomes even less clear when the abrasion resistance of low alloyed martensitic steels is compared to that of other steel grades, such as ferritic, pearlitic steel and bainitic steels [17,25,26] and Hadfield austenitic steels [1,2]. Most studies showed that the martensitic microstructure displays a better abrasion resistance than ferrite, pearlite and bainite or high Mn austenite. However, systematic investigations on the abrasion resistance of a single steel of a fixed chemical composition yet heat treated to produce different microstructures such as a range of tempered martensitic microstructures as well as ferrite–martensite (DP) microstructures with different martensite volume fractions and morphologies are still lacking. The only work coming close to the objective of the present work is that of Jha et al. [27] who reported that the

---

[*] Corresponding author at: State Key Laboratory of Rolling and Automation, Northeastern University, 110819, Shenyang, China. Tel.: +86 24 83680246.
E-mail address: xuwei@ral.neu.edu.cn (W. Xu).

http://dx.doi.org/10.1016/j.wear.2016.04.005
0043-1648/© 2016 Elsevier B.V. All rights reserved.

abrasion resistance of a steel in the ferrite-martensite state can be better than that in the martensitic state, but they did not examine the relative abrasive performance for both microstructural variants for a wider range of conditions.

The aim of the present work is to clarify the response of tempered martensitic microstructures produced by different tempering temperature on scratch and abrasion behaviour for a hot rolled 22MnB5 steel under different load conditions, and to compare this to the scratch and abrasion behaviour of the same steel yet produced to distinctly different DP microstructures (as seen in [28]). This steel is being considered for industrial applications where the abrasion and local impact resistance play a key role, e.g., in earthmoving, agricultural and mining equipment. The scratch resistance and the corresponding failure mechanism of the tempered martensitic microstructure at the different load conditions was unravelled using the multi-pass dual-indenter (MPDI) scratch methodology, which has been used successfully to rank the steady state scratch resistance for a wide range steel grades and to reveal the abrasive failure mechanism [29]. The advantage of this test method is that it probes the scratch resistance of a work hardened surface layer created under well controlled conditions, rather than that of a pristine metal surface as is the case in conventional scratch testing. It is worth pointing out that the conventional scratch tests used to mimic the abrasion process and to provide some insights on wear mechanisms, but they are almost invariably done on freshly prepared new surfaces (i.e., un-deformed or non-work hardened surfaces), which are quite different from those formed during the real abrasion process. During abrasion subsurface deformation and work hardening occur and a rough work-hardened layer is formed, and hence scratching experiments on freshly prepared new surfaces do not truly reflect the response of a material during abrasion except for the run-in stage, as stated in previous work [29]. While the MPDI test essentially probes the damage formation and its interaction with the damage in the work hardened surface layer in the steady state situation closer to real abrasion process rather than during the run-in stage. In this test the work hardened state of the surface layer can be varied by changing the load employed, making it possible to mimic a wide range of abrasion conditions ranging from a mild to harsh condition. Moreover, the strain hardening analysis introduced in previous work [28,30], was utilised to correlate the tensile test strain hardening behaviour with the scratch resistance under different load conditions. Finally, it is shown that the MPDI scratch test at mild loading conditions correlates well with the standard ASTM G65 test commonly used to screen steel grades for abrasive applications.

2. Experimental procedure

The material used in this investigation was a single lean C–Mn construction steel with the composition (in wt%): Fe-0.22C-1.2Mn-0.25Si-0.2Cr. The 3 mm thick hot-rolled steel sheet was initially homogenised at 1200 °C for 24 h in a hydrogen atmosphere followed by air cooling. After homogenisation, a quenching and tempering (Q&T) treatment (after austenization at 900 °C for 10 min followed by water quenching) was performed to produce tempered martensitic (TM) microstructures. The tempering temperatures were 200 °C, 300 °C, 400 °C and 500 °C with a fixed time of 1 h. After tempering the material was quenched again in water. The heat treatment cycles are shown in Fig. 1. After the heat treatment, samples for metallurgical characterisation were polished to a high standard and subsequently etched with a 2% Nital solution. A Leica optical microscope was used for the microstructural examinations. Specimens for scratch testing (15 mm × 9 mm), ASTM G65 abrasion testing (75 mm × 25 mm), and tensile testing (sample geometry A25) were prepared such that the longitudinal direction of the sample was in the rolling direction. Micro-hardness measurements were carried out using a Vickers indenter at 2 N load and the average value of 10 measurements is reported. Per condition only two tensile tests were performed given the small scatter for these highly standardized tests. The strain rate was 10^{-3}/s.

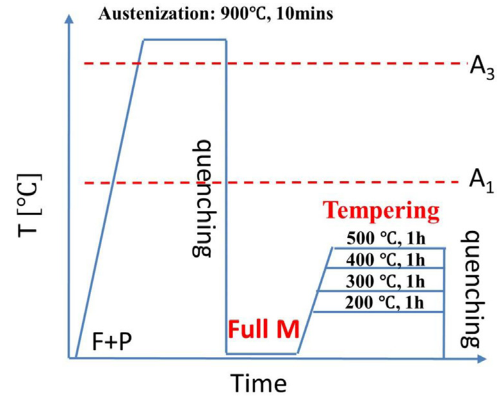

Fig. 1. Schematic representation of the various heat treatment procedures.

The multi-pass dual-indenter (MPDI) scratch test [29] and ASTM G65 test were employed to investigate the scratch and abrasive wear behaviour for all sample grades. In the MPDI test, two diamond Rockwell indenters with different tip radius and cone angles were employed. The scratch resistance is evaluated by sliding a small pointed indenter (a cone angle of 60° and a radius of 5 μm) with single pass and a load 0.2 N along the very centre of a wear track produced by sliding a large blunter indenter (a cone angle of 120° and a radius of 100 μm) with 10 identical passes over the pre-polished surface. The load on the large indenter was varied between 0 N (i.e. scratching on pristine surface by small indenter only) to 25 N aiming to create an extensively well-defined strain hardened surface as formed during steady state in a real life abrasion. The sliding direction was kept perpendicular to rolling direction. The scratch depths to be reported refer to the penetration depth by the small indenter scratching only with respect to the bottom of the wear track produced by the large indenter. The measurement of scratch depth consists of two steps: firstly, pre-scanning the profile of surface referring to the wear track by the large indenter using the small indenter at a very low load of 0.03 N and secondly, scratching at the same track with the small indenter using a fixed load of 0.2 N. The penetration depth as a final scratch depth is derived from the difference of the two steps. Further details on the MPDI test and its interpretation can be found elsewhere [29,31].

In order to benchmark the MPDI scratch response, a standardized ASTM G65 abrasion tests were performed up to a total of 2000 wheel rotations at a speed of 200 rpm with standard Ottawa silica sand as the abrasive medium following procedure B. Samples along the rolling direction were prepared and the surface was mechanically pre-grinded following a standard metallography method. The weight loss of the samples was measured to an accuracy of 1 mg before and after the test. Finally, scanning electron microscope (SEM) operating at 5 kV was employed to investigate the characteristics of the worn surface.

3. Results

3.1. Microstructures and mechanical properties

Characteristic microstructures generated by tempering at different temperatures are shown in Fig. 2. It can be seen that all