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The effect of ferrite–martensite morphology on the scratch and abrasive wear behaviour of a dual phase construction steel

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ABSTRACT

A systematic experimental investigation concerning the effect of ferrite–martensite morphology on the scratch and abrasion resistance of ferrite–martensite dual phase (DP) steels is reported. A hot rolled 22MnB5 steel was subjected to different heat treatments to generate dual phase microstructures with different ferrite–martensite morphologies. The effects of morphology on the scratch resistance and the corresponding failure mechanisms were unravelled using a multi-pass dual-indenter (MPDI) scratch test applying different load combinations. Results show that the ferrite–martensite morphology has a significant influence on scratch resistance and that the effect is contact load dependent. The scratch behaviour is linked to the strength coefficient K in the Hollomon model ($\sigma = K\varepsilon^n$) as well as the initial indentation hardness. Results suggest that the strength coefficient K corresponds well with the scratch resistance. The optimal microstructure to yield the best combination of abrasion resistance and hardness depends on the working conditions. At a low loading condition the relative ranking of the scratch resistance of the various microstructures created is in good agreement with that of the ASTM G65 abrasion test.

1. Introduction

Dual phase steels are increasingly used for automobile constructions and other structural applications because of their good balance of strength and ductility, a good strain hardening capability as well as a good formability due to the presence of both a ductile ferrite phase and a hard martensitic phase [1–3]. The attractive mechanical properties are the result of the composite nature of the dual phase microstructure, i.e. a combination of load bearing by the hard constituent (such as martensite) and strain accommodation by the soft and ductile phase (ferrite). There are many microstructural factors which influence the mechanical behaviour of dual phase microstructure. In particular, the volume fractions of each phase, the morphology, and the specific properties of ferrite and martensite all affect the mechanical properties [4–8]. These factors certainly influence the abrasion resistance of materials. Our previous research efforts have focused on the effect of martensitic volume fraction in DP steels on their abrasion resistance [9]. The response of martensitic volume fraction on the scratch resistance strongly depends on the loading conditions applied. Under the low load condition, the scratch depth generally decreases with increasing the martensite volume fraction up to 100%. While under the high load condition, the scratch depth firstly decreases and then increases with increasing the martensite fraction. An optimal fraction exists in DP steels in such condition. In this paper, we refine the discussion to unravel the effect of ferrite–martensite morphology and the spatial distribution of the martensite with respect to its difference in the size, shape and spatial configuration on the scratch and abrasion resistance for a hot rolled 22MnB5 steel. This steel grade is being considered for industrial applications where the abrasion and impact play a key role, e.g., in earthmoving, agricultural and mining equipment. When heat treated to a dual phase structure this steel grade is reported to show a better scratch/abrasion resistance compared to when in the martensite state, especially in harsh conditions [9]. The effect of the ferrite–martensite morphologies produced by different heat treatments on the tensile deformation behaviour [6,10–13], the quasi-static/dynamic torsional deformation [14,15], the fatigue resistance [16–18], the impact behaviour [19], and the stain hardening [5,20,21] has already been studied by others. Given the facts that the abrasion resistance is not an intrinsic material property but is the complex response of a multi-parameter tribosystem and that the different properties of both phases and the different morphology for ferrite–martensite DP steel will result in complex strain/stress partitioning and different

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load response, the scratch and abrasion resistance has not been studied in great detail yet.

As reviewed in [22], in dual phase steels the ferrite–martensite morphology is the critical parameter in controlling the wear resistance [22]. Other studies [23–25] reported that a DP steel with a continuous ferrite network encapsulating martensite displayed better wear resistance than those with a continuous martensite network encapsulating ferrite at the same martensite fraction. In another study related to the effect of size of martensite colony on abrasion resistance of a DP steel [26], it is demonstrated that for DP steels with coarser martensite colonies (but accompanying the increase of martensite fraction) showed a better performance against abrasive wear than a finer distribution of martensite islands. To separate the effect of martensite fraction and size of martensite colony, Bhowmick et al. [27] produced DP steels with different morphologies at fixed martensite fractions, which showed that the highest abrasion resistance is obtained for the DP steel having large martensite colony. In contrast, some works reported by Khatirkar et al. [28] on En24 steel, Baburaj et al. [29] on En31 steel, Singh et al. [30] on D2 steel and Fu et al. [31] on rolling mill liner steels show that a coarser martensite reduces the abrasion resistance. Lindroos et al. [32] also pointed out that the morphological features (the prior austenite, packet, block and lath sizes) of the martensitic structure have a strong effect on the strength and work hardening behaviour of the high strength steels and hence influence the wear resistance. Moreover, Deng, et al. [33] investigated the effect of ferrite morphology on abrasion resistance of DP steel at the same martensite fraction. The results showed that the acicular ferrite–martensite DP steel possesses a better abrasion resistance than the polygonal ferrite–martensite DP steel. While these studies certainly clarified some issues, in these studies either the effect of morphology was determined for one loading (abrasion) condition or the effect of volume fraction was not well separated from that of morphology. Systematic investigations into the effect of ferrite–martensite morphology (shape, size and distribution) on abrasion/scratch resistance of DP steels at different load conditions and at fixed martensite fraction are still lacking. Hence, the response of different morphologies in DP steels on scratch and abrasion resistances under different load conditions is still not yet clear.

The objective of the present work is to clarify the effect of the different ferrite–martensite morphologies on the scratch and abrasive wear behaviour in DP steels at different load levels. In order to separate the effects of the individual parameters (morphology), the volume fractions of the martensite and the properties of ferrite and martensite which are intrinsically coupled were tailored by heat treatments designed on the basis of a local equilibrium (LE) kinetic transformation model [34]. The scratch resistance of resulting microstructures with three different well-characterized morphologies was evaluated using the multi-pass dual-indenter (MPDI) scratch test method [35]. Moreover, the strain hardening analysis using two-stage tensile strain hardening model introduced in the previous work [9] was used to correlate the tensile test strain hardening behaviour with the scratch resistance under different load conditions. Finally, the standard ASTM G65 test was performed to rank the abrasion resistance for the various microstructures and to establish a correlation between the scratch test with the standard ASTM G65 abrasion test.

2. Experiments

2.1. Material, heat treatment and sample preparation

A hot rolled 22MnB5 steel (Fe–0.22C–1.2Mn–0.25Si–0.2Cr, in wt%) was chosen for this study. The 3 mm thick steel sheet was firstly homogenized at 1200 °C for 24 h in a hydrogen atmosphere followed by air cooling. After homogenization, the isothermal transformation heat treatment was carried out using a Nabertherm furnace – Modell L 5/13/B180. The variation of temperature on the sample sheet is measured to be within ± 5 °C. Three different heat treatment routes (as seen in Fig. 1) were performed to generate DP steels with different morphologies: (a) full **A**ustenisation, then **I**ntercritical annealing to form ferrite structures followed by **Q**uenching (AIQ); (b) **I**ntercritical annealing, directly from the **F**errite/pearlite starting microstructure followed by **Q**uenching (FIQ); and (c) **I**ntercritical annealing from an almost fully **M**artensitic starting state followed by **Q**uenching (MIQ). The detailed heat treatments are described below:

- AIQ: full austenisation followed by intercritical annealing at 700 °C, 725 °C, 750 °C and 760 °C for 1 h followed by water quenching, as shown in Fig. 1a.
- FIQ: intercritical annealing of the initial ferrite–pearlite microstructure at 750 °C, 775 °C, 790 °C and 800 °C for 1 h and water quenching, as shown in Fig. 1b.
- MIQ: first full austenisation followed by water quenching; then intercritical annealing at 750 °C, 775 °C, 790 °C and 800 °C for 1 h followed by water quenching, as shown in Fig. 1c.

In Fig. 1, the A1 and A3 temperature calculated using Thermo-Calc to be 661 °C and 806 °C respectively, are also indicated. The heat treatment parameters and resulting microstructures are summarized in Table 1. After annealing, specimens for scratch testing (15 mm × 9 mm), ASTM G65 testing (75 mm × 25 mm), and tensile testing (sample geometry A25) were prepared with the longitudinal direction of the sample in the rolling direction.

2.2. Multi-pass dual-indenter (MPDI) scratch test and ASTM G65 abrasion test

The multi-pass dual-indenter (MPDI) scratch experiments [35] were performed with a CSM micro-scratch tester to investigate the scratch behaviour for all microstructural variants. In this test, two diamond Rockwell indenters with different tip radius and cone angles were employed, i.e., a small indenter with a tip radius of 5 μm and a cone angle of 60° and a large indenter with a tip radius of 100 μm and a cone angle of 120°. The scratch resistance is evaluated by sliding a small pointed indenter with a load 0.2 N along the very centre of a wear track produced by sliding a large blunter indenter with 10 passes over the pre-polished surface. The load on the large indenter was varied from 0 N to 25 N aiming to create an extensively strain hardened surface as formed in a real life abrasion during steady state. The sliding speed in the test was 30 mm/min. The test parameters are specified in Table 2. 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 with respect to the bottom of the wear track produced by the large indenter. The scratch depths as determined by profilometry were averaged over a representative length of the scratch tracks. The measurement of scratch depth consists of two steps: firstly, pre-scanning the profile of surface with 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, reported as a final scratch depth, is the difference between the two profiles measured with the low probing load. Further details on the MPDI test and its interpretation can be found elsewhere [35,36].

To benchmark the MPDI scratch responses, standardized ASTM G65 abrasion tests were performed with total rotations of 2000 at a speed of 200 rpm using standard Ottawa silica sand as the abrasive medium following the procedure B. Samples aligned