A study on correlating microstructural features with abrasion resistance of a high strength low alloy steel

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Abstract: Scratch tests were carried out in order to investigate correlations of the scratch resistance, representing the abrasion resistance to a certain extent, with various microstructural features as well as different resulting hardness of a high strength low alloy (HSLA) steel. The HSLA steel was subjected to selected heat treatment cycles in order to produce different microstructural combinations, thereby obtaining various abrasion resistance. Results of scratch tests suggested that a high hardness alone cannot guarantee a high scratch (abrasion) resistance, and the microstructural features play a vital role in determining the abrasion resistance. More specifically, it was shown that a dual phase (ferrite plus martensite) microstructure with a relatively low hardness possesses a better abrasion resistance than a full martensite with a higher hardness. Moreover, observations of scratch scars revealed different features of scar surface and debris: the dual phase microstructure results in a smooth scar surface and with plate debris, while a full martensite leads to a relatively coarse scar surface with sharp debris, which is very harmful to the abrasion resistance due to its secondary damage to the surface. Furthermore, results suggested the scratch test can well mimic the nature of abrasion wear and hence provide fast, reproducible, and quantitative information on abrasion resistance of different microstructures.

Keywords: scratch test; microstructure; dual phase; abrasion resistance; low alloy steel

Introduction

Abrasive wear is a commonly occurring wear mechanism invariably observed in various industrial applications, such as automotive, transportation, mining, mineral processing, agricultural and earth moving industries [1, 2], and it represents a very costly problem. Abrasion is a very complex phenomenon and the abrasion resistance is affected by many parameters. To a first approximation, hardness is frequently used as the most significant indicator to rank the abrasion resistance of metallic materials, following the general hypothesis that there is a monotonous relationship between the abrasion resistance and the hardness of a material [3, 4]. However, over last decades many investigations clearly demonstrated that steels often display non-monotonous relationships of abrasion

resistance versus hardness [5, 6], but "V" or "S" shaped correlations [7, 8]. Notwithstanding, the hardness of a steel grade is still considered as the main indicator of its abrasion resistance. As a result, current development of abrasion resistant steel market is mostly oriented at a higher hardness. However, from a durability point of view, an alternative and more attractive approach is to focus on the abrasion resistance itself. Recent studies have shown that multiphase steels with a relatively lower hardness may possess significantly improved abrasion resistance as compared to single phase steel grades with higher hardness [11, 12]. Therefore, a better abrasion resistant grade can be achieved through microstructure control by tailored heat treatments to obtain the optimal microstructural combination, abrasive resistance and other mechanical properties.

In order to investigate correlations of the abrasion resistance and the microstructure, a high strength low alloy steel was subjected to selected heat treatment cycles to obtain different microstructural combinations. Scratch test, which has been proved to be an efficient tribological method to determine the abrasion resistance [13, 14], was performed to determine the abrasion resistance of various microstructures. Correlations among scratch resistance, microstructure and hardness are discussed, as well as different features of abrasive surface and debris formation.

2. Experiments

2.1 Heat treatment and samples preparation

The composition of the HSLA steel in the current study is 0.15C-1.9Mn-0.20Si-0.15Cr. Dilatometer samples of $10x4\times1mm^3$ (longitudinal, transverse and thickness directions) were prepared and three types of heat treatment cycles were performed: (a) fully austenitization followed by furnace cooling, (b) fully austenitization followed by intercritical annealing at 810℃ and 790℃ respectively, and water quench and (c) fully austenitization followed by water quench aiming to obtain high hardness fully martensitic microstructure. Here, the microstructure of fully fresh martensite, other than tempered martensite, was chosen so as to directly compare its contribution in dual phase microstructure which also possesses non-tempered martensite. Table 1 summarizes the heat treatment in details.

2.2 Microscopy and Hardness measurement

The metallography samples were prepared and etched with 2% Nital solution. Volume fractions of different phases were quantified by Photoshop and Matlab. Vicker's Hardness was measured with a 2N load and an average value of 8 indents was used. The scratch surface was characterized using Optical Microscopy (OM), Scanning Electron Microscopy (SEM) and Confocal Laser Scanning Microscopy (CLSM).

2.3 Scratch test

Abrasion resistance was characterized by employing the scratch test with a CSM Instrument. A schematic drawing of the test configuration is shown in Fig.1. The scratch test is performed with a constant load of 5N and a scratch distance of 1 mm with a speed of 0.5mm/s. During the test, the instrument firstly makes a pre-scan of the sample surface with a low load of 0.03N. The second step is to perform the scratch with the applied load as specified above. After the scratch, a post-scratch scan is applied on the worn scar with again a low load of 0.03N. Therefore, the Residual depth (Rd) can be calculated as the difference of the Post-scan minus the Pre-scan. The average value of residual depth for each sample is reported in Table 1. Typical images of scratch surface are shown in Fig.2. Scratch test was repeated 3 times on each sample.
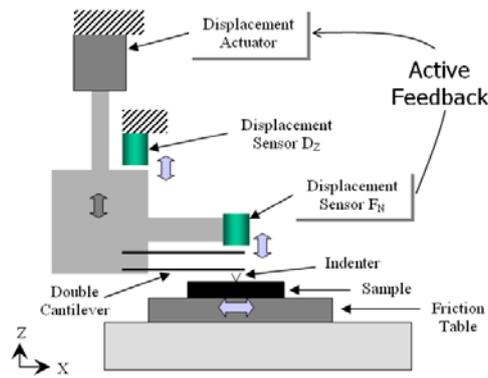
Fig.1 A schematic drawing of scratch test machine [15].
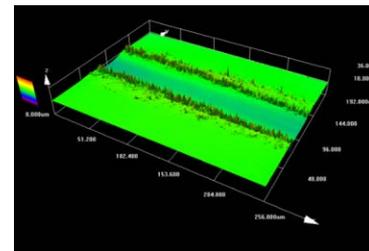
(a)   (b)

Fig.2 Scratch morphology by (a) OM and (b) Confocal Microscopy.

Table 1 Heat treatment conditions and resulting hardness, residual depth and microstructures

Heat treatment cycles	Hardness, $Hv_{0.2}$	Residual depth μm	Microstructure
T1: Austenitization at 900 ^{o}C for 5 mins followed by furnace cooling	217± 5	2.76±0.213	Ferrite +pearlite (44%)
T2: Austenitization at 900 ^{o}C for 30 s followed by intercritical annealing at 790 ^{o}C for 10 mins, and water quenching.	399± 7	1.09±0.0005	Ferrite +martensite (84%)
T3: Austenitization at 900 ^{o}C for 30 s followed by intercritical annealing at 810 ^{o}C for 10 mins, and water quenching	413± 10	1.11±0.010	Ferrite +martensite (88%)
T4: Austenitization at 900 ^{o}C for 5 mins followed by water quenching	482± 9	1.25±0.068	Martensite (100%)

3. Results

3.1 Microstructure

Microstructures of samples after different heat treatments are shown in Fig.3. Sample T1 following fully austenitization and furnace cooling displays a typical ferrite and pearlite mixture as shown in Fig.3 (a). Samples T2 and T3 subjected to intercritical annealing and water quench result in a microstructure combination of ferrite and martensite as indicated in Fig.3 (b) and (c). The relative high intercritical annealing temperatures leads to a high volume fraction of martensite and a small fraction of ferrite, mainly along the prior austenite grain boundaries. The volume fractions of ferrite are quantified to be 16% and 12%, for annealing temperatures of 790 and 810°C respectively, as shown in Table 1, which

are in the same order of magnitude as predicted by thermodynamic calculation via ThermoCalc. Sample T4 after fully austenitization and water quench displays fully martensitic microstructure without a notable amount of retained austenite.

(a) F+P

(b) 790 F+M

(c) 810 F+M

(d) Full M
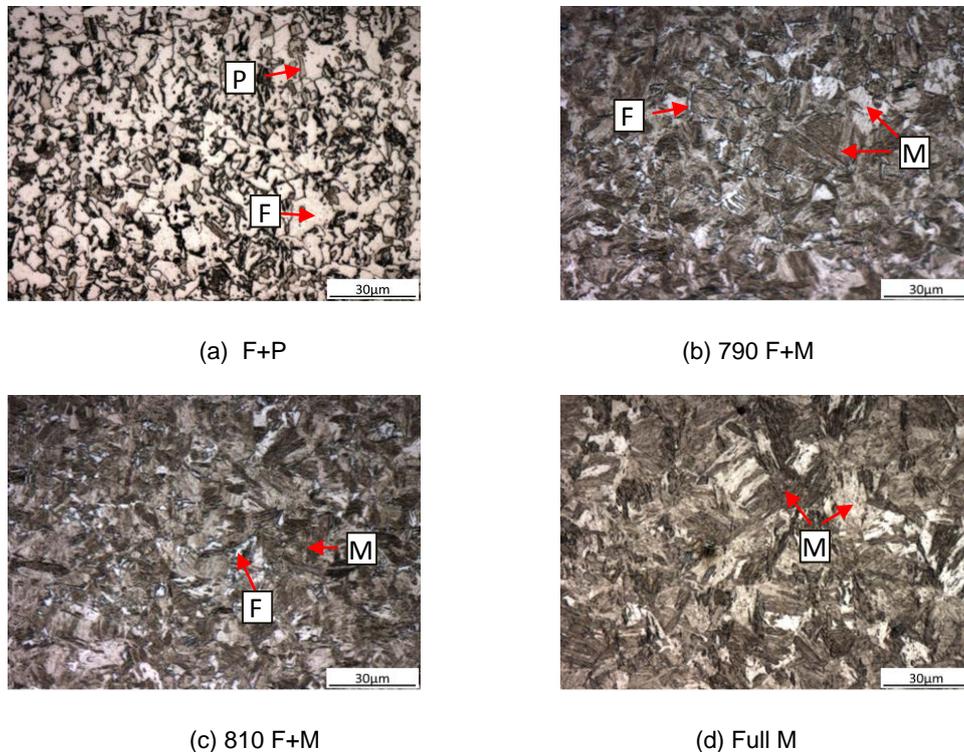
Fig.3 The microstructure after heat treatment of (a) T1; (b) T2; (c)T3; (d)T4. F: Ferrite (white), P: pearlite (black), M: martensite (black and brown).

3.2 Hardness

Hardness of all samples are shown in Table1. The fully martensitic sampleT4 displays the highest hardness of 482Hv. Hardness of intercritical annealed samples T2 and T3 possess intermediate hardness owing to the mixture of hard phase martensite and a small amount of ferrite, and the hardness is in good agreement with the intercritical temperature, i.e. hardness decreases as intercritical annealing temperature arises. The furnace cooled sample has the lowest hardness because of the ferrite and pearlite mixture.

3.3 Scratch test

For the scratch test, three scratches were produced and results are very reproducible. In each test, the residual penetration depth stabilizes after a scratch distance of 0.1mm. Therefore, the residual depth is calculated from thereon, and the average of 3 tests was calculated. The average residual penetration depths of four different samples are presented in Fig. 4, as a function of their Vicker's hardness. The associated microstructures are also indicated in the plot. It can be observed that the scratch resistance does not follow a monotonous relationship with hardness, i.e. the sample of dual phase (ferrite and martensite) displays lower residual penetration depths compared to a fully martensitic microstructure, although their hardness are lower than that of the fully martensitic. The very soft ferrite and pearlite mixture behaves the worst in the scratch resistance.
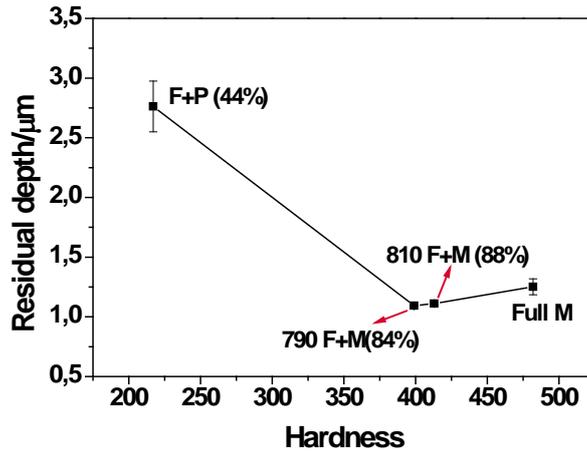
Fig.4 Residual penetration depth and Vicker's hardness of four different samples.

3.4 Scratch surface

Fig.5 (a) presents the scratch surface of sample T2, a ferrite and martensite mixture after intercritical annealing at 790 ^{o}C and water quench, while Fig. 5(b) shows the scratch scar of T4 fully martensitic sample. It can be observed that the dual phase steel shows relatively smooth scar grooves and edges, while the martensitic steel displays relatively coarse scar. In addition, the debris formed in T2 is more rounded plate shape, while in T4 sharp debris are formed, which is very harmful to abrasion resistance owing to its potential of secondary damage during the process.
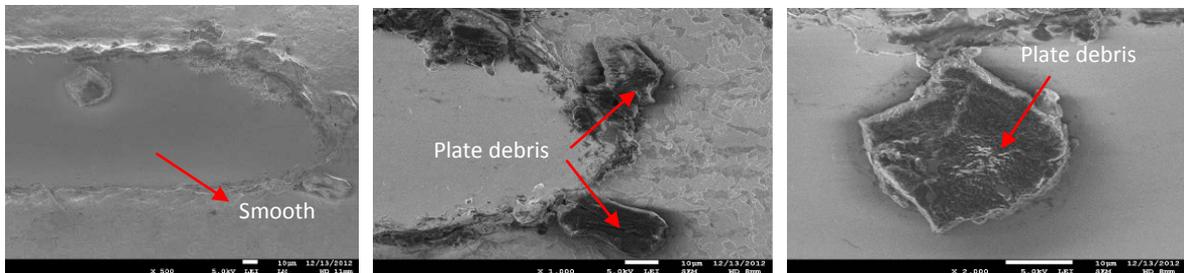
(a)
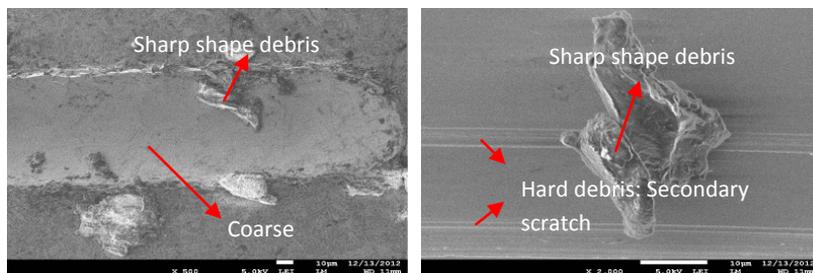
(b)

Fig.5 Scratch surfaces of (a) T2 dual phase and (b) T4 full martensite samples.

4. Discussion

The comparison of different microstructures suggests that the ferrite and pearlite mixture suffers the maximum residual penetration depth, which is attributed to the soft natures of both phases, i.e. both phases can accommodate severe plastic shear deformation, and hence the material can be easily plastically deformed or detached from the matrix, and hence generate deep groves and more wear loss. The full martensite possesses the highest hardness, but not the optimal scratch resistance due to the brittle feature of martensite. A good abrasion/scratch resistance requires a combination of good hardness and toughness, or from a microstructural point of view, not only hard constituent to resist against the applied load, but also a soft constituent to accommodate deformation and absorb (impact) energy. Therefore, samples T2 and T3 possessing a good balance of hard phase martensite and soft phase ferrite, or from the mechanical property point of view, a balance or strength/hardness and ductility/toughness, display optimal scratch resistance in the current investigation. The dual phase microstructure also results in smooth grooves and edges attributed to the plasticity of soft ferrite, and the smooth surface consequently reduces the friction and decreases further abrasion. On the contrary, the full martensite forms coarse grooves together with hard and sharp debris, which would cause secondary damage to the surface and exaggerates further abrasion process.

The scratch resistance in the current study presents a similar trend as the abrasion resistance of dual phase microstructure characterized by ASTM G65 test reported by Jha [11], which indicates that the scratch test could provide a fast and more reproducible method in characterizing the abrasion resistance. For further validation, ASTM G65 abrasion test is planned on same samples investigated in this paper and to provide a direct comparison of abrasion resistance and scratch resistance. More comprehensive investigations regarding mechanisms involved in both abrasion test and scratch test are needed to ensure the comparability. Further work is also required to find the optimal combination of ferrite and martensite (or bainite), i.e. volume fraction and morphology, achieved by tailored heat treatment schemes.

5. Conclusion

1. A HSLA steel grade is heat treated to obtain three types of microstructure, and corresponding scratch test shows that, the ferrite and martensite mixture possesses the best scratch resistance, followed by fully martensitic microstructure without being tempered. A mixture of ferrite and pearlite displays the most inferior scratch resistance.

2. The optimal scratch resistance originates from the mixture of hard load bearing martensite and the soft deformation accommodating ferrite, and leads to smooth scratch grooves and debris which decrease further friction and scratch loss.

3. Hardness and scratch resistance does not follow a monotonous relationship. Other mechanical properties are required, e.g. ductility and toughness, to achieve a optimal compromise.

4. Scratch test may present a fast, reproducible and quantitative method in characterizing the abrasion resistance, yet to be validated by a further direct comparison.

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