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A novel multi-pass dual-indenter scratch test to unravel abrasion damage formation in construction steels

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ABSTRACT

A proper understanding of abrasion resistance and associated damage mechanisms is of vital importance in the design of improved abrasion resistant construction steels. The conventional scratch test, sliding a rigid indenter under a controlled load and speed against a smooth surface, mimics the nature of the abrasion process and can be used to evaluate the abrasion resistance of various microstructures. However, scratch tests are mostly done on the initial surface, which can be very different from that formed during the abrasion process and hence do not truly reflect its abrasion resistant response. In the present work, a new scratch test methodology is developed to approach the real abrasion condition by carrying out a multi-pass dual indenter scratch tests, in which a small indenter scratches a pre-scratched surface produced by a large indenter. Five steel grades with different work hardening capacities, i.e. Interstitial-Free Ferritic steel (IF steel), Fully Martensitic steel (FM steel), Dual Phase steel (DP steel), Quench Partitioning steel (Q&P steel) and TWining Induced Plasticity steel (TWIP steel) were selected. Systematic scratch resistance experiments were performed to investigate the damage mechanisms, the work hardening behavior and the development of subsurface deformation layers. Results suggest that the work hardening layer formed beneath the abraded surface plays the dominant role in determining the abrasion resistance. Steels grades of DP, Q&P and TWIP display superior scratch and abrasion resistances, notwithstanding their relative low hardness compared to that of a corresponding steel with a fully martensitic microstructure.

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1. Introduction

Abrasion is a commonly occurring wear mechanism invariably observed in various industrial applications, such as automotive, transportation, mining, mineral processing, agricultural and earth moving industries, and represents a significant cost consideration in industry [1,2]. Abrasion resistance is a very complex response of a material in a tribo-system involving many variables. In addition to test conditions, the abrasion resistance can be correlated to different mechanical properties of the metallic structure, and eventually to the microstructural evolution during the process. To a first approximation, hardness is predominantly used as an indicator to rank the abrasion resistance of steels, 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 [5–10] clearly demonstrated that the simple linear relationship is not always true, and also "V" and "S" shaped correlations between the abrasion resistance and hardness have been reported. Gahr [5,11,12] attempted to develop more comprehensive abrasion resistant models taking into account other mechanical properties, such as strength, fracture toughness, as well as parameters of test conditions, e.g. particle size, shape, attack angle, and applied load etc. Considering the very complex and distinctive abrasion process it is inevitable that it raises the difficulty to build a general quantitative description of the abrasion as a function of other mechanical properties, which eventually are all determined by the microstructure. Therefore, instead of establishing correlations between abrasion resistance and other mechanical properties, an alternative and more attractive approach is to focus on its direct link to the steels microstructure and its evolution during the abrasion process. In a recent publication [13], the effects of various microstructural aspects, e.g. constituents, phase fraction, grain size, and morphology on the abrasion resistance, have been reviewed so as to understand their roles in determining the abrasion resistance. It showed that often contradictory observations have been reported. The contradictions are not only attributed to the complexity of the tribosystem and corresponding testing conditions, but also the dynamic nature of the abrasion

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process, i.e. the development of subsurface layer and its effect on further abrasion. When a material undergoes abrasion, the top surface deforms severely and may result in different local failure modes depending on the working condition, while the subsurface layer also responses to the external strain/stress and can be work hardened to different extents depending on the microstructure. The severe deformation leads to significant subsurface refinement and the thickness of such layer also varies. Many studies [6,8,14–16] have revealed that the subsurface work hardening layer plays a very important role in determining the abrasive wear resistance.

The scratch test, sliding a rigid indenter of controlled shape under a controlled load and speed against a smooth surface, mimics the abrasion process and has been used to evaluate the abrasion resistance of various microstructures [17–19]. However, the conventional scratch tests are mostly done on the initial surface [20–24], which can be very different to those that form during the abrasion process, e.g. irregularity, continuous development of subsurface deformation and work hardening etc., and hence do not automatically reflect the material abrasion resistant response. As mentioned in Refs. [25,26], the application of scratch test on initial surface to predict the abrasion mechanism in real abrasion process can lead to serious error and mislead the understanding of the abrasive wear resistance. Williams and Xie [27] commented that single pass scratching on a pristine surface is an over simplification of the actual situation, wherein the new particles scratch the worn surface which underwent previous processes. To better simulate the real process, methodologies of multiple parallel scratching have been proposed to include the interactions between scratches, e.g. Williams and Xie [27,28], Mezlini et al. [29] and Khellouki et al.[30]. Compared to the single scratch, it was observed that the wear mechanisms change due to the interactions with prior scratches. Moreover, da Silva and de Mello [31], and Da Silva et al. [32] also employed parallel scratches but introducing a superimposition between scratches, which suggested that the wear mechanisms depend on the degree of superimposition. Furthermore, in addition to parallel scratches, the repetitive scratching in the same track [33] and the interaction of crossing scratches [34] were also employed to investigate the wear mechanisms. Compared to the single pass scratch on a pristine initial surface, all multiple scratching methods provide more insights on wear mechanisms, the interactions of scratches and the effects of work hardening. Nevertheless, in all experimental setups reported to date, only one indenter was utilized and the new scratch was fully or partially superimposed to the previous scratch, which inevitably combined the effects of surface work hardening and contact geometry. Moreover, even for the work hardening itself, after only one pre-scratch, the surface and subsurface layer may not reach the stable condition with the saturated work hardening, which is most likely the case in real continuous wear process.

In the present work, a new multi-pass, dual-indenter scratch test methodology is developed to approach the real abrasion condition by carrying out scratch tests using a large indenter to generate a wide pre-scratch with stable saturated work hardening and a small indenter to evaluate the wear behavior excluding the contact geometrical effect. This test method not only probes damage formation during the actual scratching (abrasion) process but also probes its interaction with the damage in the deformed surface layer caused by prior local scratch deformations. The applied load and number of pre-scratches with the large indenter determine the amount of surface deformation hardening and deformation damage. Five steel grades with different work hardening capacity, i.e. Interstitial-Free Ferritic steel (IF steel), Fully Martensitic steel (FM steel), Dual Phase steel (DP steel), Quench Partitioning steel (Q&P steel) and TWining Induced Plasticity steel (TWIP steel) are selected. The abrasion resistance of various microstructures is investigated by carrying out the new scratch test with different pre-scratched conditions. The worn scar and the development of subsurface region are investigated. The damage mechanisms upon different test conditions are analyzed. The correlation of scratch resistance test with abrasive wear test is discussed.

2. Experimental procedure

2.1. Materials and microstructures

In the current study, five different types of construction steels with different work hardening response are chosen. Their compositions and corresponding microstructures are summarized in Table 1. Their microstructures in the form of SEM micrographs are shown in Fig. 1. The IF steel is a single phase ferritic steel with very low interstitial elements. As shown in Fig. 1a, the average grain size is about 45 μm. The FM steel possesses a single phase martensite obtained by full austenitization and water quenching the DP steel. As shown in Fig. 1b, no retained austenite is visible in the as quenched condition. The DP steel is a commercial dual phase steel grade, consisting of approximately 30% ferrite and 70% martensite (Fig. 1c), produced by intercritical annealing and subsequent water quenching. The Q&P steel possesses complex microstructure of ferrite, martensite and retained austenite in which the quenching and partitioning (Q&P) process [35] was employed to partition the C from oversaturated martensite to retained austenite and hence to increase the stability of the later. The microstructure is shown in Fig. 1d in which the retained austenite (~12%) can be clearly identified. It is embedded in a matrix mixture of ferrite (~28%) and martensite (~60%). The TWIP steel is a specific high Mn austenitic steel, which displays very high work hardening capacity by forming twins upon deformation. Some twin structures are already observed on the polished surface (Fig. 1e).

2.2. Sample preparation and hardness test

Prior to the hardness measurements and scratch testing, samples were mounted and polished following the standard metallographic preparation. Micro-hardness measurements were carried out using Vickers indenter under 2 N load and making 10 independent measurements. Hardness values are listed in Table 1. The IF steel possesses the lowest hardness owing to the soft nature of the ferrite, while the fully martensitic steel displays the highest hardness of 482 Hv because of its composition and the intrinsic structure of martensite. Hardness of DP and Q&P steel are at an intermediate level due to the mixture of ferrite and martensite phases (in Q&P steel with the presence of retained austenite). The hardness of TWIP steel is quite low, ~240 Hv, corresponding to a fully austenite matrix with limited twining upon indentation.

2.3. Scratch tests

Scratch tests were performed with a CSM microscratch tester, schematically illustrated in Fig. 2. Two spherical diamond Rockwell indenters with different tip radius and cone angles were employed in the current study: 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°. Three testing modes were employed with conditions as specified in Table 2.

- Mode I, the small indenter on the initial (polished) surface.
- Mode II, the small indenter on a pre-scratch produced by the large indenter with a single pass under different loads.

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